Part 2: Renewable Energy Technologies

Franz Trieb

MBA Energy Management, Vienna, September 12-13, 2012
Photovoltaics
Photovoltaic Applications

- grid connected rooftop
- grid connected power station
- façades
- stand alone devices
- transport
- stand alone rural
Grid-Connected Photovoltaic System
Stand Alone Photovoltaic System

- PV solar generator
  - Controller
    - Battery
    - Own consumption
Photovoltaic Energy Resources

Fixed Non-Concentrating PV
⇒ Global Irradiation on a Surface tilted towards Equator (GTI)
   (tilt angle is usually similar to latitude, or 90° for facades)

Sun-Tracking Non-Concentrating PV
⇒ Global Normal Irradiation on a Surface Tracking the Sun (GNI)

Sun-Tracking Concentrating PV
⇒ Direct Normal Irradiation (DNI)

Fixed Horizontal Array
⇒ Global Horizontal Irradiance (GHI)
Global Mean Solar Irradiance

[Map of the world showing global horizontal irradiance with color scale from 175 to 225 W/m²]
Photovoltaic Energy Resources

Example: GTI at 5 sites and mean value in Greece
Photovoltaic Energy Resources

Example: GTI at 5 sites and mean value in Greece
Photovoltaic Performance Characteristics

Capacity Credit = Contribution to firm capacity and balancing power

- No contribution to firm capacity, Capacity Credit = 0, but relatively reliable minimum supply during daytime.

Capacity Factor = Average annual utilization of the system *

- Depends on the technology and annual solar irradiation

Fluctuating Primary Energy:

Photons cannot be stored ➔ Storage only through electricity

* can also be expressed as: equivalent full load hours / total hours per year
Photovoltaic Cells Efficiency

**Best Research-Cell Efficiencies**

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

Efficiency (%) vs. Year

- 1975: 0%
- 2010: 44%

Innovative Technologies:
- NREL
- Sharp
- Sony
- Solar
- Solarex
- SunPower
- UNIZ
- Varian
- Westinghouse
- Xcel Energy

Historical Milestones:
- 1954: First solar cell
- 1960: First solar-powered satellite
- 1973: First commercial solar panels

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*WIKI PV 2009*
### Photovoltaic Systems Efficiency Examples

<table>
<thead>
<tr>
<th>System Component</th>
<th>Non-Conc. MSi</th>
<th>Conc. MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell at standard conditions 25°C, 1000 W/m², concentrated light</td>
<td>20%</td>
<td>40%</td>
</tr>
<tr>
<td>Concentration of sunlight (2-axis)</td>
<td>--</td>
<td>68%</td>
</tr>
<tr>
<td>Non-Standard Conditions</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Module Interconnection of Cells</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Array Interconnection of Modules</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td>MPP-Tracker &amp; Inverter from DC to AC</td>
<td>95%</td>
<td>95%</td>
</tr>
<tr>
<td>Parasitic losses for tracking, converter, system control, etc.</td>
<td>98%</td>
<td>96%</td>
</tr>
<tr>
<td><strong>Average Total System Efficiency</strong></td>
<td><strong>12%</strong></td>
<td><strong>16%</strong></td>
</tr>
</tbody>
</table>
Photovoltaic Performance Model

- time series of solar energy resource (minimum hourly)
- geometrical relation of sun and PV array (cosine losses, concentration)
- shading, transparency and other optical and interconnection losses
- pv junction model (one-diode, two diode, temperature effect etc.)
- mpp tracking efficiency
- dc/ac conversion efficiency
- parasitics
Simple Photovoltaic Performance Model

\[ E_{PV} = P_{PV} \cdot C_{PV} \cdot 8760 \]
\[ C_{PV} = q_{PV} \cdot GTI \cdot \eta_{PV} \cdot A_{PV} / 8760 \]

- \( E_{PV} \): Annual electricity yield from photovoltaics [kWh/y]
- \( C_{PV} \): Capacity factor as function of the annual global irradiance
- \( P_{PV} \): Installed photovoltaic power capacity at standard conditions [kWp]
- \( q_{PV} \): Annual system efficiency / standard design efficiency
- \( GTI \): Annual global irradiance on a tilted surface [kWh/m²/y]
- \( \eta_{PV} \): PV system standard design efficiency
- \( A_{PV} \): Design collector area for standard efficiency [m²/kWp]
- 8760 represents the total hours per year [h/y]
Photovoltaic Scenario Model

The net annual electricity yield is significantly lower than nominal peak output under standard conditions.

