Solar Cells in 2009 and Beyond

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Materials Science and Engineering

These slides are posted on my website (Google my name). You are welcome to use them. The video will be on iTunesU and Youtube.
To provide the world with 10 TW of solar electricity by 2030

• We need to grow the industry by ~ 35 %/year.

• Not run out of essential materials.

• Make enough money in 2 years to double the factory size.

• Get energy payback within two years so that we generate more power than we use.
The grid parity cost depends on location

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
Conventional p-n junction photovoltaic (solar) cell
Efficiency limits

Sources of energy loss
- Thermalization of excess energy
- Below band gap photons not absorbed

Increasing $V_{OC}$ and decreasing $J_{SC}$
Triple-junction cells

New World Record: 41.6% under 346 suns!

- The cells are in series; current is passed through device.
- The current is limited by the layers that produces the least current.
- The voltages of the cells add.
- The higher band gap must see the light first.

1.7-1.9 eV
1.3-1.4 eV
0.67 eV
Efficiency vs time for various technologies

Best Research-Cell Efficiencies

Efficiency (%)

Emerging PV
- Dye-sensitized cells
- Organic cells (various technologies)

Multijunction Concentrators
- Three-junction (2-terminal, monolithic)
- Two-junction (2-terminal, monolithic)

Single-Junction GaAs
- Single crystal
- Concentrator
- Thin film

Crystalline Si Cells
- Single crystal
- Multicrystalline
- Thick Si film

Thin-Film Technologies
- Cu(In,Ga)Se₂
- CdTe
- Amorphous Si:H (stabilized)
- Nano-, micro-, poly-Si
- Multijunction polycrystalline

(Sources: ARCO, Boeing, Kodak, Solarex, AMETEK, Photon Energy, United Solar, EPFL, Konarka, University of Maine, University of Linz, Groningen, Siemens, Plextronics, Sharp, Solamer Inc.)

(Courtesy of Sarah Kurtz, NREL)
Factors to consider when comparing technologies

• Efficiency (and its effect on balance of system costs)
• Cost
• Throughput of equipment
• Availability of necessary elements
• Toxicty
• Does it require direct (not diffuse) sunlight?
• Aesthetics

There might be different winners for various applications.

The Terawatt Challenge for Thin-Film PV, K. Zweibel (NREL)
Multicrystalline silicon solar cells: today’s most popular technology

15-18 % efficiency
$500/m²

\[ \text{Price ($/W)} \]
- Module $3.00
- Inverter $0.50
- Retro fit installation $4.00

\[ \text{TOTAL $7.50} \]

Average cost over 30 yrs of PV cell electricity in CA including 6 % interest payments:
$0.28/kW-hr
w/out subsidies

Average grid electricity in CA:
$0.13/kW-hr
Peak rates in CA:
$0.29/kW-hr

actually lower if the interest is deducted from taxes
will rise over 30 years
$/Wp Ranges From $4-9 Depending On Type Of Installation

Representative Costs, 2008

<table>
<thead>
<tr>
<th></th>
<th>Residential</th>
<th>Commercial</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>System size</td>
<td>3.8KW</td>
<td>210KW</td>
<td>10MW</td>
</tr>
<tr>
<td>$/Wp, in US</td>
<td>$8.98</td>
<td>$6.68</td>
<td>$4.93</td>
</tr>
<tr>
<td>¢/kWh - Phoenix, AZ</td>
<td>31.78</td>
<td>22.91</td>
<td>26.09</td>
</tr>
<tr>
<td>¢/kWh - Boston, MA</td>
<td>41.89</td>
<td>30.44</td>
<td>36.49</td>
</tr>
</tbody>
</table>

Costs for 2009 are lower, some installations are being done as low as $3 / watt

Source: SAM model, built by DOE and Sandia National Labs. Costs are representative of realistic figures, not average costs from sample installations. Does not include incentives.
SunPower’s Backside Contact Cell

- Technology invented at Stanford by Dick Swanson.
- Sunpower sells 21% efficient cells. I think they cost $1/W more than m-Si
Aesthetic advantage of not having top contacts

SunPower 215 Watt Panel

Conventional 165 Watt Panel
Inorganic Thin Film 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.

\[
\begin{align*}
&\text{CdTe} \\
&\text{CIGS} \ (\text{CuInGaSe}_2) \\
&\text{amorphous Si}
\end{align*}
\]
CdTe Solar Cell with CdS window layer

CdS: tends to be n-type, large bandgap (2.42eV)
Cadmium Telluride Solar Cells

- Direct bandgap, $E_g = 1.45\text{eV}$
- High efficiency (Record: 16.5%; Industry: 11%)
- High module production speed
- Long term stability (20 years)
CdTe: Industrial Status

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

The energy payback time is 0.8 years.

