Introduction to Photovoltaics Manufacturing Technology

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Overview

- Market/Industrial Overview
- Photovoltaic Fundamentals
- PV Technologies
- PV Systems
- Achieving Grid Parity

Market / Industrial Overview

Renewables Comparison

Technology	WW Theoretical Potential	WW Practical Potential	Strengths	Weaknesses
Wave	2.5TW	0.03TW	Most reliable renewable source.	Very limited potential. May require high maintenance.
Hydroelectric	4.6TW	1.5TW	Reliable. Long-lasting installations.	Limited siting. Requires inundation.
Wind	1200TW	3TW	Large potential.	Unreliable, output dependent on weather patterns. No intrinsic storage capability.
Geothermal	46.1TW	11.6TW	Easy to build efficient plant, once proper locale is identified. Continuous power production.	Well production sometimes unreliable.
Solar	120000TW	800TW	Plenty of capacity for needs.	No intrinsic storage capability. 10% efficiency under ideal illumination conditions.
Biomass	65TW	20TW	Can leverage current power generation infrastructure.	31% of total landmass. 0.3% efficiency. Best case carbon neutral.

Year	Total WW Need
1990	12TW
2050	28TW

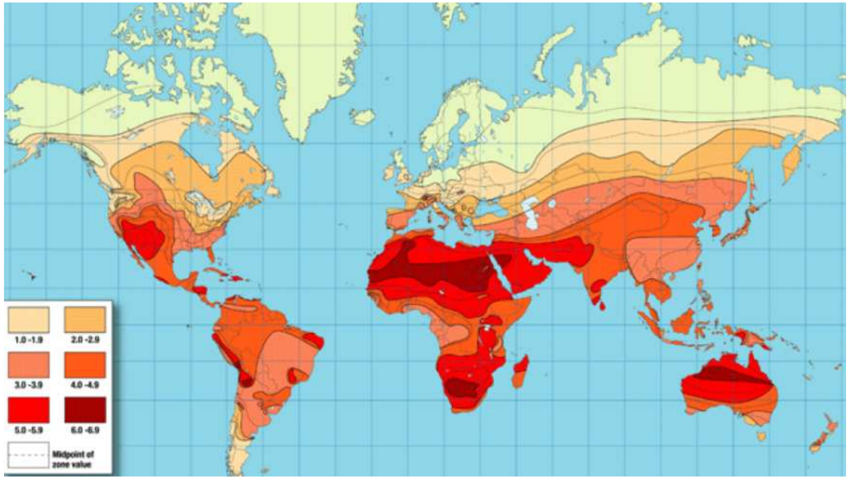
Solar has the largest potential to satisfy world needs.

Source: Nathan S. Lewis, California Institute of Technology

Global Solar Energy Resources & Potential

Average insolation [kWh/m^2/day]

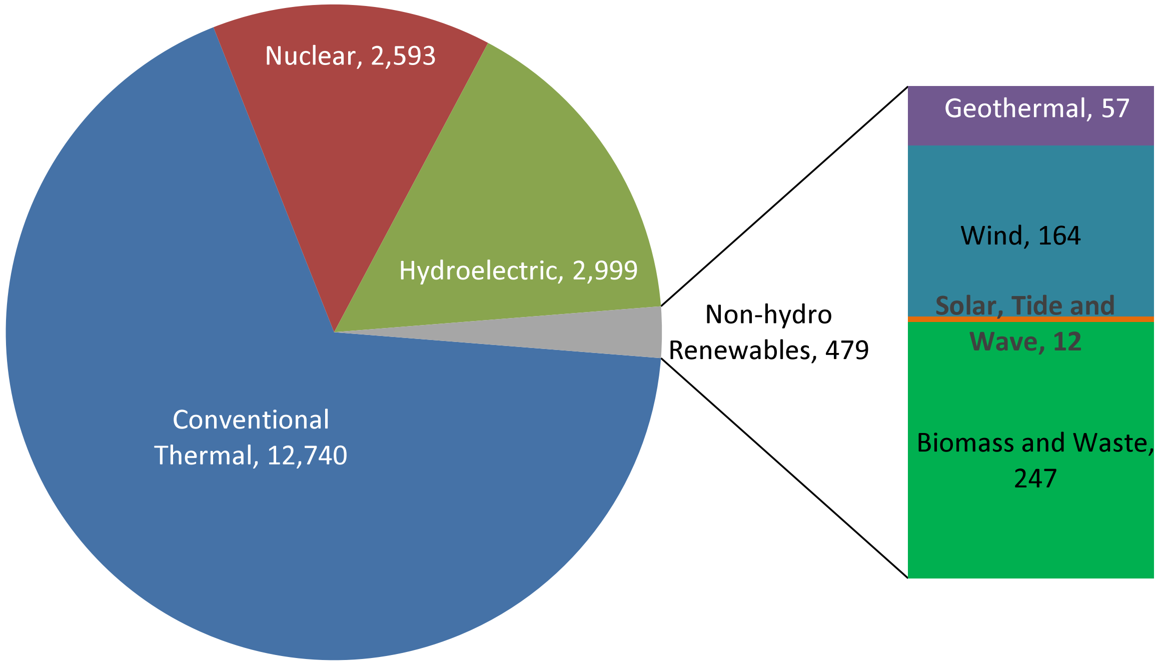
Efficiency 6 squares @ 3.3TW ea.



- Worldwide Solar Energy:
  - Theoretical » 120,000 TW – energy in one hour of sunlight ° 14 TW
  - Practical » 600 TW
- US consumption » 3.6 TW
  - 10% 200 mi x 200 mi
  - 20% 165 mi x 165 mi
  - 30% 115 mi x 115 mi
  - 40% 100 mi x 100 mi

Source: NREL & California Institute of Technology

Solar Energy

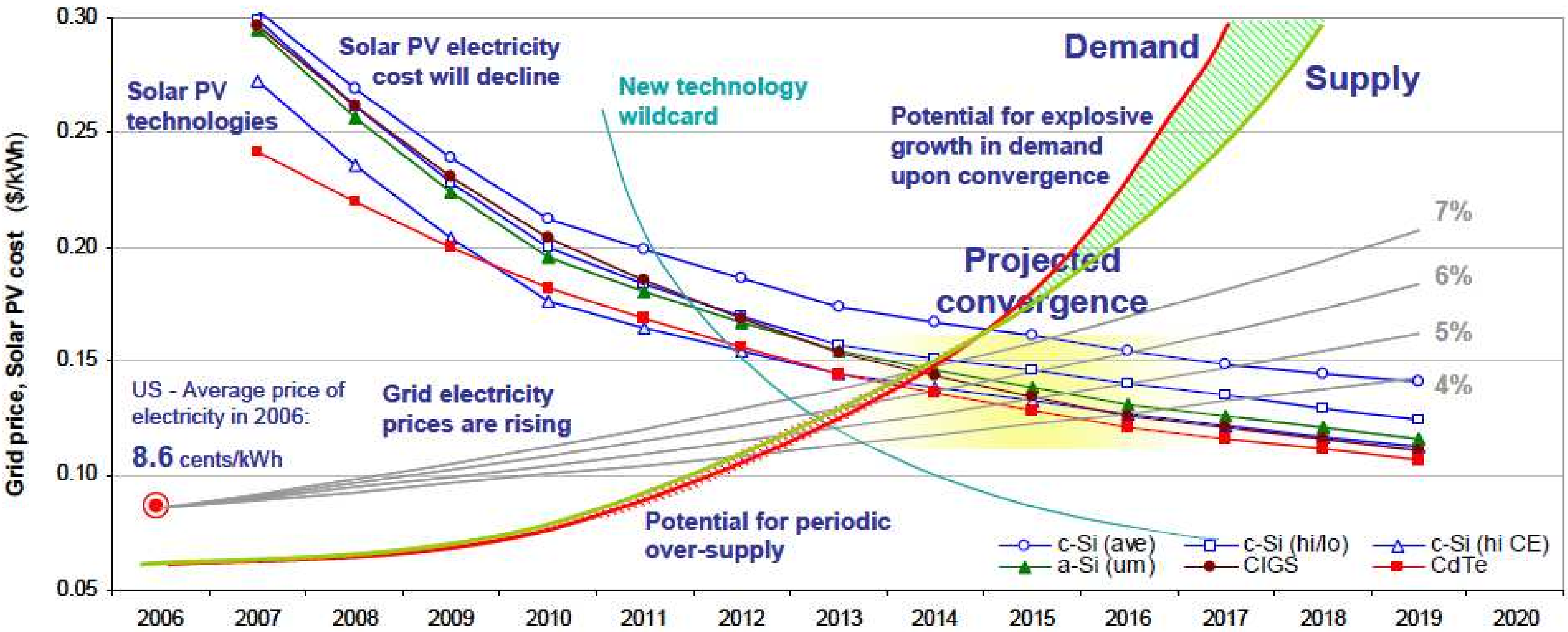


Enough solar energy hits the earth in one hour to power all human energy needs, both motive and stationary, for one year