After strong improvement until 2020, moderate improvements are expected.

Model Parameter: \( q_{PV} = f(t) \)

\( q_{PV} = \text{annual system efficiency} / \text{standard design efficiency} \)
Photovoltaic Scenario Model

The capacity factor of a PV system varies according to the annual solar irradiation and to system performance which will increase as technology is improved.

Model Parameter:
\[ C_{PV} = f(t, GTI) \]

Assumptions:
- \( \eta_{PV} \): Initial PV standard system efficiency = 10%
- \( A_{PV} \): Design collector area for standard efficiency = 10 m²/kW
Environmental Impacts of Photovoltaic Systems

- Accidents affecting workers and/or the public
- Effects on visual amenity
- Atmospheric emissions during manufacturing, construction and servicing
- Hazardous materials from production and disposal of equipment
- Land use negligible for rooftop, 6-10 km²/(TWh/y) for large PV systems
- Carbon emissions 100 – 150 g/kWh
Photovoltaic Life Cycle Carbon Emissions

GHG Emissions: 100 - 150 g/kWh
Energy Payback Time: 2 - 5 years
Photovoltaic Life Cycle Land Use

Wind Power
Wind Power Applications

On-Shore Wind Park

Off-Shore Wind Park

Stand-alone Devices

Rural Power & Pumping
Grid Connected Wind Power Systems

Wind Generator or Park

Transformer

Electricity Meter

Public Grid
Stand-alone Wind Power Systems

Wind Generator
   AC/DC Converter
      Battery
         Own Consumption
Wind Energy Resources

Wind speed is the primary indicator for wind energy availability. It has always to be corrected from the height where it was measured to the height of the rotor shaft of the wind turbine.

\[ v(h) = v(h_0) \cdot \frac{\ln(h/z_0)}{\ln(h_0/z_0)} \]

- \( v(h) \): wind speed at shaft height \( h \)
- \( v(h_0) \): wind speed at measured height \( h_0 \)
- \( z_0 \): ground roughness at site
- \( \ln \): natural logarithm
- wind speed in units of m/s

<table>
<thead>
<tr>
<th>Type of terrain</th>
<th>( Z_0 ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud flats, ice</td>
<td>0.00001</td>
</tr>
<tr>
<td>Smooth sea</td>
<td>0.0001</td>
</tr>
<tr>
<td>Sand</td>
<td>0.0003</td>
</tr>
<tr>
<td>Snow surface</td>
<td>0.001</td>
</tr>
<tr>
<td>Bare soil</td>
<td>0.005</td>
</tr>
<tr>
<td>Low grass, steppe</td>
<td>0.01</td>
</tr>
<tr>
<td>Fallow field</td>
<td>0.03</td>
</tr>
<tr>
<td>Open farmland</td>
<td>0.05</td>
</tr>
<tr>
<td>Shelter belts</td>
<td>0.3</td>
</tr>
<tr>
<td>Forest and woodland</td>
<td>0.5</td>
</tr>
<tr>
<td>Suburb</td>
<td>0.8</td>
</tr>
<tr>
<td>City</td>
<td>1</td>
</tr>
</tbody>
</table>

Brischke 2005
Wind Energy Resources

Example: Wind speed at 80 m for 5 sites and mean value in United Kingdom
Wind Energy Resources

Example: Wind speed at 80 m for 5 sites and mean value in United Kingdom
Wind Performance Characteristics

Capacity Credit = Contribution to firm capacity and balancing power

- Limited contribution to firm capacity, Capacity Credit below 30%, in Germany 8% onshore and 12% offshore

Capacity Factor = Average annual utilization of the system *

- Depends on the technology and annual average wind speed

Fluctuating Primary Energy:

Wind cannot be stored ➔ Storage only through electricity

* can also be expressed as: equivalent full load hours / total hours per year
Wind Performance Model

- wind speed at rotor shaft time series (minimum hourly)
- model of wind energy through rotor area
- start and stop limits of wind speed
- mechanical conversion efficiency
- electric efficiency
- parasitic losses
Wind Performance Model

Electric Power from Wind [MW]:

\[ P_{el} = c_p \cdot \frac{1}{2} \cdot \rho_{air} \cdot A \cdot v^3 \cdot k_e \]