Average Manufacturing Cost
2006: $1.40/watt
2007: $1.23/watt
2008: $1.08/watt
One reason cells on the roof don’t have 16.5 % efficiency.

The challenge in industry is to implement thin CdS layers without having a pinhole.

From Reuben Collins
How much of a problem is the toxicity of Cd?

- It is probably manageable. First Solar will recycle the panels when the customer is done with them.
- Ask John Benner next week.
Is there enough Te?

The amount of Te in a cell is

\[(\text{thickness})(\text{density})(\text{mass fraction Te}).\]

2-\(\mu\text{m}\) thick cells require

\[(2 \ \mu\text{m})(5.7 \ \text{g/cm}^3)(0.52) = 5.7 \ \text{g/m}^2.\]

The sun gives us 1 kW/m\(^2\), so a 10 \% efficient cell produces

\[
\frac{100 \ \text{W/m}^2}{5.7 \ \text{g/m}^2} = \frac{16 \ \text{W}}{\text{g Te}}.
\]
The Reserve of Te

• According to the United States Geologic Survey, the world reserve of Te is 47,000 tons.

• If all of it was used to make solar cells, we could generate 0.68 TW during peak conditions or about 0.14 TW averaged throughout the day.

• We want >5 TW.

• The Reserve is defined as the amount that can be economically recovered.
The cost of Te

• In 2008 Te cost $250/kg. Continuing the example from before, that translates to 0.015 $/W

• The cost of Te could go up a lot before affecting the price of solar cells

• By my estimate, First Solar used half of the world’s annual production of Te last year. The near future should be interesting.
Can we find more Te?

• Te is a byproduct of Cu mining.

• As the price goes up, more Cu plants will install equipment to capture the Te.

• Until recently, no known Te ores were known.

• We might find a lot more Te when we look for it.

• Martin Green, “Estimates of Te and In Prices from Direct Mining of Known Ores,” Prog in PV 17 (2009) p. 347.
• Cyrus Wadia, Paul Alivisatos and Dan Kammens, “Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment,” Environmental Science and Technology, (2009)
Searching for more abundant materials

Relative abundance of the chemical elements in Earth’s upper continental crust

Abundance, atoms of element per $10^6$ atoms of Si

Major industrial metals in **Bold**

Precious metals in *Italic*

Rarest “metals”

U.S. Geological Survey Fact Sheet 087-02

Stanford University
Solar Cells Using *Non-Toxic Abundant* Materials

- **CuInGaSe$_2$** – 19.5% efficient – thin film architecture
- **Cu$_2$ZnSnS$_4$ (CZTS)**
  - 6.7% efficiency (Katagiri et al.)
  - 1.45 eV Eg
- CZTS has kesterite structure

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Cu</td>
<td>$3.35/lb</td>
</tr>
<tr>
<td>Zn</td>
<td>$1.59/lb</td>
</tr>
<tr>
<td>Sn</td>
<td>$6.61/lb</td>
</tr>
<tr>
<td>S</td>
<td>$0.02/lb</td>
</tr>
<tr>
<td>Ga</td>
<td>$209/lb</td>
</tr>
<tr>
<td>In</td>
<td>$361/lb</td>
</tr>
<tr>
<td>Se</td>
<td>2002 $4, 2007 $33/lb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu - 6.0 x 10$^{-5}$</td>
</tr>
<tr>
<td>Zn - 7.0 x 10$^{-5}$</td>
</tr>
<tr>
<td>Sn - 2.3 x 10$^{-6}$</td>
</tr>
<tr>
<td>S - 10$^{-4}$</td>
</tr>
<tr>
<td>Ga - 1.9 x 10$^{-5}$</td>
</tr>
<tr>
<td>In - 2.5 x 10$^{-7}$</td>
</tr>
<tr>
<td>Se - 5 x 10$^{-8}$</td>
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Stacey Bent and Bruce Clemens are making cells with CZTS at Stanford.
Cu(In$_x$Ga$_{1-x}$)Se$_2$

- World record efficiency = 20.0%.
- Many companies are evaporating, printing, sputtering and electrodepositing it.
- Some are just starting to ship cells.
- Handling a 4-element compound is tough.