Source: US Energy Information Administration

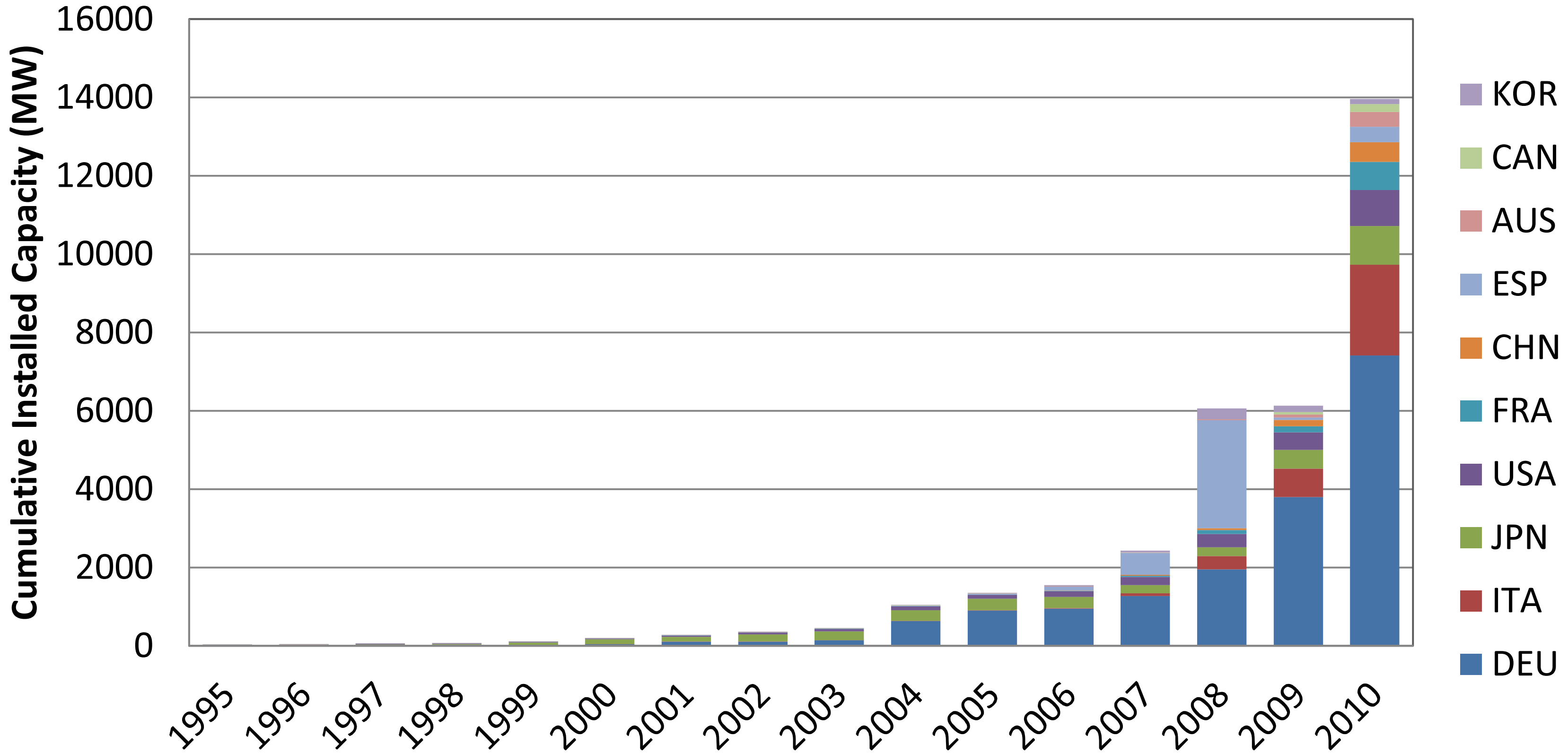
Long-term View of the Solar PV Industry

A complex marketplace



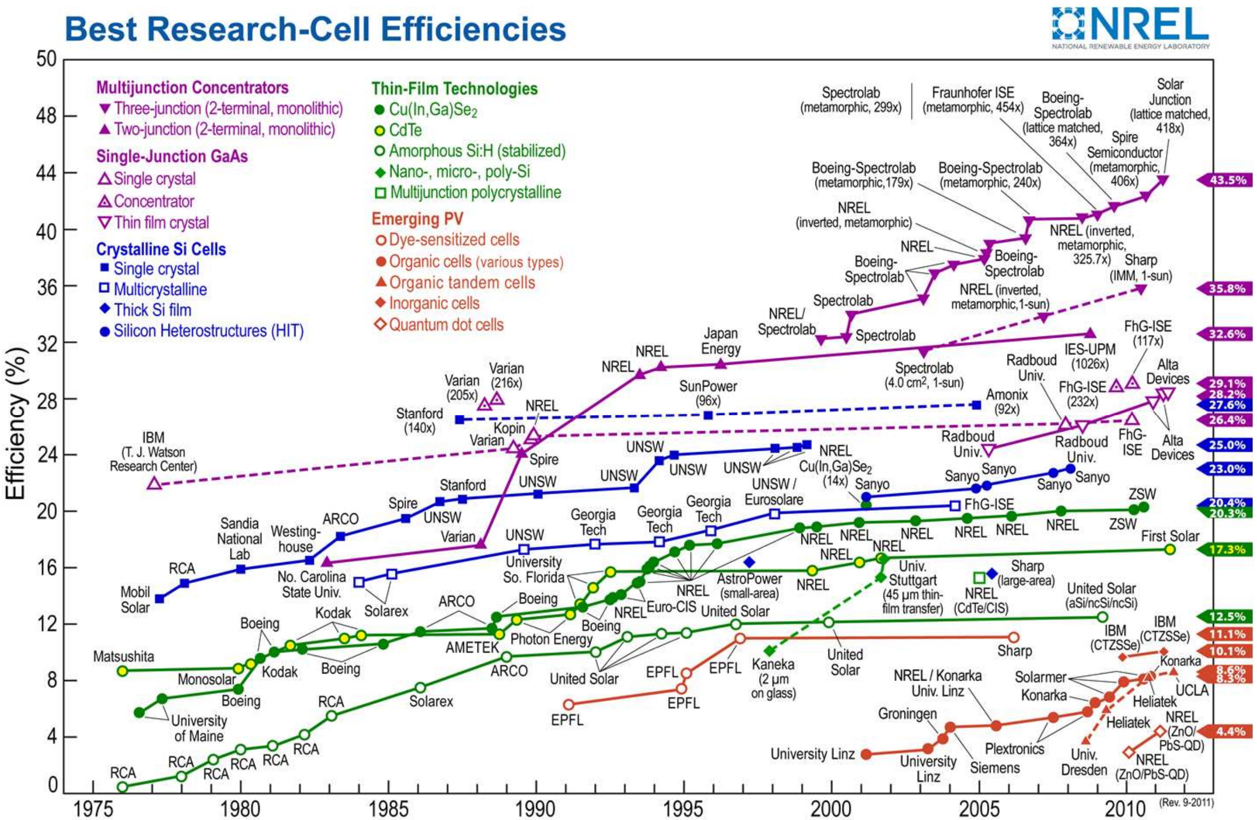
Source: "Solar Photovoltaic Industry", Deutsche Bank, May 2008

Global Cumulative Installed Capacity of PV



Source: "Trends in photovoltaic applications". IEA PVPS. September 2011.

NREL Best Research Cell Efficiencies



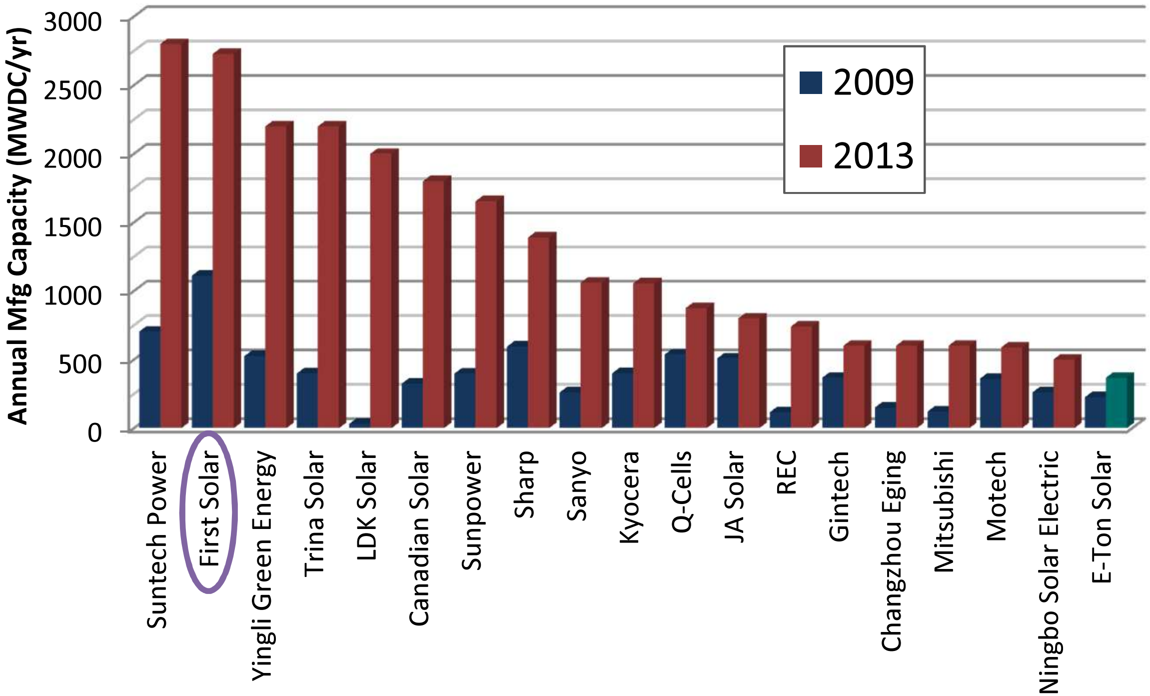
Source: Keith Emery National Renewable Energy Laboratories, (NREL, 2010)

- Best CPV 43.5%. (Solar Junction)
- Best c-Si 27.6% (Amonix)
- Best thin-film 28.2% (Alta Devices)
- Best low-cost high-volume: 17.3% (First Solar)
- High volume mfg. tends to lag R&D cells ~15 years.

Module Manufacturers

c-Si	poly-Si	a-Si:H	CdTe	CIGS	Other PV
REC Solar SCHOTT solar Q.CELLS SUNPOWER	SUNTECH CALISOLAR Trinasolar LDK LIGHT OUR FUTURE KYOCERA KYOCERA Solar, Inc. YINGLI SOLAR JA SOLAR JinKO ReneSola CanadianSolar SolarWorld THE SUNPOWERED COMPANY Solarfun	UNI-SOLAR United Solar Ovonic SHARP SIMPLY THE BEST Solar moserbaer Photo Voltaic Kaneka BSC BANGKOK SOLAR CO., LTD QS Solar	First Solar. PrimeStar Solar Making it Happen calyxo abound solar Alion ARENDI	MiaSolé Thin-film solar STION Ascent SOLAR SOLOPOWER nanosolar SOLIBRO HelioVolt Johanna Solar Technology NanoWin Thin Film Tech SOLYNDRA	ALTADEVICES SOLEXEL Solexant G24 INNOVATIONS echo KONARKA Cyrium Technologies

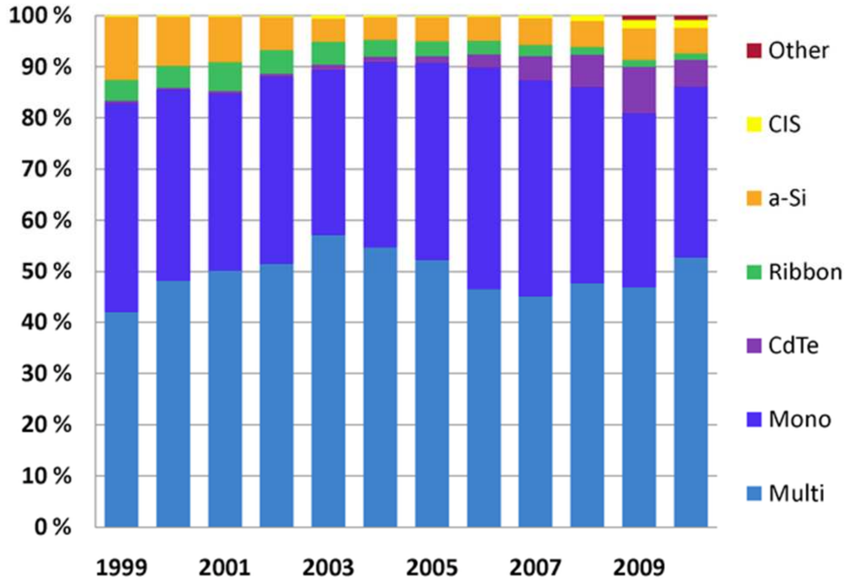
Top Module Manufacturers by Mfg Capacity



- 9 Chinese
- 4 Japanese
- **1 US**
- 2 Taiwanese
- 2 European

PV Technologies

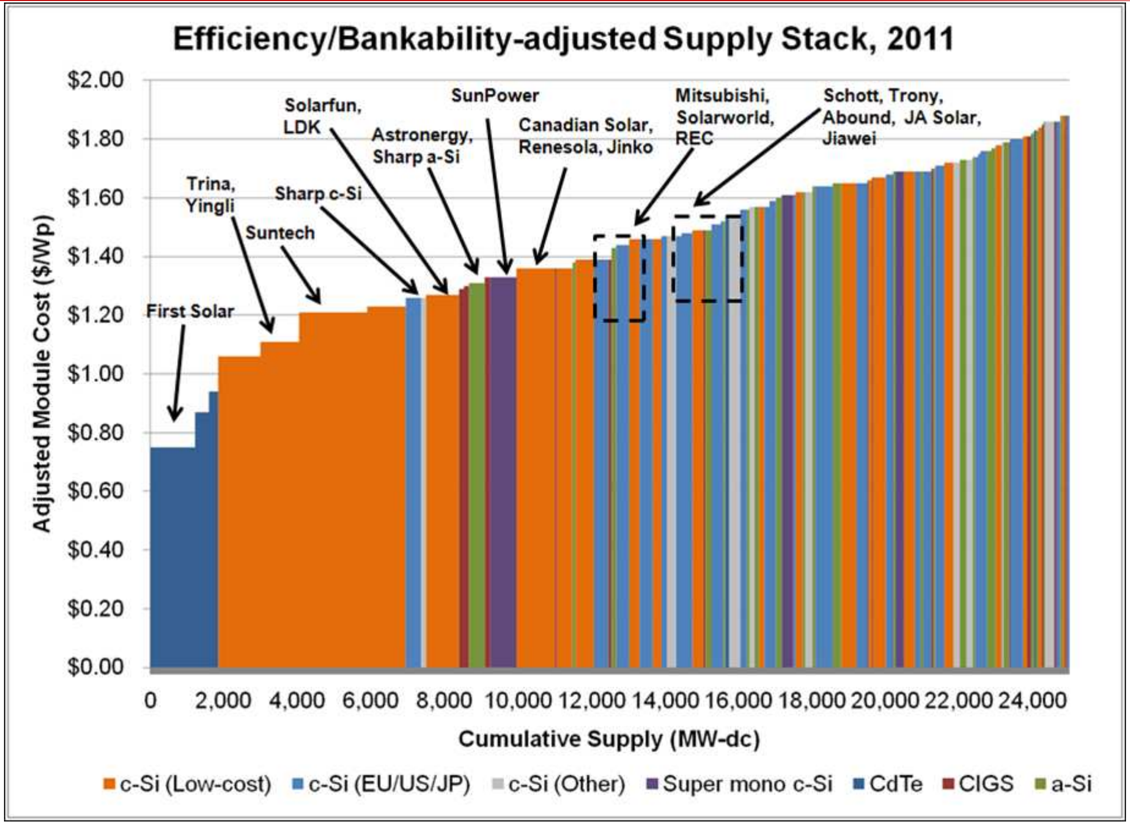
2010 Technology mix



- Silicon wafer based, 84%.
- Thin film, 15%.