- \( v \) Wind Speed [m/s]
- \( A \) Rotor Area [m²]
- \( c_p \) Power Coefficient (depends on turbine type and wind speed)
- \( k_e \) Energy Pattern Factor \( k_e = 1 + 0.28 \cdot v^{-0.87} \)
- \( \rho_{air} \) Density of Air [kg/m³]
Wind Generator Efficiency Example

Wind power through rotor area 100%

Theoretical Maximum (Betz) 59%

Realistic Maximum 50%

Nominal Point Efficiency 35%

Average Annual Efficiency 30%

<table>
<thead>
<tr>
<th>Wind Speed m/s</th>
<th>Wind Power (kW)</th>
<th>Betz Limit (kW)</th>
<th>2 MW Turbine</th>
<th>Efficiency vs. Betz</th>
<th>Total Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,2</td>
<td>36</td>
<td>21</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>4,5</td>
<td>285</td>
<td>169</td>
<td>100</td>
<td>59%</td>
<td>35%</td>
</tr>
<tr>
<td>6,7</td>
<td>962</td>
<td>570</td>
<td>400</td>
<td>70%</td>
<td>41%</td>
</tr>
<tr>
<td>8,9</td>
<td>2280</td>
<td>1352</td>
<td>950</td>
<td>70%</td>
<td>41%</td>
</tr>
<tr>
<td>11,2</td>
<td>4453</td>
<td>2641</td>
<td>1600</td>
<td>61%</td>
<td>36%</td>
</tr>
<tr>
<td>12,5</td>
<td>6257</td>
<td>3710</td>
<td>2000</td>
<td>54%</td>
<td>32%</td>
</tr>
<tr>
<td>13,4</td>
<td>7695</td>
<td>4563</td>
<td>2000</td>
<td>44%</td>
<td>26%</td>
</tr>
<tr>
<td>15,6</td>
<td>12220</td>
<td>7246</td>
<td>2000</td>
<td>28%</td>
<td>17%</td>
</tr>
<tr>
<td>17,9</td>
<td>18241</td>
<td>10817</td>
<td>2000</td>
<td>18%</td>
<td>11%</td>
</tr>
<tr>
<td>20,1</td>
<td>25972</td>
<td>15401</td>
<td>2000</td>
<td>13%</td>
<td>8%</td>
</tr>
<tr>
<td>22,4</td>
<td>35626</td>
<td>21126</td>
<td>2000</td>
<td>9%</td>
<td>5%</td>
</tr>
<tr>
<td>24,6</td>
<td>47419</td>
<td>28119</td>
<td>2000</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>25,0</td>
<td>50053</td>
<td>29681</td>
<td>2000</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>26,8</td>
<td>61563</td>
<td>36507</td>
<td>0</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>
Simple Wind Performance Model

\[ E_{\text{wind}} = P_{\text{wind}} \cdot CF_{\text{wind}} \cdot 8760 \text{ h/y} \]

\[ CF_{\text{wind}} = 0.07 \cdot v_{\text{wind}} - 0.2155 \]

\[ CC_{\text{wind}} = 0.0613 \cdot v_{\text{wind}} - 0.304 \]

\( v_{\text{wind}} \) Average annual wind speed at rotor height [m/s]

\( E_{\text{wind}} \) Annual electricity yield from wind power [MWh/y]

\( CF_{\text{wind}} \) Capacity Factor as function of the average annual wind speed

\( CC_{\text{wind}} \) Capacity Credit as function of the average annual wind speed

\( P_{\text{wind}} \) Installed nominal wind power capacity [MW]

8760 Total hours per year [h]
Simple Wind Performance Model

![Graph showing capacity credit and capacity factor vs. average wind speed. The graph includes lines for capacity credit and capacity factor, with an annotation that the curves are based on an estimate for large regions with several wind parks assuming a perfect grid and non-correlated wind parks.]

Estimate for large regions with several wind parks
Environmental Impacts of Wind Power Systems

- Accidents affecting workers and/or the public
- Effects on visual amenity
- Impact on marine life and shipping routes in case of offshore plants
- Danger of collisions in case of offshore parks
- Effects on bird habitats and routes
- Effects of noise emissions on amenity
- Atmospheric emissions during manufacturing, construction and servicing
- Land use negligible for offshore, 30 - 50 km²/(TWh/y) onshore, possible integration to farming areas
- Life cycle greenhouse gas emissions 10 - 20 g/kWh
- Impact on flying insects?
Wind Power Life Cycle Carbon Emissions

GHG Emissions: 10 - 20 g/kWh
Energy Payback Time: 3 - 7 months
Wind Power Life Cycle Land Use