- Shell Solar, CA
- Global Solar Energy, AZ
- Energy Photovoltaics, NJ
- ISET, CA
- ITN/ES, CO
- **NanoSolar Inc., CA**
- DayStar Technologies, NY/CA
- **MiaSole, CA**
- HelioVolt, Tx
- **Solyndra, CA**
- SoloPower, CA

- Wurth Solar, Germany
- SULFURCELL, Germany
- CIS Solartechnik, Germany
- Solarion, Germany
- Solibro, Sweden
- CISEL, France
- Showa Shell, Japan
- Honda, Japan

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness/Type</th>
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</thead>
<tbody>
<tr>
<td>ZnO, ITO</td>
<td>2500Å</td>
</tr>
<tr>
<td>CdS</td>
<td>700Å</td>
</tr>
<tr>
<td><strong>CIGS</strong></td>
<td>1-2.5μm</td>
</tr>
<tr>
<td>Mo</td>
<td>0.5-1μm</td>
</tr>
<tr>
<td>Glass, Metal Foil, Plastics</td>
<td></td>
</tr>
</tbody>
</table>
PRINTED SEMICONDUCTOR

Printed Semiconductor + Rapid Thermal Processing (RTP)

Nanoparticle Dispersion

Electrode → Precursor Layers → PV Film Stack

Transparent Conductors

Nanoparticle Layer

Thin-film Device
Nanosolar’s Roll-to-Roll Coating

See videos of the coating machine and module packaging on Nanosolar’s website.
There is a 16-page white paper on the Nanosolar website describing this technology.
Figure 14: Nanosolar Back-Contact Cell Architecture: Two laminated aluminum foils with conductive vias.

Figure 15: Nanosolar MWT back-contact cells are interconnected into electrical circuits via tabs on each cell that are simply the overhang of one of the two laminated aluminum foils.
Solyndra’s CIGS modules

www.solyndra.com
A comparison of Solyndra’s modules to their competitors
Wind Performance
Ability to Avoid Heating

Please view the videos on their website to see the manufacturing and installation processes.

Read http://www.nanosolar.com/company/blog/tubular-pv for another view on this design.
Amorphous silicon (a-Si:H)

- No scarce elements are needed
- Efficiencies in the lab for multijunction cells are up to ~13%, but modules are only 5-9%
- 10-15% degradation occurs

• a-Si is deposited by PECVD at 0.1 nm/sec
• It takes 50 min to deposit 0.3 mm.
5.7 m² a-Si panels dropped into place with a crane

- Large modules might be the key to reducing installation costs.
- Google “Applied Materials solar” to see videos of a solar farm being installed
Organic Semiconductors

Attractive properties:
• Abundant: \(~100,000 \text{ tons/year}\)
• Mature industry/markets
• Low materials cost: \(~1\$/g \rightarrow 17\$/m^2\)
• Low-cost manufacturing
• Non-toxic

CuPc
Copper Phthalocyanine
Large Scale Printing of Semiconductors!
Polymer-Fullerene Bulk Heterojunction Cells

- Donor polymer (i.e. P3HT) absorbs light generating an exciton (i.e. bound electron hole pair).

- Exciton must diffuse to the Donor/Acceptor (e.g. PCBM) interface to split.

- Electrons travel to the back electrode.

- Holes travel to the front electrode.
The world record cell in June 2009: 6.1 %

- $E_g = 1.9 \text{ eV}$
- The LUMO-LUMO offset is 0.7 eV.

November 2009: 6.77 %

\[ V_{oc} = 0.7631 \text{ V} \]
\[ I_{sc} = 0.63240 \text{ mA} \]
\[ J_{sc} = 13.364 \text{ mA cm}^{-2} \]
\[ P_{max} = 0.32030 \text{ mW} \]
\[ \text{Efficiency} = 6.77\% \]

Yang Yang, Luping Yu et al
Quantum Efficiency vs $\lambda$

- Internal quantum efficiency is essentially 100%.

- The active layer thickness for CF is 97 nm.

- $\sim 1/3$ of the light not absorbed.

- For CF, the polymer hole mobility is $7 \times 10^{-4}$ cm$^2$/Vs.

- There are still opportunities for improvement!!

Yang Yang, Luping Yu et al
How high can the efficiency be?

Need to optimize the band gap and LUMO-LUMO offset

![Energy level diagram](image)
How good can a **practical** single junction cell be?

Assumptions

\[
\text{EQE} = 65\% \text{ for photons with energy } \geq E_g \\
\text{FF} = 0.65
\]

\[
V_{OC} = \frac{1}{e} \left( |E_{HOMO}^{Donor}| - |E_{LUMO}^{PCBM}| \right) - 0.3
\]

How good can a practical double junction cell be?

Assumptions

- Two cells are stacked in series. The total current is given by that of the subcell with the lower current.
- Fill Factor = 0.65.
- EQE is approximately 85% (see the paper for details)
- The acceptor is PCBM
- The Donor LUMO is at -4.0 eV

\[ V_{oc} = \frac{1}{e} (|E_{\text{Donor}}^{\text{HOMO}}| - |E_{\text{PCBM}}^{\text{LUMO}}|) - 0.3 \]

The two band gaps should be 1.3 and 1.7 eV.