<u>Source:</u> CleanEnergy.

Module Cost vs Cumulative Supply, 2011

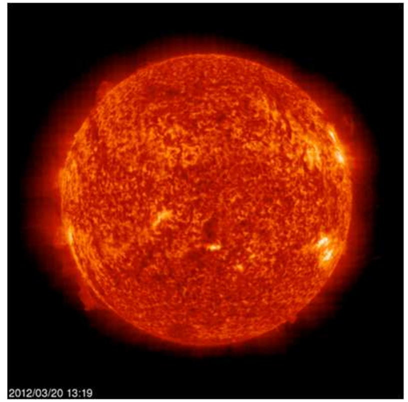


Source: GTM Research, PV Competitive Dynamics in 2011 and Beyond (excerpt), (from http://www.greentechmedia.com/articles/print/pv-competitive-dynamics-in-2011-and-beyond-the-battle-resumes/)

Photovoltaic Fundamentals

Sun-Light

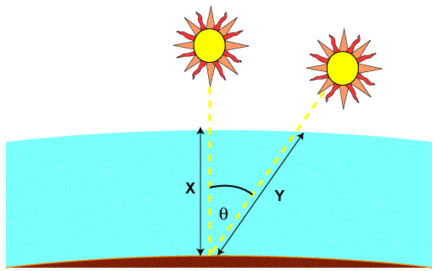
- The sun is powered by H fusion:
  - Core temp- 2 x 10^7°K, surface temp- 6000°K.
  - Power 9.5 x 10^{13} TW.
  - Power density radiating from the surface: 6.25 x 10^7 W/m^2.
  - Power density at earth's atmosphere(AM0):1.35 kW/m^2.



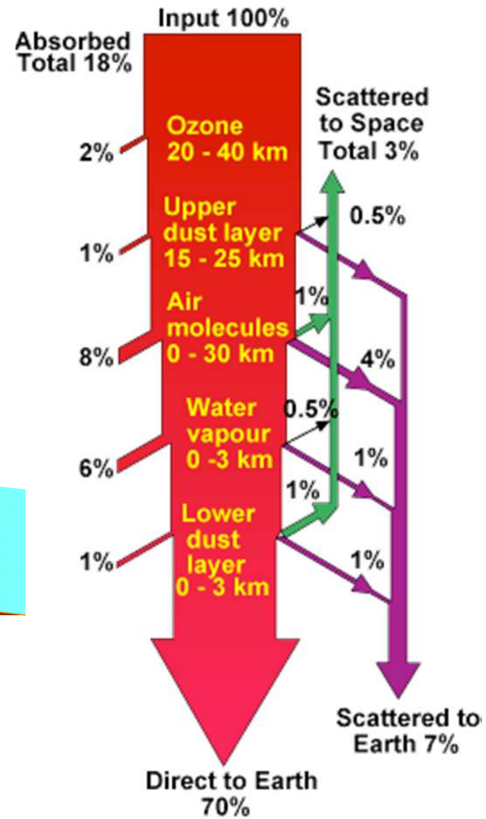
Terrestrial Light Losses

- As light transits the atmosphere it is absorbed or reflected in the air column.
- Air Mass (with horizon corrections):

$$AM = \frac{1}{\cos\theta + 0.50572(96.07995-\theta)^{-1.6364}}$$

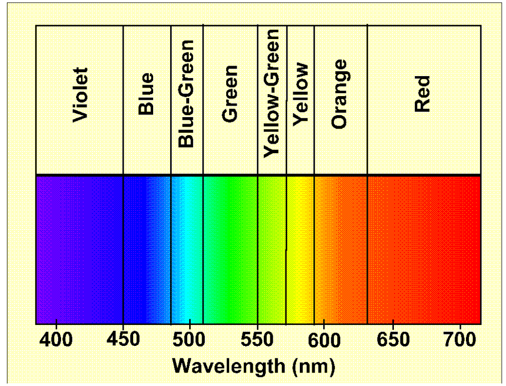


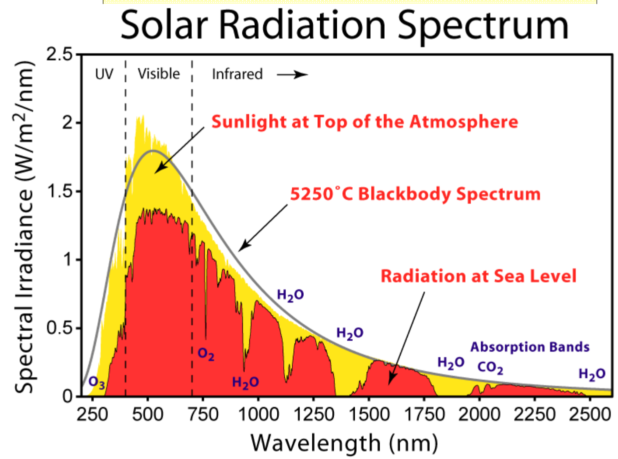
- Power density at earth's surface AM1.5G: 1.0 kW/m².



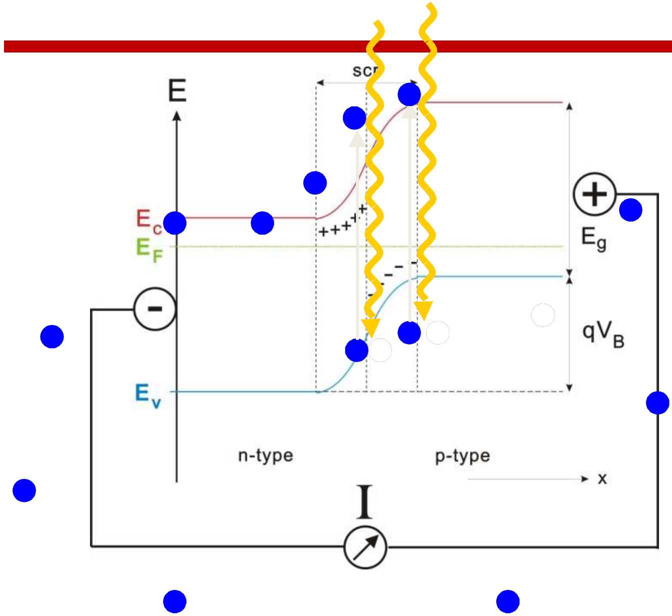
Photovoltaic Effect

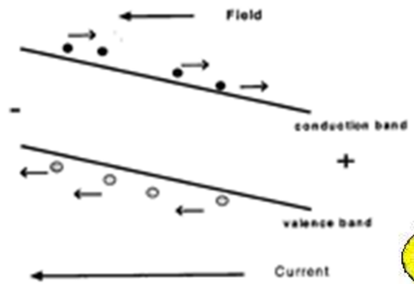
- Photovoltage in electrode/electrolyte system, (Becquerel 1839)
- Photoconductivity observed in solid selenium, (Smith 1873)
- Wave-particle dualism (Einstein- 1905)
  - light composed of particles called photons
  - photons have different energies
  - photons are reflected, absorbed or pass through matter
  - photons with proper energies generate electrical current
- 1954 first practical solar cell (c-Si; h = 6%)

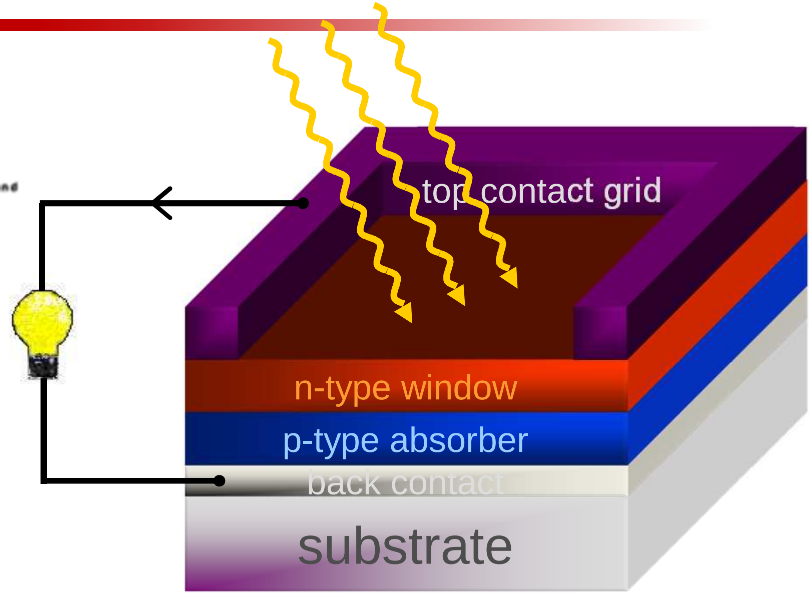




Cell Junction Theory







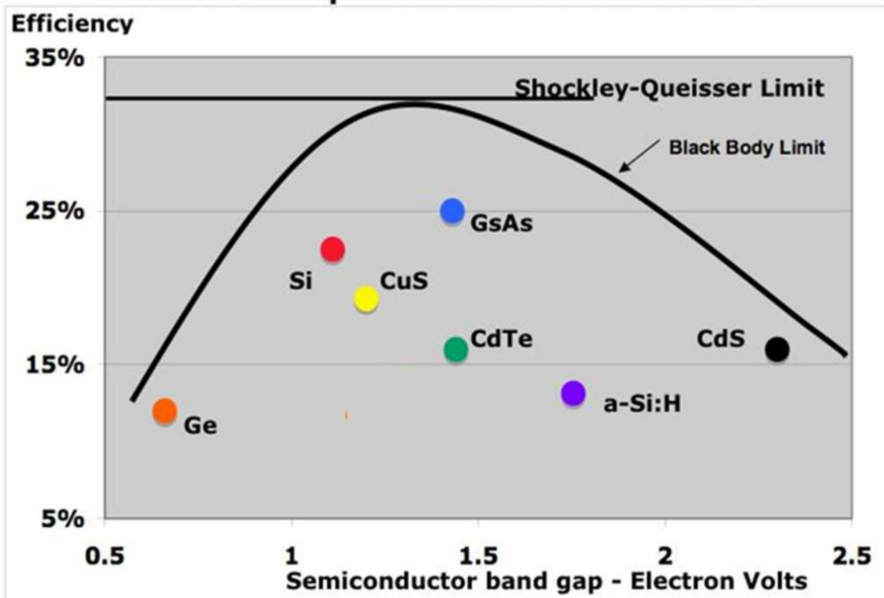
- solar cells are minority carrier devices
  - minority carriers are injected by the energy of incident photons
  - need to collect these injected minority carriers before they recombine
  - internal electric field accelerates minority carriers across scr where they become majority carriers
  - if external circuit is closed charge will flow doing work
  - carriers recombine at cell terminals rendering the circuit electrically neutral

Courtesy: Markus Beck

Conversion Efficiency Potential

- GaAs, CdTe have optimal bang-gaps.
- Shockley-Queisser Limit
  - Assumptions
    - Single p-n junction.
    - Sunlight intensity is 1kW/m^2.
    - Excess energy in the photons is lost.
  - Results
    - Maximum available power is 33.5% for a single junction.
    - Maximum available power for infinite junctions, 68%.
- Best devices to date:
  - 28.2% GaAs cell, Alta Devices (Santa Clara), 2011.
  - 43.5% triple junction GaAs cell, Solar Junction (San Jose), 2011.