Concentrating Solar Thermal Power
Concentrating Solar Power Applications

Grid Connected

Grid Connected with Storage

Stand Alone

Multi Purpose
Concentrating Solar Thermal Collectors

- Parabolic Trough (PSA)
- Solar Tower (SNL)
- Linear Fresnel (MAN/SPG)
- Dish-Stirling (SBP)

- Up to 550 °C: Steam Turbines
- Over 1000 °C: Gas Turbines, Engines

Gas Turbines, Engines
Principle of a Concentrating Solar Thermal Power Plant

- concentrated, easily storable solar thermal energy as fuel saver
- spinning reserve
- firm capacity, power on demand
- combined generation of process heat for cooling, industry, desalination, etc.

Concentrating Solar Collector Field (Mirrors) → Thermal Energy Storage → Thermal Power Cycle (e.g. Steam Turbine) → Process Heat → Electricity → Fuel → Solar Heat
ANDASOL 1+2, Guadix, Spain
2x50 MW, 7 h Storage, 2009
3500 full load hours per year

http://de.wikipedia.org/wiki/Andasol
Gemasolar
Sevilla, 2010
19.9 MW
15 h storage
5500 h/y
500 °C
Molten Salt

www.torresolenergy.com
No Compulsive Consumption of Cooling Water

Heller Dry Cooling Towers for 450 MW Steam Turbine in Bursa, Turkey, and conventional air cooler in front right

Air cooling leads to higher fuel consumption of conventional plants and to lower surplus during hot days for CSP plants.

http://www.geaict.com
Slide 44

Trieb

Configurations of CSP Desalination Plants

CSP / RO

- Solar Field
- Storage
- Power Plant
- RO
- Water
- Power

CSP / MED

- Solar Field
- Storage
- Power Plant
- MED
- Water
- Power

MED: Multi-Effect-Distillation
RO: Reverse Osmosis Membrane Desalination
Global Annual Direct Normal Irradiation Map

Data based on NASA SSE 6.0 dataset for a 22-year period (July 1983 - June 2005)
(http://eosweb.larc.nasa.gov/sse/)

Map created and map layout by DLR 2006
(http://www.dlr.de)
CSP Energy Resources

Example: DNI at 5 sites and mean value in Morocco
CSP Energy Resources

Example: DNI at 5 sites and mean value in Morocco
CSP Performance Characteristics

Capacity Credit = Contribution to firm capacity and balancing power
⇒ Potential full contribution to firm capacity, up to 90%

Capacity Factor = Average annual utilization of the system *
⇒ Depends on storage and annual solar irradiation, up to 90%

Storable Primary Energy:
Heat can be stored ➔ daytime storage, no seasonal storage

* can also be expressed as: equivalent full load hours / total hours per year
CSP Systems Efficiency Example

<table>
<thead>
<tr>
<th>Component Efficiency</th>
<th>Nominal</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical Efficiency (cosine, shading, etc.)</td>
<td>92%</td>
<td>70%</td>
</tr>
<tr>
<td>Optical Efficiency (transparancy, absorptivity, reflectancy)</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Thermal Efficiency (infrared emissivity, insulation, transport, storage)</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td>Power Block Efficiency (Steam Cycle)</td>
<td>37%</td>
<td>34%</td>
</tr>
<tr>
<td>Parasitics (tracking, pumps, etc.)</td>
<td>93%</td>
<td>93%</td>
</tr>
<tr>
<td><strong>Average Total System Efficiency</strong></td>
<td>21%</td>
<td>15%</td>
</tr>
</tbody>
</table>
CSP Performance Model

- time series of direct normal irradiance (minimum hourly)
- geometrical relation of sun and collectors (cosine losses, concentration)
- reflectancy, transparency, absorptivity and other optical losses
- insulation, heat transport and storage
- power cycle
- parasitics
CSP Performance Model

**Average Land Use Efficiency (LUE)**

\[ \text{Average LUE} = \text{Solar-Electric Efficiency} \times \text{Land Use Factor} \]

- For parabolic trough steam cycle with dry cooling tower, the average LUE is 4.5%.

