Why solar cells?

World consumption of fossil fuels

1. solar age

2. solar age

1000× Mtoe

-1000 0 1000 2000 3000 4000 5000

Time [years]
Why solar cells?

• Photovoltaic (PV) energy conversion will become an important energy source in the world energy production.

• Photovoltaic energy conversion takes place in advanced semiconductor devices: solar cells.

• Noble mission: contribution to sustainable human progress.
Depleting energy sources

BP oil platform

Coal power plant in Thailand

Nuclear fast-breeder reactor
Renewable energy sources
Why solar cells?

Creating the future
Why solar cells?

**ENERGY**
- Increasing energy need
- Exhaustion of fossil fuels
- Diversification of energy sources
- Energy for all (2 billion people without electricity)

**ECOLOGY**
- Pollution of environment
- Climate change

**ECONOMY**
- We want to make money
- ! Custom-made energy !
- Added value (building elements)
Fossil-fuel energy consumption

Two major global problems:
1. Shortage of energy
2. Climate change

Solutions:
1. Efficient use of energy
2. Renewable energy source

Brent Crude Oil $/barrel 2007 (source BBC)
Crude oil: 0.85$/l
CocaCola: 1.00$/l

Mexico, Tabasco floods, November 2007 (source BBC)
Energy consumption

Active young man:
- **2500 kcal/day**
- **1055 kWh/year**
- **0.120 kW**

Primary energy global use:
- **120 \times 10^{12} kWh/year**
- **19500 kWh/(person*year)**
- **1.4 \times 10^{10} kW**
- **2.30 kW/person**

6 \times 10^9 people
World energy consumption

2004:

- Gas: 23%
- Coal: 25%
- Oil: 38%
- Rest: 14%

Total: 473 EJ

- Biomass: 27%
- Hydro: 23%
- Nuclear: 41%
- Renew: 9%

Rest: 66 EJ

- Solar thermal: 41%
- Wind: 27%
- Biofuels: 17%
- Geothermal: 12%

Renewables: 6 EJ

Source: BP, Statistical review of world energy, June 2006

10 000 Mtoe = 420 EJ, 1 PJ = 278 GWh, 1 PJ ~ 32 MW installed power
Future energy consumption

Advisory Council to the German government on global climate change WBGU (2003)

Abbildung 4.4-3
Quelle: WBGU
Energy radiation:
380 × 10^{21} \text{ kW}
3.2 × 10^{27} \text{ kWh/year}

Earth receives:
6000 × 10^{10} \text{ kW}
1 × 10^4 \text{ kW/person}
2.30 × 10^0 \text{ kW/person (global use)}
Solar energy resource

At 10% overall efficiency (generation & storage):
1200x1200 km² to supply 2050 energy needs (~1000 EJ)
# Primary energy sources

<table>
<thead>
<tr>
<th>Depleting energy [78%]</th>
<th>Renewable energy [22%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nuclear energy</strong> 4 %</td>
<td><strong>Solar direct</strong> 1 %</td>
</tr>
<tr>
<td><strong>Fossil energy</strong> 74 %</td>
<td><strong>Solar indirect</strong> 21 %</td>
</tr>
<tr>
<td><strong>Nuclear power</strong> &lt;260 years 4 %</td>
<td><strong>Clean gases unlimited 0.01 %</strong></td>
</tr>
<tr>
<td><strong>Coal</strong> &lt;220 years 25 %</td>
<td><strong>Hydro &amp; tidal unlimited 6 %</strong></td>
</tr>
<tr>
<td><strong>Oil</strong> &lt;40 years 32 %</td>
<td><strong>Solar PV unlimited 0.01 %</strong></td>
</tr>
<tr>
<td><strong>Natural gas</strong> &lt;60 years 17 %</td>
<td><strong>Biomass unlimited 14 %</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Solar thermal unlimited 1.0 %</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Wind unlimited 0.1 %</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Geo, ocean &amp; ambient 0.2 %</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Geo &amp; ocean unlimited 0.1 %</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Heat pumps unlimited 0.1 %</strong></td>
</tr>
</tbody>
</table>

Prime energy

Primary energy sources

Coal 25%
Oil 32.5%
Gas 17%
Biomass 14%
Nuclear 5%
Hydro 6%

Renewables 0.5%

Solar PV 0.5%
Wind 10.5%
Biofuels 11%
Geothermal 18%
Biomass 27%
Solar thermal 32%

Electricity generation

**Primary Energy**

- Nuclear: 5%
- Others: 14%
- Hydroelectric: 6%
- Natural gas: 17%
- Coal: 25%
- Oil: 33%

**Electricity Generation**

conversion losses

- Residential: 40%
- Industry: 47%
- Transmission losses: 13%

**Electricity Consumption**

- Residential: 13%
- Industry: 15%
- Transmission losses: 19%
- Conversion losses: 40%
- Transmission losses: 13%

