The Status and Future of the Photovoltaics Industry

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While PV shipments increase only slightly in 2009, Lux Research forecasts that shipments will increase to 9.3 GWp (or $39 billion) in 2010.
While Europe has been the largest consumer of PV in recent years (> 50% of all installations), China and Taiwan have become the largest producers.
Applications of Photovoltaics

The grid-connected market now dominates the PV business
Shipments will exceed 100 GWp per year by 2018 if the CAGR = 45%
Forecast for PV Electricity Production

- Sharp forecasts that PV will supply 10% of the world’s electricity by 2032
- 3 TWp of solar electricity will reduce carbon emissions by about 1 Gton per year (7 Gtons of carbon were emitted as CO2 in 2000)
### The Major Players

<table>
<thead>
<tr>
<th>Crystalline Si</th>
<th>a-Si/μc-Si</th>
<th>CIGS</th>
<th>CdTe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp</td>
<td>United Solar</td>
<td>Avancis</td>
<td>First Solar</td>
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<td>SolarPower</td>
<td>Kaneka</td>
<td>Solar Frontier</td>
<td>Antec Solar</td>
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<tr>
<td>Kyocera</td>
<td>Fuji Electric</td>
<td>Wurth Solar</td>
<td>Abound Solar</td>
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<td>BP Solar</td>
<td>Sharp</td>
<td>Global Solar</td>
<td>PrimeStar Solar</td>
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<td>Q-Cells</td>
<td>Mitsubishi</td>
<td>Honda Soltec</td>
<td>Calyxo</td>
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<td>Mitsubishi</td>
<td>Schott Solar</td>
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<td>SolarWorld</td>
<td>SunTech</td>
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<td>Panasonic</td>
<td>EPV</td>
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<tr>
<td>(Sanyo)</td>
<td>PowerFilm</td>
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<tr>
<td>Schott Solar</td>
<td>AMAT</td>
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<td>Isofoton</td>
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<td>Motech</td>
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<td>Suntech</td>
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<tr>
<td>Evergreen Solar</td>
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</tbody>
</table>

- There are currently more than 300 companies developing or producing solar cells.
- With prices continuing to decrease, and more companies entering the market, many small companies and start-ups are likely to fail.
This device structure is used by most manufacturers today.

- The front contact is usually formed by POCl₃ diffusion
- The rear contact is formed by firing screen-printed Al to form a back-surface field

The cell efficiencies for screen-printed multicrystalline silicon cells are typically in the range of 14 – 17%.
Operation of a Solar Cell

Sources of Standard PV-Cell Efficiency Loss

1) Lattice thermalization
2) Junction voltage drop
3) Contact voltage drop
4) Recombination
5) Non absorbed photons

The theoretical limit for a crystalline silicon solar cell is ~ 29%.
PV module prices have followed an experience curve with a slope of ~80% (a 20% decrease in price with every doubling of cumulative production).
There has been steady progress in the improvement of conversion efficiencies for a number of PV technologies over the last few decades.
## PV Module Conversion Efficiencies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Modules</th>
<th>Cells (Lab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dye-sensitized solar cells</td>
<td>3 – 5%</td>
<td>8.2%</td>
</tr>
<tr>
<td>Amorphous silicon (multijunction)</td>
<td>6 - 8%</td>
<td>13.2%</td>
</tr>
<tr>
<td>Cadmium Telluride (CdTe) thin film</td>
<td>8 - 10%</td>
<td>16.5%</td>
</tr>
<tr>
<td>Copper-Indium-Gallium-Selenium (CIGS)</td>
<td>9 - 11%</td>
<td>19.9%</td>
</tr>
<tr>
<td>Multicrystalline or polycrystalline silicon</td>
<td>12 - 15%</td>
<td>20.3%</td>
</tr>
<tr>
<td>Monocrystalline silicon</td>
<td>14 - 16%</td>
<td>23.4%</td>
</tr>
<tr>
<td>High performance monocrystalline silicon</td>
<td>17 - 20%</td>
<td>24.7%</td>
</tr>
<tr>
<td>Triple-junction (GaInP/GaAs/Ge) cell (~ 250 suns)</td>
<td>-</td>
<td>40.7%</td>
</tr>
<tr>
<td>Triple-junction (GaInP/GaInAs/Ge ) (454 suns)</td>
<td>-</td>
<td>41.1%</td>
</tr>
</tbody>
</table>