<table>
<thead>
<tr>
<th>Collector &amp; Power Cycle Technology</th>
<th>Solar-Electric Aperture Related Efficiency</th>
<th>Land Use Factor</th>
<th>Land Use Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic Trough Steam Cycle</td>
<td>11 - 16%</td>
<td>25 - 40%</td>
<td>3.5 - 5.6%</td>
</tr>
<tr>
<td>Central Receiver Steam Cycle</td>
<td>12 - 16%</td>
<td>20 - 25%</td>
<td>2.5 - 4.0%</td>
</tr>
<tr>
<td>Linear Fresnel Steam Cycle</td>
<td>8 - 12%</td>
<td>60 - 80%</td>
<td>4.8 - 9.6%</td>
</tr>
<tr>
<td>Central Receiver Combined Cycle*</td>
<td>20 - 25%</td>
<td>20 - 25%</td>
<td>4.0 - 6.3%</td>
</tr>
<tr>
<td>Multi-Tower Solar Array Steam or Combined Cycle*</td>
<td>15 - 25%</td>
<td>60 - 80%</td>
<td>9.0 - 20.0%</td>
</tr>
</tbody>
</table>

*www.dlr.de/tt/csp-resources*
Effect of Thermal Energy Storage on the Availability of CSP

SM = Solar Multiple
1 Solar Field = 6000 m²/MW
1 Storage = 6 hours (full load)

CF = \((2.5717 \cdot DNI + 694) \cdot (-0.0371 \cdot SM^2 + 0.4171 \cdot SM - 0.0744)/8760\)
Effect of Site Conditions on the Availability of CSP

SM = 4
Simple CSP Performance Model

\[ E_{\text{CSP}} = P_{\text{CSP}} \cdot (C_{\text{F, solar}} + C_{\text{F, fuel}}) \cdot 8760 = E_{\text{solar}} + E_{\text{fuel}} \]

- \( E_{\text{CSP}} \): Annual electricity yield [MWh/y]
- \( E_{\text{solar}} \): Annual solar electricity yield [MWh/y]
- \( E_{\text{fuel}} \): Annual fossil electricity yield [MWh/y]
- \( C_{\text{F, solar}} \): Capacity factor as function of Solar Multiple and DNI
- \( C_{\text{F, fuel}} \): Capacity factor complementing supply and demand by fuel
- \( P_{\text{CSP}} \): Installed capacity [MW]
- \( 8760 \): represents the total hours per year
Concentrating Solar Power Impacts on Environment

- Pollution during production and construction of equipment
- Visual impact on amenity, noise of cooling towers
- Smell from synthetic oil heat transfer fluid
- Synthetic oil heat transfer fluid considered hazardous material
- Pollution of soil and water from spilling HTF oil
- Impact of concentrated beam radiation on persons, birds and insects
- Impact of large plants on regional albedo
- Land use 5-10 km²/(TWh/y)
- Life cycle greenhouse gas emissions 20 - 30 g/kWh
- Impact of central receivers on birds and insects (hot spot)
CSP Life Cycle Carbon Emissions

GHG Emissions: 20 - 30 g/kWh
Energy Payback Time: 4 - 8 months
CSP Life Cycle Land Use

Hydropower
Hydropower Applications

Storage Dam

河水流量

泵储

BMU 2009
Hydropower Systems

→ Dam storage power plant and run-of-river power plant

Sources: Tauernkraft/Verbund und ExpoStadt

Principle of a dam storage power plant and of a run-of-river power plant

Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft
Hydropower Systems

Goldisthal Pump Turbine Cross Section
Hydropower Resources (River Runoff)

Hydropower Resources (River Runoff)

Example: Daily Mean Water Flow at the Rhine River at Diepoldsau in m³/s
Hydropower Performance Characteristics

Capacity Credit = Contribution to firm capacity and balancing power
- Potential full contribution to firm capacity, up to 90% with storage, depending on flow for river runoff

Capacity Factor = Average annual utilization of the system *
- Depends on storage and annual flow, up to 90%

Storable Primary Energy:
Water can be easily stored ➔ daytime and seasonal storage

* can also be expressed as: equivalent full load hours / total hours per year
Hydropower Performance Model

- time series of water flow (minimum daily)
- height through which the water falls
- piping losses (filters, tube friction, bows, valves etc.) 5-10%
- mechanical turbine efficiency 93-97%
- electric generator efficiency 93-97%
- internal parasitic consumption and transformer losses 1-4%
- overall hydropower efficiency 80-90%
- overall pump storage efficiency 70-80%
Hydropower Performance Model

\[ P = \rho \cdot Q \cdot g \cdot h \cdot (1 - \zeta) \cdot \eta_{\text{turbine}} \cdot \eta_{\text{generator}} \cdot (1 - \Phi) \]