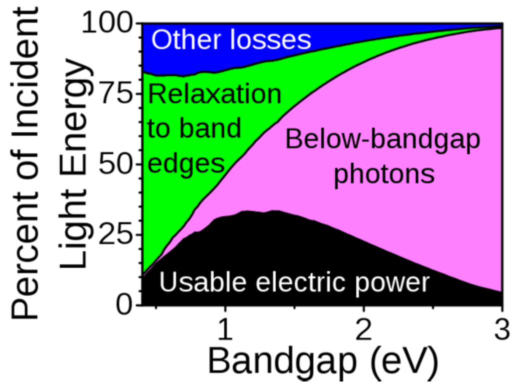
Band Gap and Efficiencies



Source: DOE, Lewis Group at Caltech, J. Theil

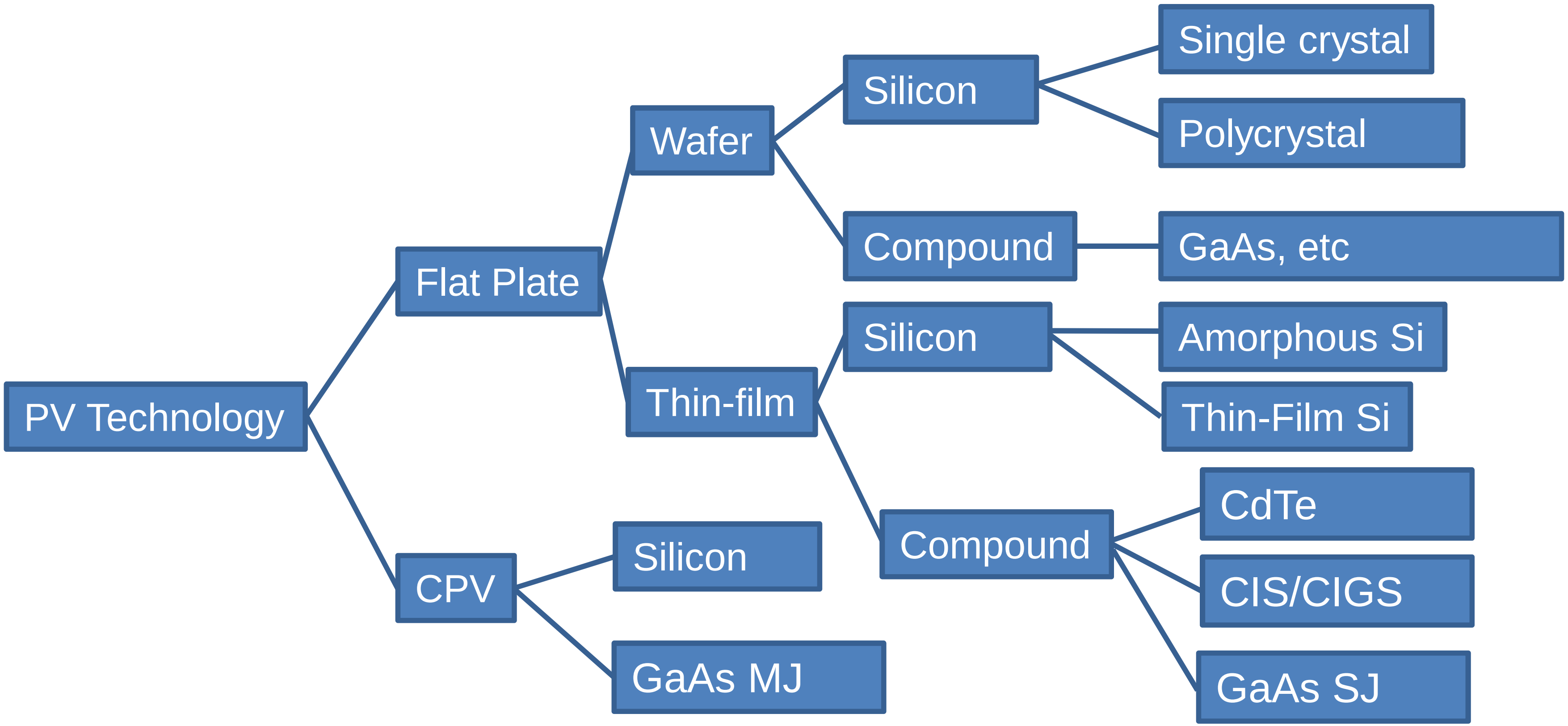
Strategies to Surpass the Shockley-Queisser Limit

Strategy	Description	Reference
Light Concentration	Rely on increasing the efficiency of the cell's operating point by increasing the current generates.	A. S> Brown, *ournal of Applied Physics*, Volume 92, Issue 1 August 2002, pg. 1392
Multiple Carrier Generation	Use quantum dots within the gap to convert excess energy into an extra photon.	A. J. Nozik, "Quantum Dot Solar Cells", National Renewable Energy Laboratory, October 2001
Photon Upconversion (Fluorescent and Thermophotovoltaic)	Take multiple photons whose individual enegy is below the band-gap and upconvert them into a single higher energy photon above thee bandgap.	Bahram Jalali, Sasan Fathpour, and Kevin Tsia, "Green Silicon Photonics", *Optics and Photonics News*, Vol. 20, Issue 6, pp. 18-23 (2009)
Down conversion	Take higher energy photons and down convert them to minimize thermalization losses.	Bahram Jalali, Sasan Fathpour, and Kevin Tsia, "Green Silicon Photonics", *Optics and Photonics News*, Vol. 20, Issue 6, pp. 18-23 (2009) Nils-Peter Harder and Peter Würfel, "Theoretical limits of thermophotovoltaic solar energy conversion", *Semiconductor Science and Technology*, Volume 18 Issue 5 (May 2003)
Hot Electron Capture	Use quantum confinement techniques to collect excess photon energy that would otherwise be thermalized.	Nils-Peter Harder and Peter Würfel, "Theoretical limits of thermophotovoltaic solar energy conversion", *Semiconductor Science and Technology*, Volume 18 Issue 5 (May 2003)
Impurity Photovoltaics	Develop deep level states within the gap to capture low-energy photons.	A. S> Brown, *ournal of Applied Physics*, Volume 92, Issue 1 August 2002, pg. 1392

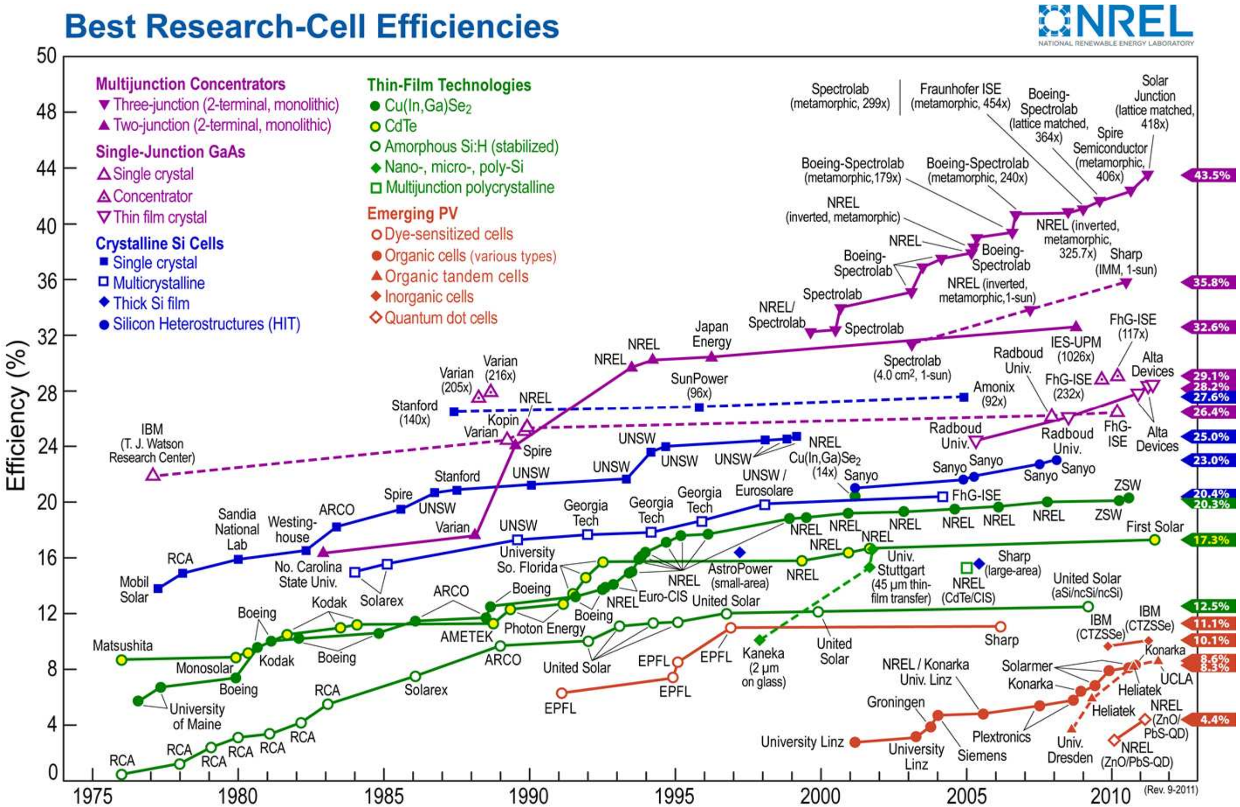


PV Technologies

Categories of Solar Cells



NREL Best Research Cell Efficiencies

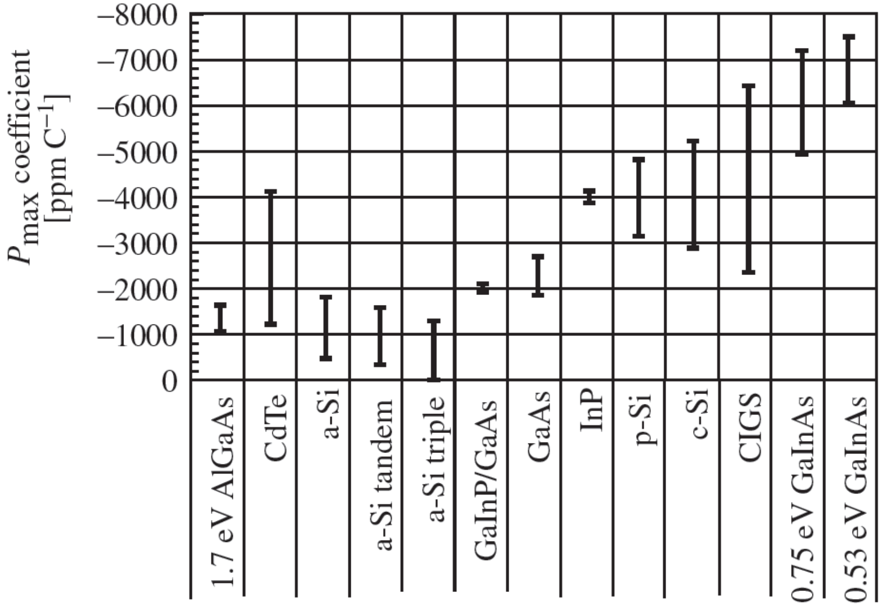


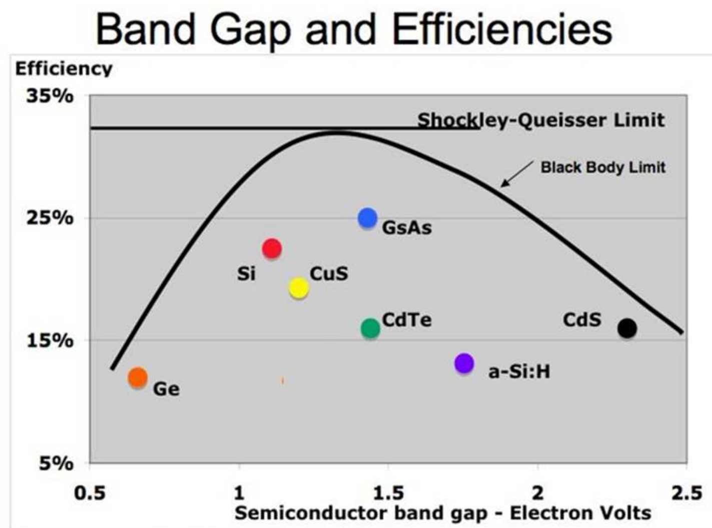
Source: Keith Emery National Renewable Energy Laboratories, (NREL, 2010)

PV Technology Comparison

Technology	Advantages	Drawbacks	Record Cell Efficiency
CdTe	Lowest-cost large-scale technology in production. (14.4% module efficiency demonstrated.)	Low doping concentration. High work-function, difficult to make Ohmic contacts.	17.3%
CIGS	Highest thin-film efficiency demonstrated 17.1%. Built-in E-field for more efficient. Most radiation hard semiconductor known.	Quaternary material system, difficult to manufacture.	20.3%
c-Si	Highest flat-plate efficiency on the market.	Highest material costs of any flat plate technology.	25.0%
a-Si:H	Simplest manufacturing technology.	Limited efficiency upside.	12.5%
GaAs SJ	Highest potential thin-film technology.	Unproven in volume. Cost structure not well defined.	28.2%
GaAs CPV	Highest absolute efficiency. Steady daily power generation.	Higher system costs, complex system. Higher maintenance costs. Economic geographic area limited to high DNI locales.	43.5%

