Photovoltaics

Photovoltaics (PV) literally means "light-electricity"

- direct conversion of light into electricity based on the photovoltaic effect
- advanced semiconductor device: solar cells (do not confuse with solar collectors)
- the main energy source for the "post-fossil-era"
Advantages:
• environmentally friendly
• no noise, no moving parts
• no emissions
• no use of fuels and water
• minimal maintenance requirements
• long lifetime, up to 30 years
• electricity is generated wherever there is light, solar or artificial
• PV operates even in cloudy weather conditions
• modular “custom-made” energy can be sized for any application from watch to a multi-megawatt power plant

Limitations:
• PV cannot operate without light
• high initial costs that overshadow the low maintenance costs and lack of fuel costs
• large area needed for large scale applications
• PV generates direct current special DC appliances or an inverter are needed
• in off-grid applications energy storage is needed
Solar cell operation is based on the photovoltaic effect:
The generation of a voltage difference at the junction of two different materials in response to visible or other radiation.
Solar cell external parameters

I-V measurement

Standard test conditions:
- AM1.5 spectrum
- irradiance 1000 W/m²
- temperature 25°C

External parameters:
- Short circuit current $I_{sc}$ [A]
- Open circuit voltage $V_{oc}$ [V]
- Fill factor $ff$
- Maximum (peak) power $P_{max}$ [Wp]
- Efficiency $\eta$

Peak Power $P_{max}$ [Wp]
Efficiency $\eta$

\[
P_{max} = V_{mp} I_{mp} = ff V_{oc} I_{sc}
\]
\[
\eta = \frac{P_{max}}{P_1} = ff V_{oc} I_{sc} / P_1
\]
Theoretical efficiency as a function of semiconductor band gap

Main energy losses:
• Non-absorption of low-energy photons
• Thermalization of excess photon energy
• Voltage factor
• Fill Factor
• Collection efficiency
• ….
Three generations of solar cells

I. Wafer based Si

II. Thin films

III. Cheap and efficient
Concepts for 3rd generation cells

- Up- and down conversion
- Intermediate band
- Hot carriers
- Superlattices
- Quantum dots
- Nanotubes
# Solar cell technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>c-Si</th>
<th>HIT</th>
<th>TF Si (stabilised)</th>
<th>CIS</th>
<th>CdTe</th>
<th>DSSC Polymer</th>
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</thead>
<tbody>
<tr>
<td>Record cell</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Efficiency [%]</td>
<td>24.7</td>
<td>22.3</td>
<td>9.3 Single</td>
<td>18.9</td>
<td>17.0</td>
<td>11</td>
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<td>Record module</td>
<td>22.7</td>
<td>?</td>
<td>10.4 Triple</td>
<td>13.4</td>
<td>10.7</td>
<td>4.7</td>
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<td>Commercial module</td>
<td>12-17</td>
<td>16-17</td>
<td>5-9</td>
<td>9-11</td>
<td>10</td>
<td>not available</td>
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<tr>
<td>Cost reduction</td>
<td>Limited</td>
<td>Limited</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++?</td>
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<tr>
<td></td>
<td>Mono</td>
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<tr>
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<td>Multi</td>
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<td>Multi</td>
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<tr>
<td></td>
<td>transfer</td>
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</table>
Bulk materials for solar cells

Bulk Crystalline Silicon
Thin-film materials for solar cells

Thin-film Silicon

Hydrogenated amorphous silicon (a-Si:H)

Hydrogenated microcrystalline silicon (µc-Si:H)
PV system

Solar cell
- semiconductor device

Solar panel (PV module)
- different than collector

Solar array

Solar system:
- solar panel
- battery
- inverters
- electrical components
- appliance
Solar cell applications