- **P**  \[\text{power capacity [W]}\]
- **g**  \[\text{acceleration by gravity} = 9.81 \text{ [m/s}^2]\]
- **h**  \[\text{height [m]}\]
- **Q**  \[\text{volumetric flow through turbine as part of total river runoff [m}^3/\text{s]}\]
- **ρ**  \[\text{density of water [kg/m}^3]\]
- **ζ**  \[\text{piping losses as function of pipe length and fittings [%]}\]
- **Φ**  \[\text{parasitics and transformation losses [%]}\]
- **η_{\text{turbine}}**  \[\text{turbine efficiency as function of load [%]}\]
- **η_{\text{generator}}**  \[\text{generator efficiency as function of load [%]}\]
Hydropower Scenario Model

The statistics on hydropower plants world wide are rather reliable. Assuming that hydropower plants will have a similar performance as similar plants in the same region, the capacity factor $\text{CF}_{\text{hydro}}$ can be estimated from documented hydropower generation ($E_{\text{hydro}}$) and installed capacity ($P_{\text{hydro}}$).

$$\text{CF}_{\text{hydro}} = \frac{E_{\text{hydro}}}{P_{\text{hydro}}} / 8760$$

$\text{CF}_{\text{hydro}}$  
capacity factor

$E_{\text{hydro}}$  
annual electricity [MWh/y]

$P_{\text{hydro}}$  
installed capacity [MW]

The electricity yield of new added hydropower capacities in a region can then be estimated inversing the equation.
Hydropower Resources

Gross Hydropower Potentials adapted from Lehner et al. 2005/
Environmental Impacts of Hydropower

- Occupational health effects
- Damage to private goods by storage dams (forestry, agriculture, settlements)
- Damage to fish population in streams by river runoff plants
- Damages to environmental goods and cultural objects
- Lower impacts by micro-hydropower than by large dams
- Flood prevention and irrigation water regulation by dams
- Methane emissions by large reservoirs
- Sludge accumulation in large dams
- Land use 50-200 km²/(TWh/y)
Hydropower Life Cycle Carbon Emissions

GHG Emissions: 10 - 20 g/kWh
Energy Payback Time: 3 - 7 months
Hydropower Life Cycle Land Use

Biomass
Biomass Applications

Biogas

Combustion & Gasification of Solid Biomass

Biofuel
Generating electricity from biomass

- **SOLID BIOMASS**
  - Combustion
  - Gasification
  - Liquefaction

<table>
<thead>
<tr>
<th>Technology</th>
<th>Electrical efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal- or gas-fired power plant</td>
<td>30 – 40 %</td>
</tr>
<tr>
<td>Steam turbine or engine</td>
<td>15 – 30 %</td>
</tr>
<tr>
<td>Stirling engine</td>
<td>10 – 15 % *</td>
</tr>
<tr>
<td>Gas turbine / Gas-and-steam plant</td>
<td>20 (GT) – 30 %</td>
</tr>
<tr>
<td>Reciprocating engine</td>
<td>ca. 25 %</td>
</tr>
<tr>
<td>Fuel cell</td>
<td>30 – 45 % **</td>
</tr>
</tbody>
</table>

Various technologies are available to produce electricity from biomass (* less power output than steam turbine; ** depending on the fuel cell type).
Biogas system

From raw material to useful energy

MANURE
- Raw material supply
- Pre-treatment
- Fermentation

ENERGY CROPS

OTHERS
- Biogas processing
- Pipeline
- Reciprocating engine
- Electricity
- Heat

Final customer

Source: IFEU

BMU 2009
Fuel production paths

Biomass

- Gasification
- Extraction
- Fermentation
  - Electrolysis of water

Renewable electricity

- Synthesis/ Conditioning
  - Re-esterification

Hydrogen
- BTL
- Bio-methanol
- Vegetable oil
- Biodiesel
- Bioethanol
- ETBE
- Biogas
- Hydrogen
- Electric vehicle