Temperature Coefficients of PV Technologies

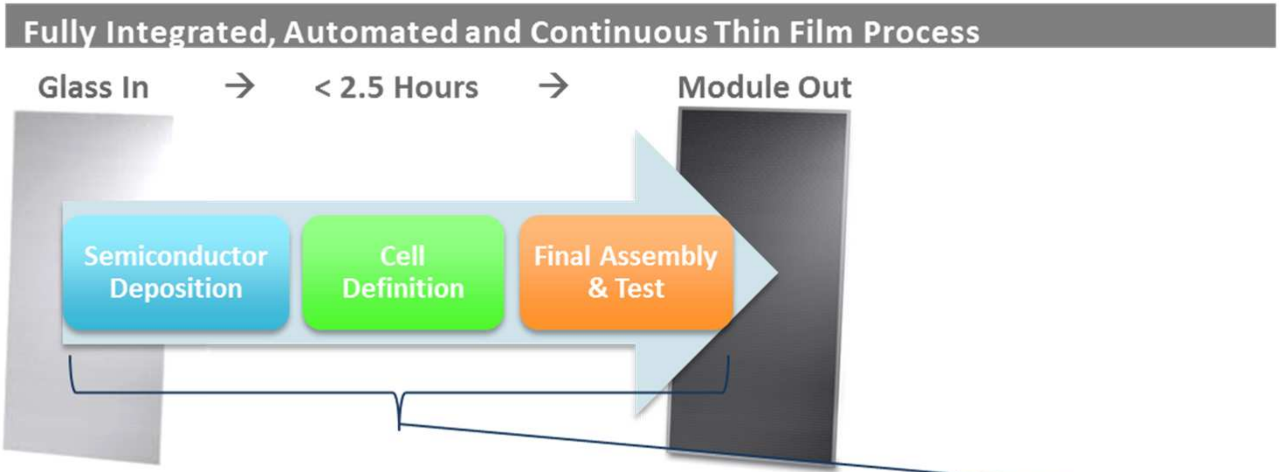




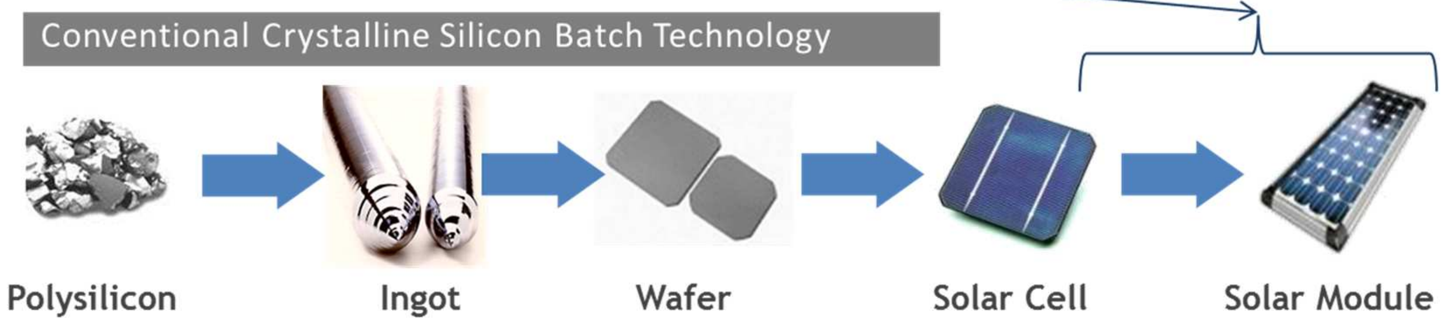
Source: DOE, Lewis Group at Caltech, J. Theil

Courtesy: Keith Emery, NREL.

Technology & Manufacturing (Thin-Film vs c-Si)



- 98-99% reduction in high-cost semiconductor material.
- Fully integrated, continuous process vs. batch processing.
- Large 60 x 120cm (2' x 4') substrate vs. 6" wafers.

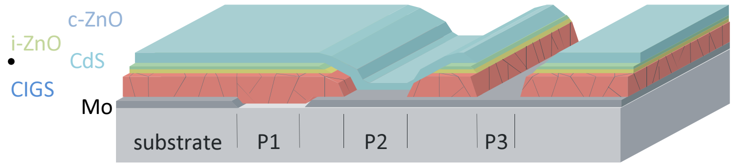


Courtesy: Markus Beck

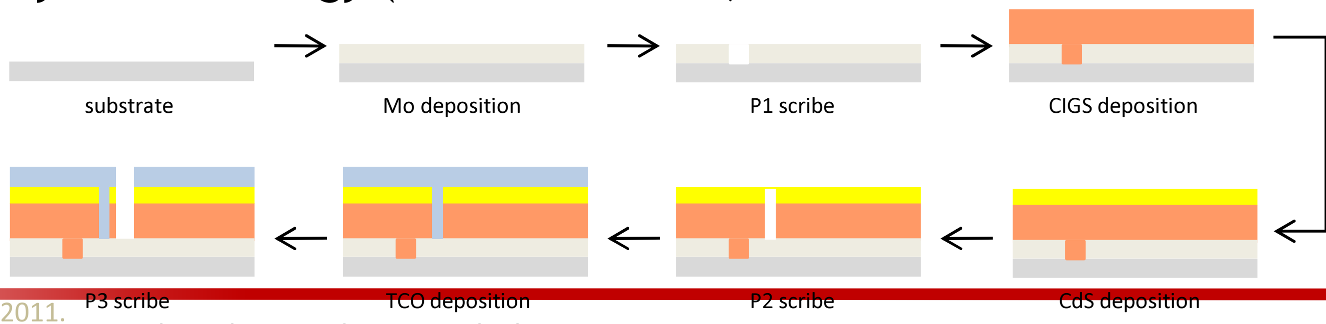
Flat Plate PV Technologies- c-Si vs Thin Film

- c-Si most common technology
  - in use for over 50 years.
  - Si very abundant (2nd only to O in earth's crust).
- Si readily available, requires extremely high purity (99.9999%)
  - high refining costs.
  - limited availability used to increase cost for PV grade Si.
- Thin films tolerate less pure raw materials
  - CdTe demonstrated maturity and clear price leadership.
  - CIGS highest laboratory efficiency of any thin film technology.
  - a-Si:H simplest to develop, lowest mfg capital cost.

PV Technologies - CIGS (copper indium gallium diselenide)



- CIGS Heterojunction device (CIGS p-type, CdS n-type).
- Wide range of absorber formation processes.
  - single or multi-stage co-evaporation
  - sequential processing
  - selenization & sulfurization of elemental layers
- Rigid (glass) or flexible substrates (metal or polymer foil)
- Complicated multi-element material system.
  - E_g tuning via Ga and/or S content (≈ 1 – 2.4eV)
- Highest efficiency of any TF technology (20.3% @ 0.5cm^2, 17.2% module*)

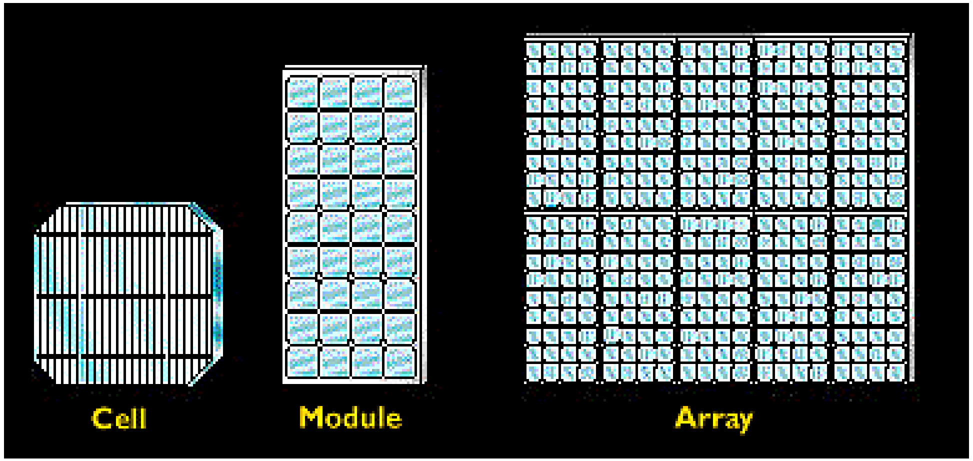


*Solar Frontier, 0.1 m^2 module, 3/2011.

Photovoltaic Systems

Definitions

- The primary building block of a PV system is the PV cell.
  - typically (multi)crystalline or thin-film (TF).
  - (poly)c-Si about 4” ´ 4”, 150 - 220 mm thick; TF 2-10 mm.
  - only small voltage (material dependent) and current (cell size dependent).
- Increase total power by series and parallel connection of cells into a module.
- Modules can be connected in parallel and/or series to even larger units, arrays.
- DC to AC via an inverter.



Courtesy: Markus Beck

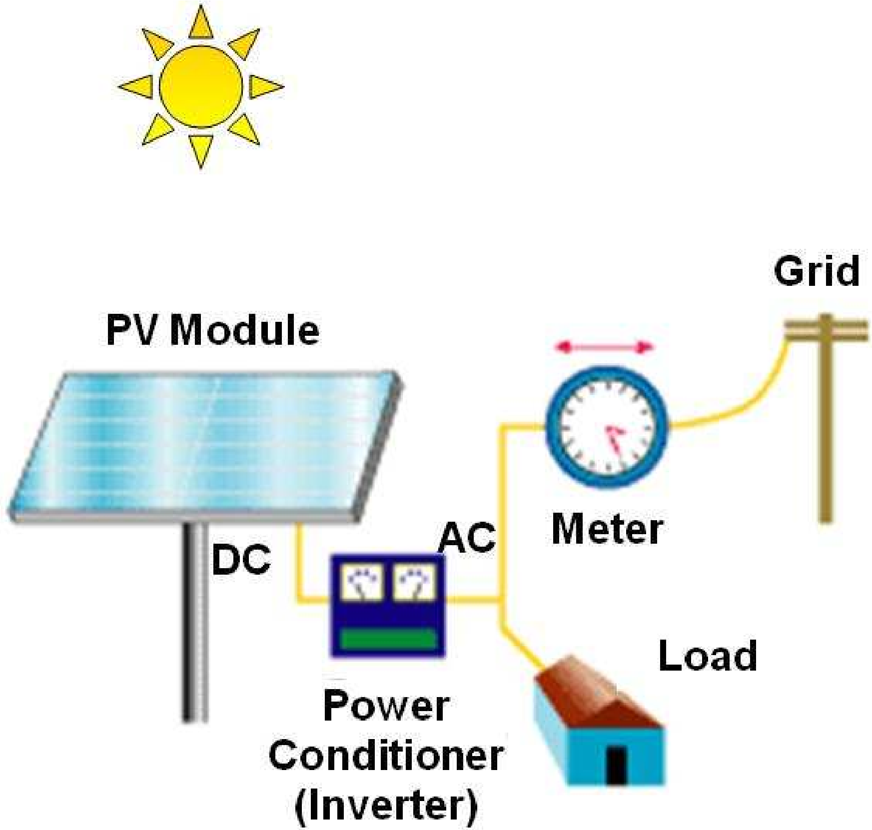
Definitions

- Wp (Watt peak): DC power output of a PV module at standard test conditions (STC)
- Installed PV System = Module + BOS
- Module
  - cell
  - connections
  - filler sheet
  - encapsulant
  - (frame)

- BOS
  - inverter
  - mounts
  - wiring
  - installation labor
  - site preparation
  - trenching and conduit