The current is matched along this diagonal.
Reliability

- Encapsulation will be needed.
- A UV filter will probably be needed.
- Many molecules are very stable in light.

Heliatek Reliability Study

Light intensity
2.2 suns

Temperature
48 °C

(33,290 hrs)(2.2) = 73,000 hrs or 8.4 years continuous use

At 5 hrs/day of peak sunlight, the lifetime is 40 years.

Important OPV papers of the last year


Schematic of Multijunction Cell

- World record efficiency: 41.6%
- 37% cells can be purchased for $50,000/m²
- These complex structures are grown very slowly under high vacuum

Ga$_{0.50}$In$_{0.50}$P: Top Cell

Ga$_{0.99}$In$_{0.01}$As: Middle Cell

Ge substrate: Bottom Cell

R.R. King; Spectrolab Inc., AVS 54th International Symposium, Seattle 2007
Concentrating Light

It is possible to track the sun and concentrate the light by 500X.

Dish Shape

Sol Focus
Concentration only makes sense in sunny places.

Concentration is only effective for direct sunlight.

1 sun = 1 kW/m²

<table>
<thead>
<tr>
<th></th>
<th>Yearly Average Solar Radiation Resource [kWh/day-m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seattle</td>
</tr>
<tr>
<td>Fixed flat panel PV @ Lat.</td>
<td>3.7</td>
</tr>
<tr>
<td>2-axis flat panel PV</td>
<td>4.9</td>
</tr>
<tr>
<td>2-axis Conc. PV</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Source: NREL Solar Radiation Data Manual
Cost Estimate

- The cost of multijunction solar cells is approximately $50,000/m² ($5/cm²). 500X concentration reduces this to $100/m².

- Let’s say the tracker and concentration cost $200/m².

- The sun gives us 1000 W/m², but this is reduced to 850 W/m² direct sunlight.

- The best commercially available cells are 37% efficient at 25 C, but this decreases to 30% at typical operating temperatures. If the optical system is 75% efficient, then we are at $0.30 \times 0.75 \times 850 \approx 200$ W/m² of electrical power.

- At $200/m² the capital cost would be $1.50/W.

Although this calculation is wildly optimistic, it represents the hopes and dreams of CPV advocates.

Steve Eglash
Multiple Exciton Generation in nanocrystals

The quantum efficiency profile we want
MEG has been observed


No decent solar cells have been made.

Advantages of Nanowires

Light Absorption along wire axis
- long path length

Charge separation along radius
- allows for “dirty” Si (short minority carrier diffusion length)

Light trapping in the plane
- nanowire periodicity ~ wavelength of light allows for photonic band structure engineering and enhanced absorption in thin silicon

Kayes and Atwater J. Appl. Phys. 97, 114302 (2005)
Garnett and Yang, Nature Nanotech., submitted

Thin, dirty silicon reduces cost while nanowire geometry allows for enhanced light trapping with minimal impact on efficiency!!!!

6.4 % efficient cells have been made.
How can you get involved?

Organic and Dye Sensitized Solar
12 professors work with the Center for Advanced Molecular Photovoltaics
See http://camp.stanford.edu/

Reliability/Degradation
Dauskardt, McGehee (MSE)
Solar Research at Stanford

Inorganic Thin Film
• CIGS and CZTS: Bent (MSE) and Clemens (MSE)
• a-Si: Cui (MSE)
• polycrystalline Si: Clemens and Salleo (MSE)

Nanowires
• Cui (MSE), Brongersma (MSE), McGehee (MSE), Nishi (EE), McIntyre (MSE), Harris (EE), Philip Wong (EE), Zheng (ME)

Multiple Exciton Generation
• Prinz (ME), Gaffney (SLAC)

Photon Enhanced Thermionic Emission
• Melosh (MSE), Shen (AP)  See GCEP website

Solar Thermal
• Peumans and Fan

Advanced Optics
• Brongersma (MSE), Fan (EE) and Peumans (EE)
• Arriving in Spring: Jen Dionne (MSE)
Courses

MATSCI 156/256: Solar Cells, Fuel Cells, and Batteries: Materials for the Energy Solution  (Prof. Bruce Clemens, Autumn)

MATSCI 302: Solar Cells (Prof. Mike McGehee, Autumn)

EE ? (Prof. Peter Peumans, Winter)
Acknowledgements

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Annie Hazlehurst (Stanford GSB)

Steve Eglash
Truly amazing things can be done when many people work towards a common goal.