Some of the possible pathways to produce fuels from renewable energy carriers

BMU 2009
## Energy Yield from One Hectare (ha) of Energy Crops

<table>
<thead>
<tr>
<th>Solid biofuels</th>
<th>Biomass yield in tons</th>
<th>Yield of final energy in GJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short rotation poplar</td>
<td>20</td>
<td>180</td>
</tr>
<tr>
<td>Triticale (whole plant)</td>
<td>14</td>
<td>170</td>
</tr>
<tr>
<td>Miscanibus × giganteus</td>
<td>16</td>
<td>180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Liquid biofuels</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar beet ethanol</td>
<td>56</td>
<td>110</td>
</tr>
<tr>
<td>Wheat ethanol</td>
<td>7 (grains)</td>
<td>55</td>
</tr>
<tr>
<td>Rapeseed oil</td>
<td>3.5 (seeds)</td>
<td>40</td>
</tr>
<tr>
<td>Biodiesel from rapeseed oil</td>
<td>3.5 (seeds)</td>
<td>40</td>
</tr>
<tr>
<td>Biomass-to-liquid diesel (BTL)</td>
<td>20</td>
<td>90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gaseous biofuel</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas from corn</td>
<td>45</td>
<td>120</td>
</tr>
</tbody>
</table>

Source: own calculations           | IFEU 2006             |
Main Future Biomass Applications

Future pathways of the main bioenergy raw materials and the most important usage options in power / CHP plants
Biomass Power Performance Characteristics

Capacity Credit = Contribution to firm capacity and balancing power

- Potential full contribution to firm capacity, up to 90% depending on biomass availability and combined heat & power

Capacity Factor = Average annual utilization of the system *

- Depends on biomass availability, combined heat & power and load, up to 90%

Storable Primary Energy:

Biomass can be easily stored ➔ daytime and seasonal storage

* can also be expressed as: equivalent full load hours / total hours per year
Biomass Scenario Model

\[ E_{\text{bio}} = E_{\text{mun}} + E_{\text{agr}} + E_{\text{wood}} \]

\[ E_{\text{mun}} = N \cdot w_{\text{mun}} \cdot e_{\text{bio}} \]

\[ E_{\text{agr}} = w_{\text{agr}} \cdot e_{\text{bio}} \]

\[ E_{\text{wood}} = p_{\text{wood}} \cdot A_{\text{forest}} \cdot e_{\text{bio}} \]

- \( E_{\text{bio}} \) Electricity from biomass [MWh/y]
- \( E_{\text{mun}} \) Electricity from municipal waste [MWh/y]
- \( E_{\text{agr}} \) Electricity from agricultural residues [MWh/y]
- \( E_{\text{wood}} \) Electricity from wood [MWh/y]
- \( e_{\text{bio}} \) Specific electricity yield from biomass [MWh/ton] \( \sim 0.5 - 1.0 \) MWh/ton
- \( w_{\text{mun}} \) Specific municipal waste production per capita [tons/capita/year] \( \sim 0.35 \) t/y
- \( w_{\text{agr}} \) Agricultural waste production [tons/year] from statistics
- \( p_{\text{wood}} \) Solid biomass productivity from wood [tons/ha/year] from mapping
- \( A_{\text{forest}} \) Forest area of a country [ha] from mapping
- \( N \) Urban population [persons] from statistics

MED-CSP 2009
Biomass Resources

Map of biomass productivity /Bazilevich 1994/

Map of forest areas /USGS 2002/
Environmental Impacts of Biomass Electricity

- Atmospheric pollution by combustion and collection of biomass
- Smell and visual impact on amenity
- Impact on wood harvesting and transport on forests
- Impact of fertilizers on soil and water
- Water demand of energy crops
- Potential overuse of fuel wood and land resources
- Potential competition with food crops
- Land use negligible for municipal and agricultural waste materials
- Land use 500-1000 km²/(TWh/y) for energy crops
- Greenhouse gas emissions 0-200 g/kWh
Biomass Life Cycle Carbon Emissions

GHG Emissions: 0 - 200 g/kWh
Energy Payback Time: 3 - 7 months
Biomass Life Cycle Land Use


per thermal GWh, for electricity multiply with 3
Biodiesel Life Cycle Carbon Emissions

Source: IFEU 2007

Greenhouse gas emissions from the production of biodiesel

CO₂ equivalents in kg/kg diesel fuel equivalent

- Fossil diesel
- Biodiesel from rape seed
- Bioethanol from wheat
- Biodiesel from palm oil (fallow land)
- Biodiesel from palm oil (former rainforest, bog soil)

Life cycle assessment of selected biofuels. Whether or not a biofuel is better than fossil diesel, and by how much, depends to a large extent on how the resource is cultivated and how the area was used previously.
Geothermal Power
Geothermal Heat Applications
Geothermal Power Options

Hydrothermal Power Plant

Blue Lagoon, Reikjavik, Island

Power from Deep Hot Dry Rock

HDR Drilling in Basel, Switzerland
Hydrothermal Systems
Hydrothermal System for Heat & Power

Hydrothermal geothermics
Hydrothermal geothermics uses existing hot thermal water (approx 100-150 °C) at 2,000-4,000 metre depth to produce electricity and heat.