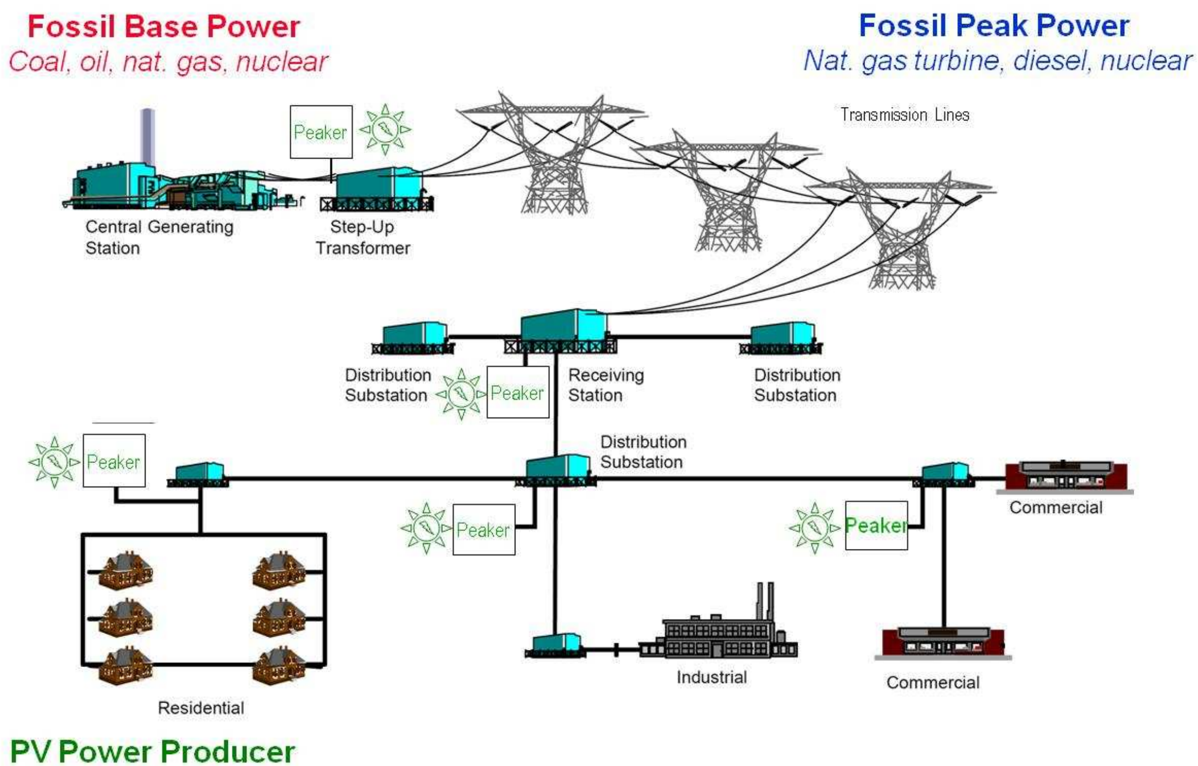
PV System Basics

- A PV system converts sunlight to AC electricity, with no fuel or emissions
- PV electricity reduces the amount of fossil fuels needed to produce electricity and can reduce or eliminate utility electric bills
- The output of a PV electricity system overlaps with peak electricity demand, so PV mostly competes with peak conventional electricity.



Courtesy: Markus Beck

Electric Grid Basics



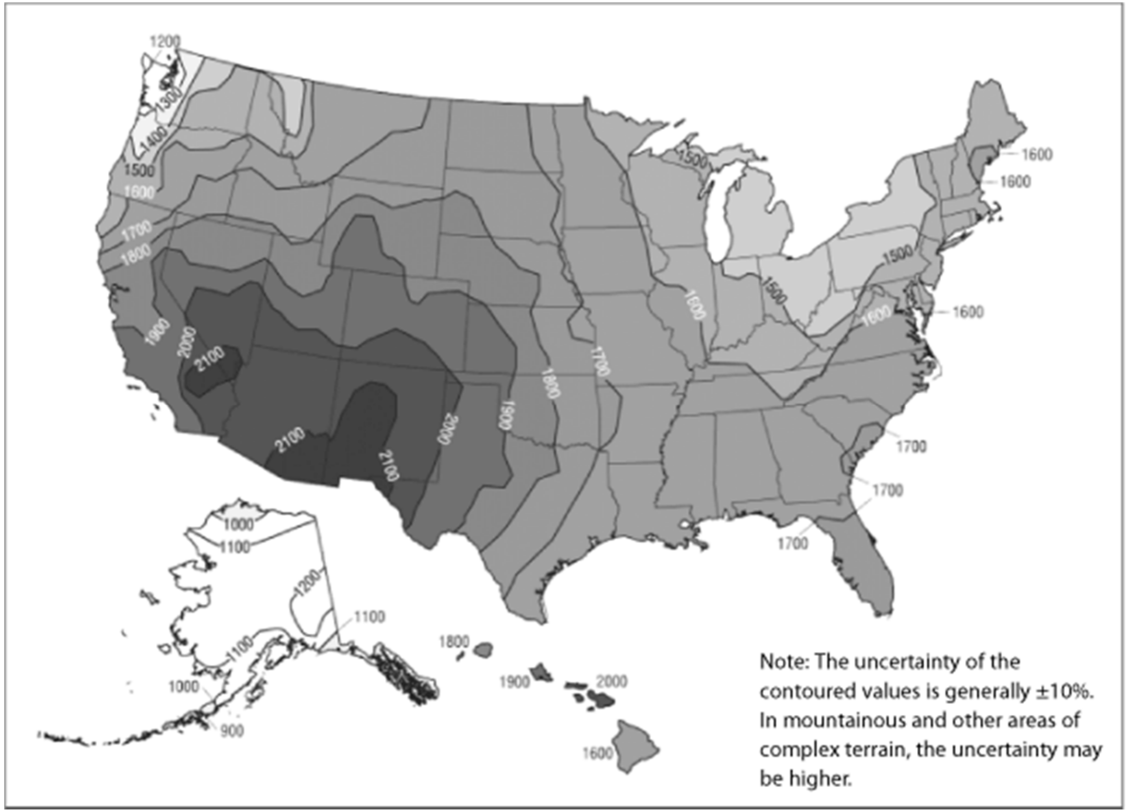
Source: EPRI

PV Benefits by Location

- Grid-Tied Photovoltaics
  - Bay Area about 1,900 kWh solar electric energy per kW AC of installed PV
  - Calculate cost savings:

$$savings = \frac{kWh}{kWyear} \times rate(\$) \times kW(PV, AC)$$

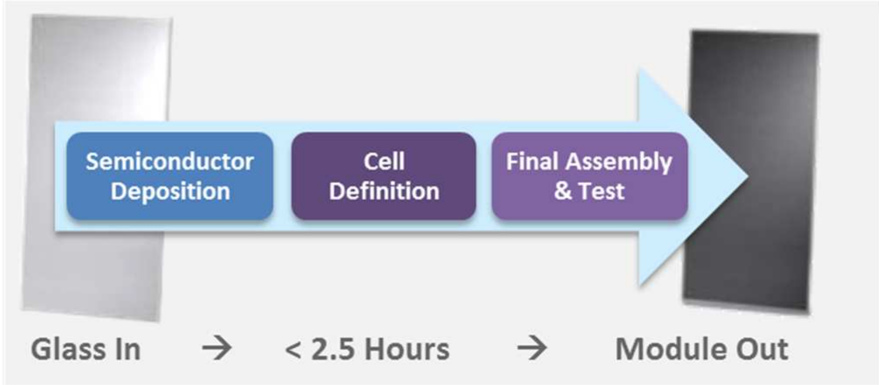
  - PGE 0.15$/kWh
  - For 3kW DC (=2kW AC)
  - Savings = $570/year



Achieving Grid Parity: Utility Scale Solar

First Solar's Offerings

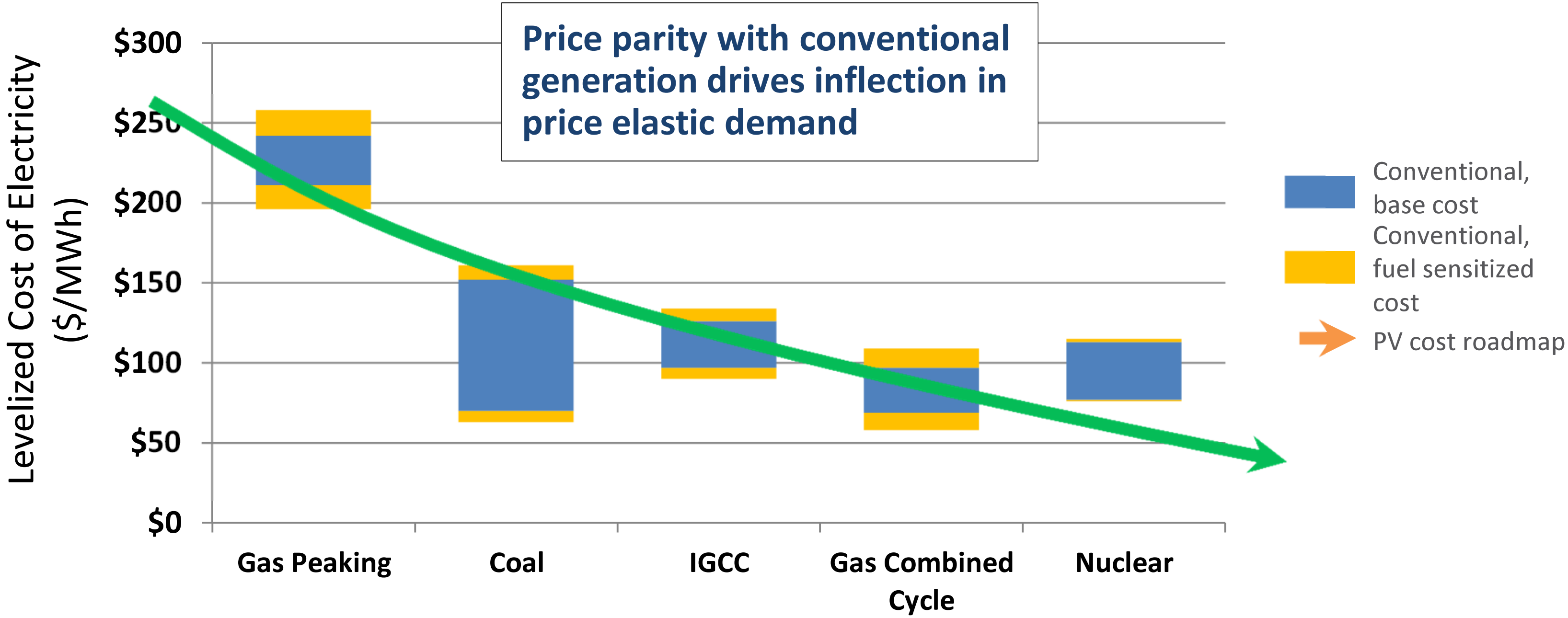
- Module Manufacturing
  - Breakthrough thin-film process technology
  - Fully integrated, continuous process
  - Continuous cost reduction driven by productivity and technology improvements
- Systems Solutions
  - Utility-scale PV systems
  - Project and site development capabilities
  - Rooftop and commercial and industrial solutions
  - Engineering, procurement, and construction capabilities (turnkey solution)
  - Monitoring and maintenance program—predictable lifetime expenses



First Solar.