Diagram shows the distribution of primary energy sources and their contributions to electricity generation and consumption.
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 $\eta$

$$P_{max} = V_{mp} I_{mp} = ff \cdot V_{oc} \cdot I_{sc}$$
$$\eta = P_{max} / P_{I} = ff \cdot V_{oc} \cdot I_{sc} / P_{I}$$
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

<table>
<thead>
<tr>
<th>Cost [US$/m²]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>US$ 0.1/W_p</td>
<td>US$ 0.2/W_p</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td>400</td>
<td>20</td>
</tr>
</tbody>
</table>

Thermodynamic limit
US$ 1.0/W_p
Present limit
US$ 3.5/W_p
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 Efficiency [%]</th>
<th>c-Si</th>
<th>HIT (Heterojunction with Intrinsic Thin Layer)</th>
<th>TF Si (stabilised)</th>
<th>CIS</th>
<th>CdTe</th>
<th>DSSC Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record cell</td>
<td>24.7 Mono</td>
<td>22.3</td>
<td>9.3 Single</td>
<td>18.9</td>
<td>17.0</td>
<td>11 unstable</td>
</tr>
<tr>
<td>Record module</td>
<td>22.7 Mono</td>
<td>?</td>
<td>10.4 Triple</td>
<td>13.4</td>
<td>10.7</td>
<td>4.7</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>Cost reduction</td>
<td>Limited</td>
<td>Limited</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+++?</td>
</tr>
</tbody>
</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></th>
<th>Space application</th>
<th>Terrestrial application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bulk c-Si</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td>η ~ 24%</td>
<td></td>
</tr>
<tr>
<td>c-Si</td>
<td>η ~ 12%</td>
<td>η ~ 15-17%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>η ~ 13-15%</td>
</tr>
<tr>
<td><strong>Thin Films</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mono c-Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIGS</td>
<td>η_{lab} ~ 19%</td>
<td>η_{lab} ~ 16%</td>
</tr>
<tr>
<td></td>
<td>η_{ind} ~ 12%</td>
<td>η_{ind} ~ 9%</td>
</tr>
<tr>
<td>Multi c-Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>η_{lab} ~ 19%</td>
<td>η_{lab} ~ 16%</td>
</tr>
<tr>
<td></td>
<td>η_{ind} ~ 9%</td>
<td>η_{ind} ~ 9%</td>
</tr>
<tr>
<td>Poly c-Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TF Si a-Si:H</td>
<td>η_{lab} ~ 13%</td>
<td>η_{lab} ~ 13%</td>
</tr>
<tr>
<td></td>
<td>η_{ind} ~ 13%</td>
<td>η_{ind} ~ 9%</td>
</tr>
<tr>
<td>Organic</td>
<td></td>
<td>η_{lab} ~ 11%</td>
</tr>
</tbody>
</table>

**GaAs** (Gallium Arsenide)

**CIGS** (Copper Indium Gallium Diselenide)

**CdTe** (Cadmium Telluride)

**a-Si:H** (Hydrogenated amorphous silicon)
PV industry

PV industry: the fastest growing industry in the world

Solar cell production 1999-2006

2006: 90% wafer-type c-Si technology

Estimation
market:
2005
~ 9 000x10^6 €
~ 70 000 jobs
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><strong>Total</strong></td>
<td><strong>63</strong></td>
<td><strong>89</strong></td>
<td><strong>201</strong></td>
<td><strong>395</strong></td>
<td><strong>658</strong></td>
</tr>
<tr>
<td><strong>Average price (US$/W_p)</strong></td>
<td><strong>4.25</strong></td>
<td><strong>4.00</strong></td>
<td><strong>3.50</strong></td>
<td><strong>3.50</strong></td>
<td><strong>3.00</strong></td>
</tr>
</tbody>
</table>

Primary challenge for PV

Cost reduction of factor 5
to become competitive with conventional electricity

Today PV module price: $3.5-5.0\,€/W_p$  \hspace{2cm} (W_p = Watt peak)

Integral approach:

- Reducing module costs
  - ↓ raw materials & labor, investments
  - ↑ efficiency, lifetime

- Optimizing systems integration
  - ↓ area and power related costs

*Note: overall optimum ≠ highest efficiency*
Learning curve

The combined effect of technology development and manufacturing experience.
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

Wim Sinke (ECN, Leader of WG 3: Science, technology & applications of EU PV Technology Platform)

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)

<table>
<thead>
<tr>
<th>Year</th>
<th>PV Electricity Price (€ / kWh)</th>
<th>Consumer Electricity Price (€ / kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>0.20</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>0.14</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>
PV electricity price

2030

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