<table>
<thead>
<tr>
<th>Space application</th>
<th>Terrestrial application</th>
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</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>Bulk c-Si</td>
</tr>
<tr>
<td>c-Si</td>
<td>Multi c-Si</td>
</tr>
<tr>
<td>Mono c-Si</td>
<td>CIGS</td>
</tr>
<tr>
<td>Multi c-Si</td>
<td>CdTe</td>
</tr>
<tr>
<td>Poly c-Si</td>
<td>TF Si</td>
</tr>
<tr>
<td>Organic</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>$\eta_{lab}$</th>
<th>$\eta_{ind}$</th>
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</thead>
<tbody>
<tr>
<td>GaAs (Gallium Arsenide)</td>
<td>$\sim 24%$</td>
<td>$\sim 12%$</td>
</tr>
<tr>
<td>Mono c-Si</td>
<td>$\sim 15-17%$</td>
<td>$\sim 13-15%$</td>
</tr>
<tr>
<td>CIGS</td>
<td>$\eta_{lab} \sim 19%$</td>
<td>$\eta_{ind} \sim 12%$</td>
</tr>
<tr>
<td>CdTe</td>
<td>$\eta_{lab} \sim 16%$</td>
<td>$\eta_{ind} \sim 9%$</td>
</tr>
<tr>
<td>Poly c-Si</td>
<td>$\eta_{lab} \sim 16%$</td>
<td>$\eta_{ind} \sim 9%$</td>
</tr>
<tr>
<td>TF Si $a$-Si:H</td>
<td>$\eta_{lab} \sim 13%$</td>
<td>$\eta_{ind} \sim 9%$</td>
</tr>
<tr>
<td>Organic</td>
<td>$\eta_{lab} \sim 11%$</td>
<td></td>
</tr>
</tbody>
</table>

CIGS (Copper Indium Gallium Diselenide)
CdTe (Cadmium Telluride)
a-Si:H (Hydrogenated amorphous silicon)
PV industry: the fastest growing industry in the world

Solar cell production 1999-2006

2006: 90% wafer-type c-Si technology

MW

<table>
<thead>
<tr>
<th>Year</th>
<th>Market (x10^6 €)</th>
<th>Jobs</th>
<th>Predictions</th>
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<tbody>
<tr>
<td>2005</td>
<td>~ 9000</td>
<td>~ 70000</td>
<td></td>
</tr>
</tbody>
</table>

Photon International, March 2007
PV applications

1. Off-grid (stand alone) residential power systems
   (solar home systems for individual household)

2. Grid connected PV systems
   (roofs and outer walls of buildings, noise barriers along the motorways)

3. Off-grid industrial power systems
   (water management, lighting, and telecommunication)

4. Consumer products
   (watches, calculators, and lanterns)

5. Space applications
# PV module market

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer products</td>
<td>18</td>
<td>22</td>
<td>35</td>
<td>45</td>
<td>65</td>
</tr>
<tr>
<td>US off-grid residential</td>
<td>5</td>
<td>8</td>
<td>13</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>World off-grid rural</td>
<td>8</td>
<td>15</td>
<td>31</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>Communications/signal</td>
<td>18</td>
<td>23</td>
<td>35</td>
<td>46</td>
<td>70</td>
</tr>
<tr>
<td>PV/diesel commercial</td>
<td>10</td>
<td>12</td>
<td>25</td>
<td>36</td>
<td>50</td>
</tr>
<tr>
<td>Grid connected</td>
<td>2</td>
<td>7</td>
<td>60</td>
<td>199</td>
<td>365</td>
</tr>
<tr>
<td>Central power</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>63</td>
<td>89</td>
<td>201</td>
<td>395</td>
<td>658</td>
</tr>
<tr>
<td>Average price (US$/W_p)</td>
<td>4.25</td>
<td>4.00</td>
<td>3.50</td>
<td>3.50</td>
<td>3.00</td>
</tr>
</tbody>
</table>

Primary challenge for PV

Cost reduction of factor 5
to become competitive with conventional electricity

Today PV module price: $3.5-5.0 \text{ €/W}_p$ \hspace{1em} (W$_p$ = Watt peak)

Integral approach:

Reducing module costs
\hspace{1em} \downarrow \text{raw materials & labor, investments}
\hspace{1em} \uparrow \text{efficiency, lifetime}

Optimizing systems integration
\hspace{1em} \downarrow \text{area and power related costs}

Note: overall optimum \neq \text{highest efficiency}
Learning curve

The combined effect of technology development and manufacturing experience

*Future-year markers are based on 25% annual growth rates.
Cost reduction of PV systems

Requirements:

- low cost solar energy material
- high efficiency and good stability
- low manufacturing cost with good yield
- environmental safety and short energy pay back time

Energy pay back time: the time required for an energy conversion system or device to produce as much energy as is consumed for its production
PV electricity price

2005

PV electricity prices*)
compared with typical consumer electricity prices

*) depreciation 25 yrs, real interest rate 4%, O&M cost 1%/yr, PR 0.75 (example)

“grid parity”
PV electricity price

2010

PV electricity prices compared with expected consumer electricity prices (+ 1%/yr)
PV electricity prices compared with expected consumer electricity prices (+ 1%/yr)
PV electricity prices compared with expected consumer electricity prices (+ 1%/yr)
PV electricity price

2030

PV electricity prices compared with expected consumer electricity prices (+1%/yr)