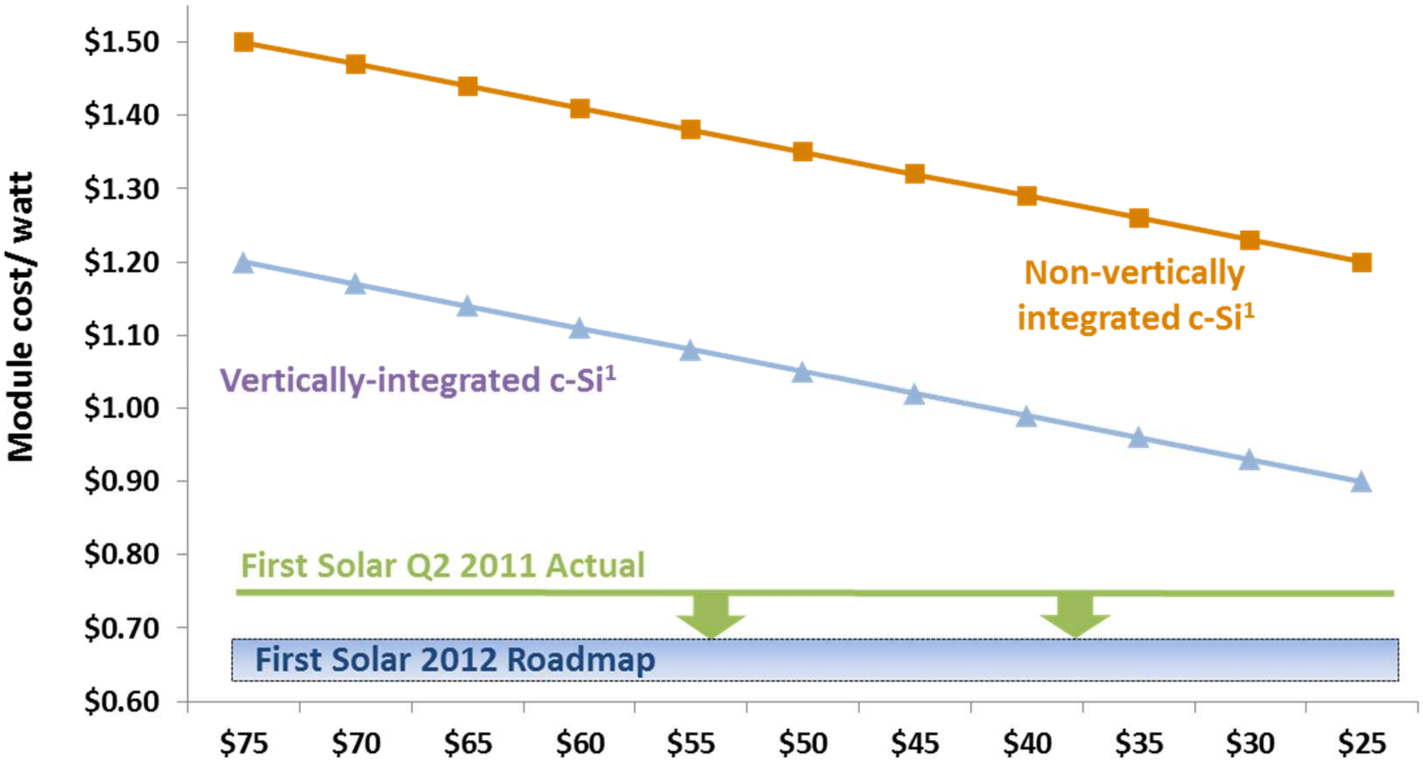
Crossing Over to Sustainable Markets

- Conventional generation based on Lazard LCOE Analysis v 5.0; June 2011. Assumes coal price of $2.50/MMBtu and natural gas price of $5.50/MMBtu.
- High end of coal and IGCC costs incorporates 90% carbon capture. Fuel sensitivity assumes +/- 25% fuel cost. Nuclear does not reflect decommissioning costs.



Courtesy: First Solar Inc., (2011)

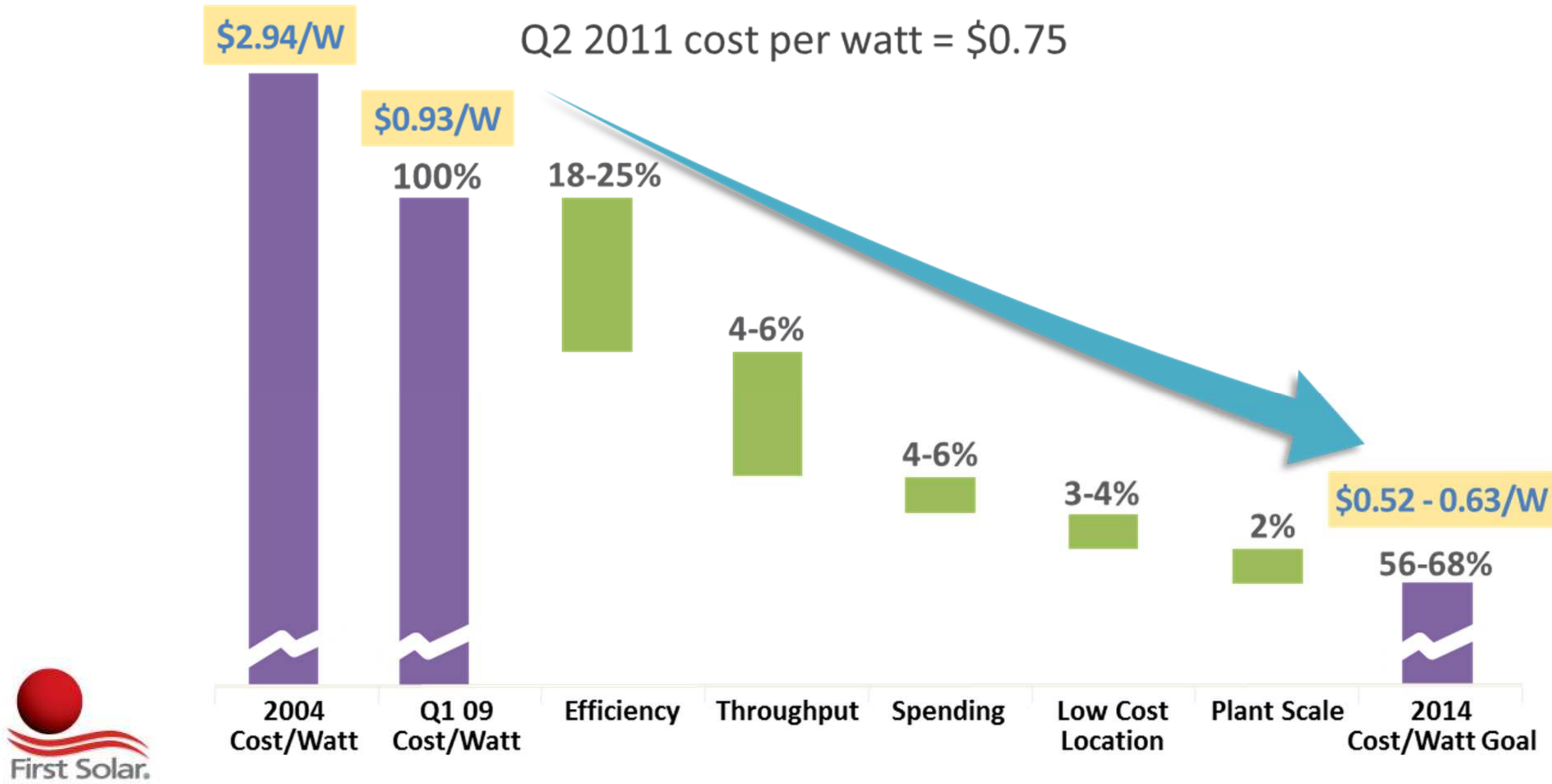
Competitive Cost Environment



First Solar.

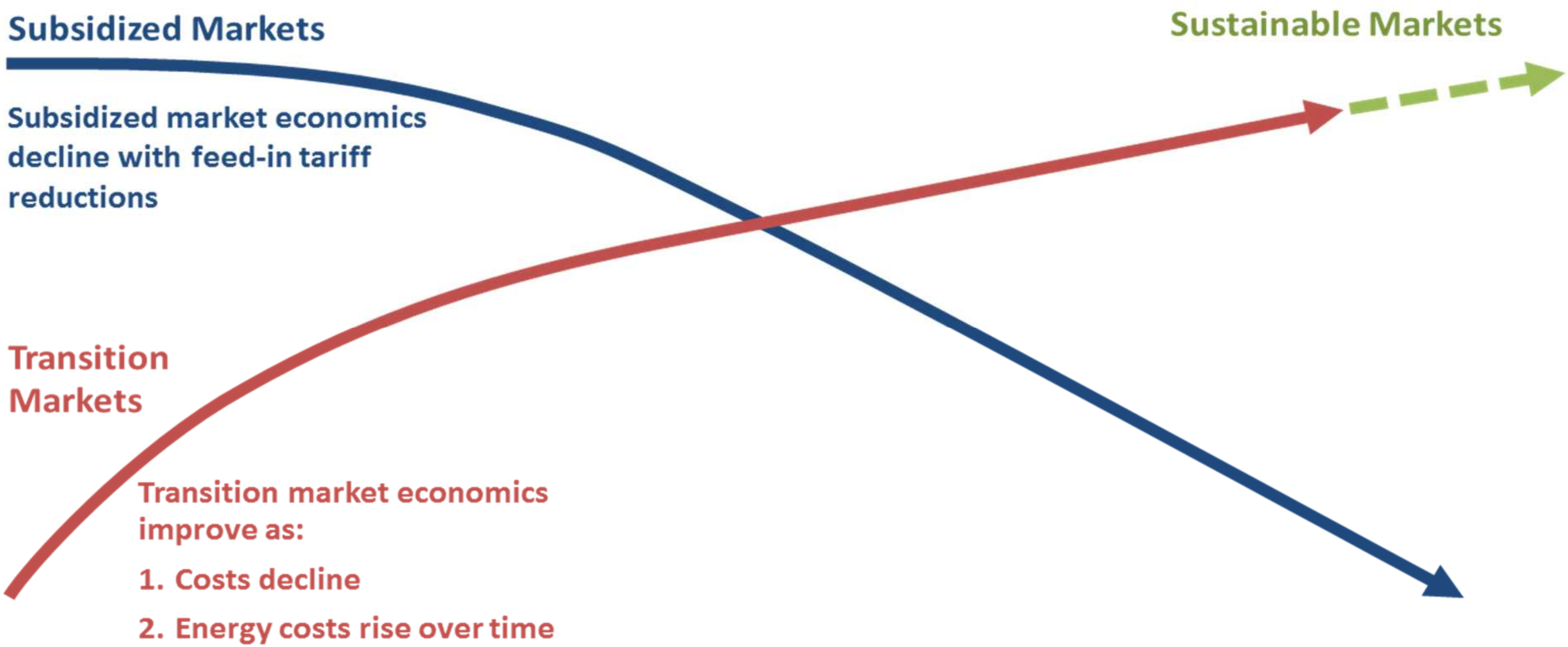
(1) Assumes best of breed c-Si competitors at $0.75 per watt non-polysilicon processing costs and 6.0 g/watt of polysilcon. Non-vertically integrated c-Si assumed +$.30/W vs. vertically integrated c-Si.

Module Manufacturing Cost Reduction Roadmap



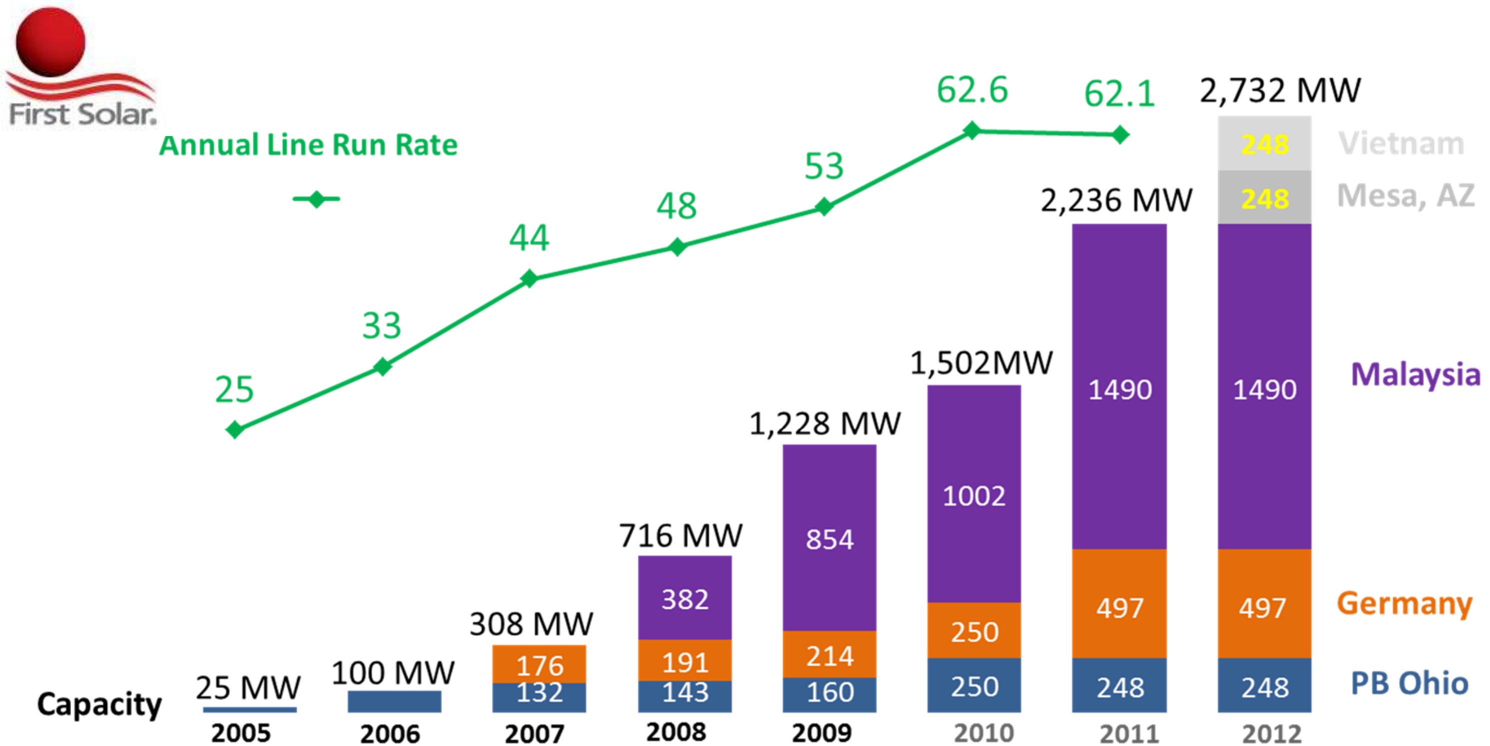
Subsidized vs. Transition Market Economics