- **Injection well**
  - The 100-150 °C hot thermal water is brought to the surface via an extraction well.

- **Extraction well**
  - The 100-150 °C hot thermal water is brought to the surface via an injection well.

- **Natural aquifer reservoir**
  - At least 500 m distance between the wells to avoid mixing of hot and cold water in the extraction well.

- **2,000 to 4,000 metre depth**
  - The hot water is brought to the surface of the earth via an extraction well. After use the cooled thermal water is fed via an injection well back into the deep where it heats up again.

- **2. Turbine cycle**
  - The hot water heats low boiling material (ORC and Kalina method), to produce steam for the turbine.

- **1. Thermal water circuit**
  - The geothermal energy (approx 101 °C at 300 metre depth) rises out of the interior of the earth to the surface. "New heat is constantly produced in the interior of the earth by the decay of radioactive elements."
Hot Dry Rock System for Heat & Power

1: Reservoir
2: Pump house
3: Heat exchanger
4: Turbine hall
5: Production well
6: Injection well
7: Hot water to district heating
8: Porous sediments
9: Observation well
10: Crystalline bedrock
Geothermal Resources

rock temperature at 6 km depth
Geothermal Power Performance Characteristics

Capacity Credit = Contribution to firm capacity and balancing power
⇒ Full contribution to firm capacity, up to 90%

Capacity Factor = Average annual utilization of the system *
⇒ Base load, peak load or CHP possible, up to 90%

Storable Primary Energy:
Geothermal heat is stored energy ⇒ daytime and seasonal storage

* can also be expressed as: equivalent full load hours / total hours per year
Geothermal Power Performance Example

Recovery Factor for HDR System (R)  5%
Cycle Efficiency of ORC at 200°C (\(\eta\))  13%
Parasitics p  2%

Overall Efficiency = \(\eta \cdot R \cdot (1 - p) = 0.65\%\)
Geothermal Power Model

\[ H_0 = c_R \cdot \rho_R \cdot V \cdot (T_R - T_0) \]

\[ H_1 = R \cdot H_0 \]

\[ H_{el} = \eta \cdot H_1 \]

- \( H_0 \): Heat in place [J]
- \( H_1 \): Accessible heat [J]
- \( H_{el} \): Electric energy [J]
- \( c_R \): Specific heat capacity of the rock [J/kg]
- \( \rho_R \): Rock density [kg/m\(^3\)]
- \( V \): Rock volume [m\(^3\)]
- \( T_R \): Rock temperature [°C]
- \( T_0 \): Temperature at the surface [°C], (mean annual temperature)
- \( R \): Recovery factor [1]
- \( \eta \): Efficiency [1]
### Geothermal Power Model Parameters

<table>
<thead>
<tr>
<th>Temp.-class [°C]</th>
<th>Hot water aquifer</th>
<th>Faults, Crystalline rock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>η</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>CHP</td>
</tr>
<tr>
<td>100-130</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>130-160</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>160-190</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>190-220</td>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td>220-250</td>
<td></td>
<td>5.3</td>
</tr>
</tbody>
</table>


- Rock density \( \rho_R = 2600 \text{ kg/m}^3 \)
- Specific heat \( c_R = 840 \text{ J/kg} \)
- Electricity \( E_{geo} = \frac{H_{el}}{(t_{exploit} \cdot 3.6 \cdot 10^{12})} \) [GWh/y]
- Exploitation time \( t_{exploit} = 100 \text{ years} \)

---

Jung et al. 2005
Environmental Impacts of Geothermal Electricity

- Thermal and chemical atmospheric, water and soil pollution by well blow-outs and leakage and during drilling
- Noise from drilling and from cooling towers
- Ground stability affected by drilling
- Contamination from solid waste disposal and disposal of brines (radioactive)
- Visual impact on amenity from pipelines and cooling towers
- Sinking of land surface
- Surface installations small, but considerable land use from piping and impacts on subsoil stability
- Greenhouse gas emissions 40-80 g/kWh
Geothermal Life Cycle Carbon Emissions

GHG Emissions: 40 - 80 g/kWh
Energy Payback Time: 7 - 10 months
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