- For most PV technologies there is a large gap between the best laboratory efficiencies and those achieved in production PV modules
Paths to Ultra-High Conversion Efficiencies

- Multijunction solar cells (currently used for some thin-film cells and for the highest efficiency cells)
- Multiple absorption path solar cells (impact ionization, multiple exciton generation)
- Multiple energy level solar cells (localized levels or intermediate bands)
- Multiple spectrum solar cells (up and down conversion of photons)
- Multiple temperature solar cells (utilization of hot carriers)

✧ All these approaches have theoretical efficiency limits > 60%.

✧ The theoretical efficiency limit is > 80% for multijunction cells utilizing other high efficiency approaches.
The PERL solar cell has a passivated emitter with a rear locally diffused base contact, and efficiencies as high as 25% have been obtained with this structure.
The SunPower cell has all its electrical contacts on the rear surface of the cell.

- Production cells ~ 22.4% efficiency; new prototypes at 23.4%.
- Diffusion lengths > 3 x cell thickness (using 145 μm thick CZ-Si at end of 2008).
The HIT cell utilizes amorphous Si intrinsic layers (~ 5 nm) as passivation layers. The cell is symmetric except for the a-Si p⁺ emitter layer (~ 10 nm) on the front and the a-Si n⁺ contact layer (~ 15 nm) on the rear.

Best lab efficiency = 22.3% (open-circuit voltages as high as 739 mV).
The Emitter-Wrap-Through (EWT) Cell

- The EWT cell has ~45,000 holes per wafer with cell efficiencies ~15%.
- Advent Solar started selling limited quantities of EWT cells in 2007, but encountered difficulties and the assets were acquired by Applied Materials.
Photovoltech is commercializing the MWT solar cell; efficiencies ~ 15%.
Origin Energy (Australia) is commercializing the Sliver® Solar Cell.
They have demonstrated cell efficiencies > 20%.
Companies such as Sharp and Mitsubishi are developing variants of the micromorph solar cell.

Applied Materials and Oerlikon have each sold several manufacturing lines that can produce single-junction amorphous silicon and micromorph solar cells.
Cadmium Telluride Solar Cells

- The CdS/CdTe heterojunction solar cell is typically formed by using a chemical bath technique to deposit the CdS and close space vacuum sublimation to deposit the CdTe.
- Toxicity of Cd is perceived by some to be an issue.
- Best lab efficiency = 16.5%.
- First Solar has reported manufacturing costs of ~ $0.94/Wp.
- First Solar shipped more than 1 GWp of CdTe modules in 2009 with an average selling prices of ~ $2/Wp.
NREL has demonstrated an efficiency of 19.9% for the CIGS solar cell.

Typically requires relatively high temperature processing (> 500°C).
Spectrolab’s Triple-Junction Solar Cell

- Spectrolab has reported a conversion efficiency of 40.7% with this solar cell structure operating at ~ 250 suns.
- More recently Fraunhofer ISE has obtained an efficiency of 41.1% with a triple-junction cell operating at ~ 454 suns.
Dye-sensitized solar cells utilize a few monolayers of ruthenium-based dye molecules on titanium oxide particles in an electrolyte.

- The best initial efficiency for small cells is 12.3% but the stabilized efficiency is closer to 8%.
Residential Building-Integrated PV

- Building-integrated PV may become pervasive in the next few decades.
The levelized cost of electricity should fall to $\sim 6 \, \text{¢/kWh}$ by 2015 for large grid-connected arrays.
Some forecasts predict that solar will provide most of our energy needs in the latter half of this century.
The levelized cost of PV electricity could fall to ~ 6 ¢/kWh by 2015.

Disruptive technologies with theoretical limits of > 60% may emerge in the next few decades.

Assuming a CAGR of 35% (average over the last few decades), the cumulative PV production would be ~ 3.5 TWp by 2026.

3 TWp of solar electricity will reduce carbon emissions by about 1 Gton per year (7 Gtons of carbon were emitted as CO₂ in 2000).

Thus, by about 2030 PV could be producing about 10% of the world’s electricity and start to play a major role in reducing CO₂ emissions.