- Long term economics are superior in transition markets



Courtesy: First Solar Inc., (2011)

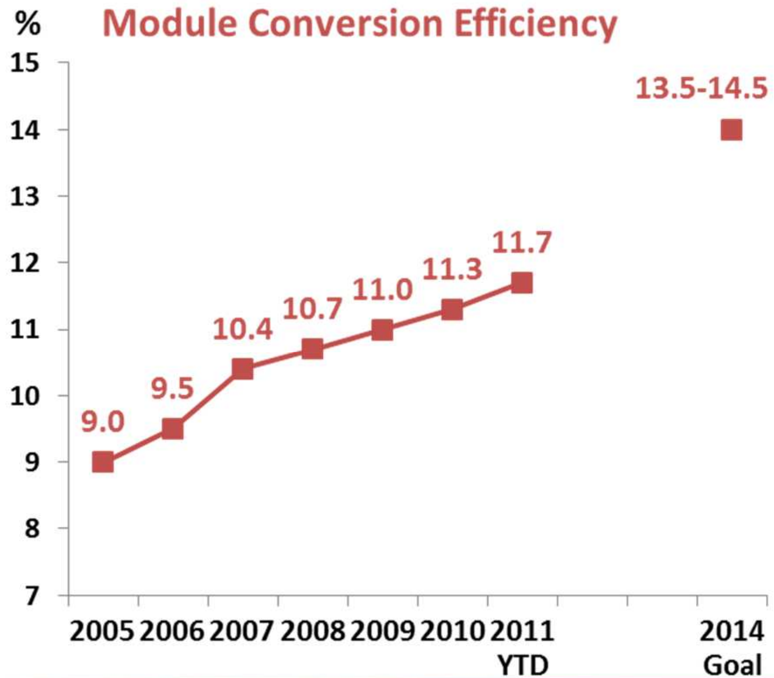
Production Capacity Growth (Year-end Capacity)



Representation of year-end capacity. 2005 & 2006 based on Q406 run rate; 2007 based on Q407 run rate; 2008 based on Q408 run rate; 2009 based on Q409 run rate; 2010 based on Q4 2010 run rate; 2011-2012 based on Q2 2011 run rate. Line run rate based on actual production days in each quarter.

Record CdTe 17.3% Cell Efficiency

- Cells constructed using only full-scale manufacturing processes with commercial
that we believe can be reproduced economically.
- Also demonstrated 14.4% module efficiency (January 2012).



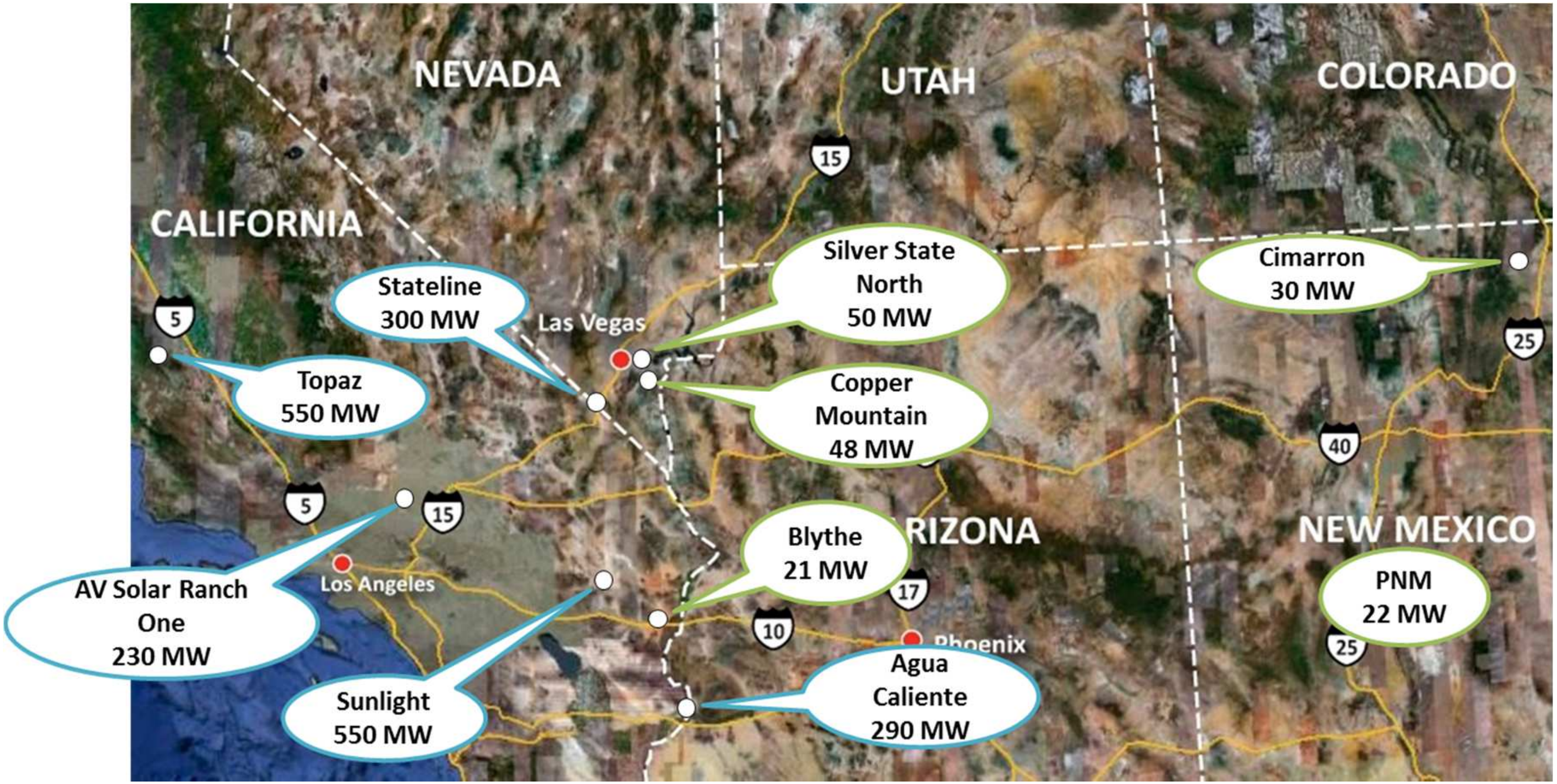
Record 17.3% CdTe thin-film cell confirmed by NREL

First Solar Manufacturing: Kulim, Malaysia- Plants 1-4

First Solar.

Source: Google maps, 2011.

Utility-Scale Projects in Southwestern U.S. – 2.0 GW AC (2011)

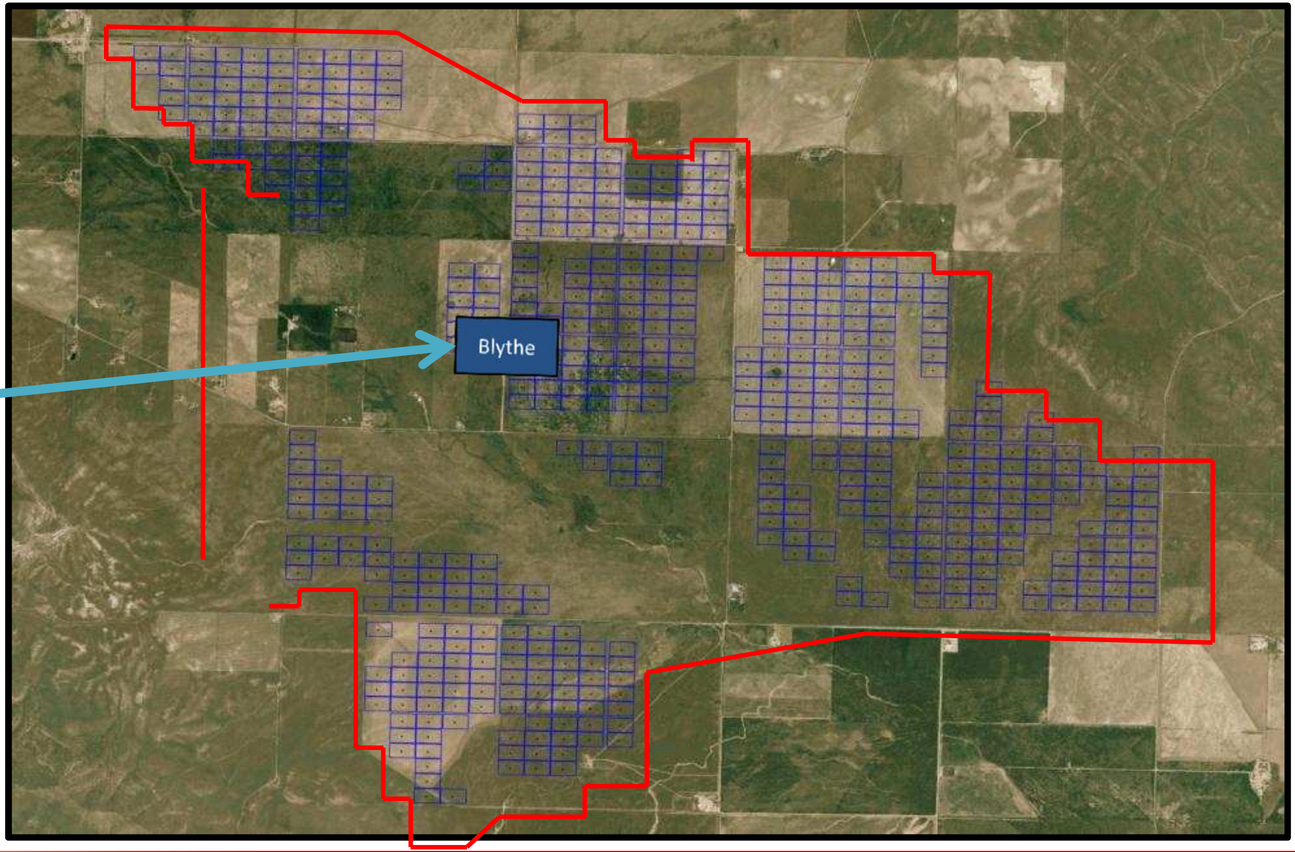


Sarnia, Ontario, Canada

System Size:	80MW (AC)
Commisioned:	October, 2010
Developer:	First Solar, Inc.
Owner:	Enbridge Inc.
Module Type:	FS-272, 275, 277

The Sarnia Solar Farm is the largest PV solar energy facility in North America. The project provides enough power to serve the needs of about 10,000 local homes per year while displacing approximately 22,000 metric tons of carbon dioxide emissions annually—the equivalent of taking about 5,500 cars off the road.

From Blythe (21 MW) To Topaz (550 MW)



Conclusions

- PV is a cost-effective, scalable, and sustainable solution to global climate problems.
- Grid parity leading to inflection in price elastic demand
  - Conventional electricity rising in price; PV reducing cost
  - Exponential demand leading to continued growth of PV
- Thin film technologies (e.g. CdTe) clear leader in LCOE for PV
  - c-Si will continue to play a major role