Part 2: Renewable Energy Technologies

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MBA Energy Management, Abu Dhabi, November 30, 2009

Photovoltaics

Photovoltaic Applications

grid connected rooftop

grid connected power station

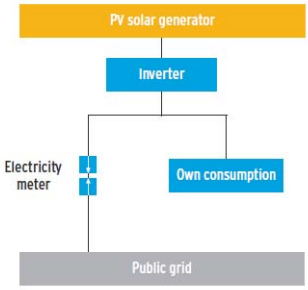
façades

stand alone rural

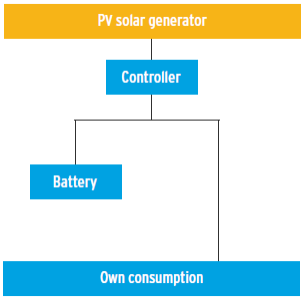
stand alone devices

transport

Grid-Connected Photovoltaic System



Stand Alone Photovoltaic System



Photovoltaic Energy Resources

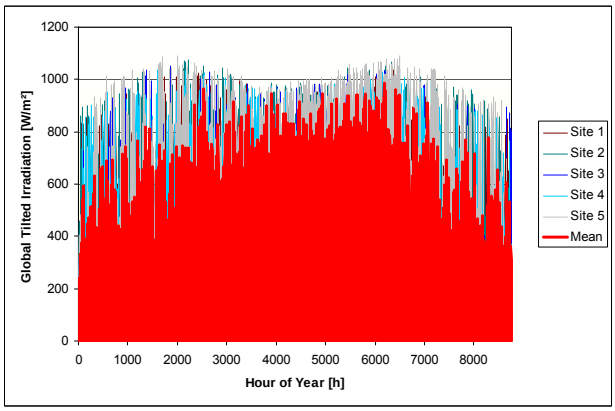
Fixed Non-Concentrating PV
➔ Global Irradiation on a Surface tilted towards Equator (GTI)
(tilt angle is usually similar to latitude, or 90° for facades)

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

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

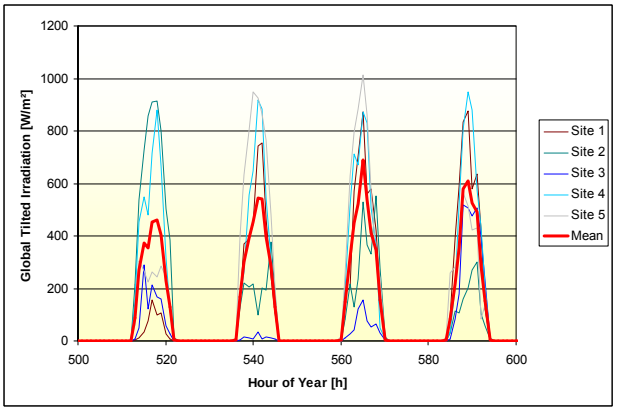
Fixed Horizontal Array
➔ Global Horizontal Irradiance (GHI)

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.

Capacity Factor = Average annual utilization of the system *

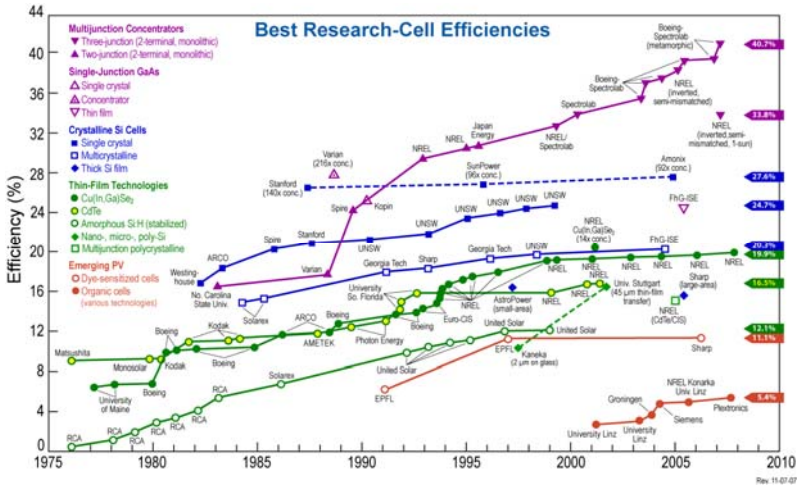
➔ Depends on the technology and annual solar irradiation

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



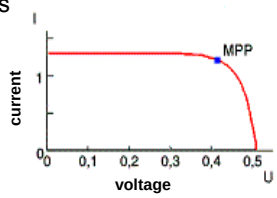
WIKI PV 2009

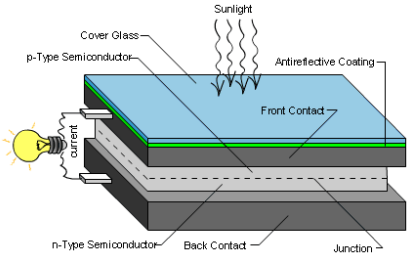
Photovoltaic Systems Efficiency Examples

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

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} = $P_{PV} \cdot CF_{PV} \cdot 8760$

CF_{PV} = $q_{PV} \cdot GTI \cdot \eta_{PV} \cdot A_{PV} / 8760$

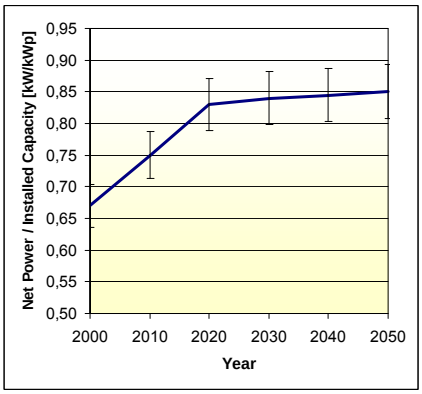
E_{PV}	Annual electricity yield from photovoltaics [kWh/y]
CF_{PV}	Capacity factor as function of the annual global irradiance
P_{PV}	Installed photovoltaic power capacity at standard conditions [kW_p]
q_{PV}	annual system efficiency / standard design efficiency
GTI	Annual global irradiance on a tilted surface [kWh/m²/y]
η_{PV}	PV system standard design efficiency
A_{PV}	Design collector area for standard efficiency [m²/kW_p]
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.

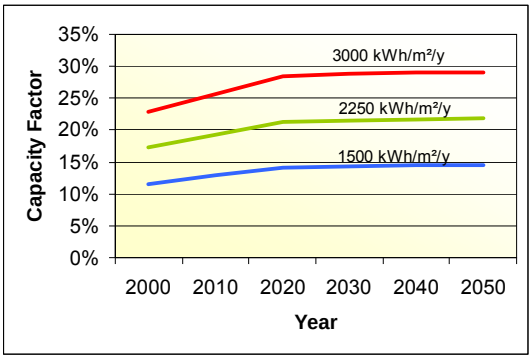
Model Parameter: $q_{PV} = f(t)$



q_{PV} = annual system efficiency / 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.



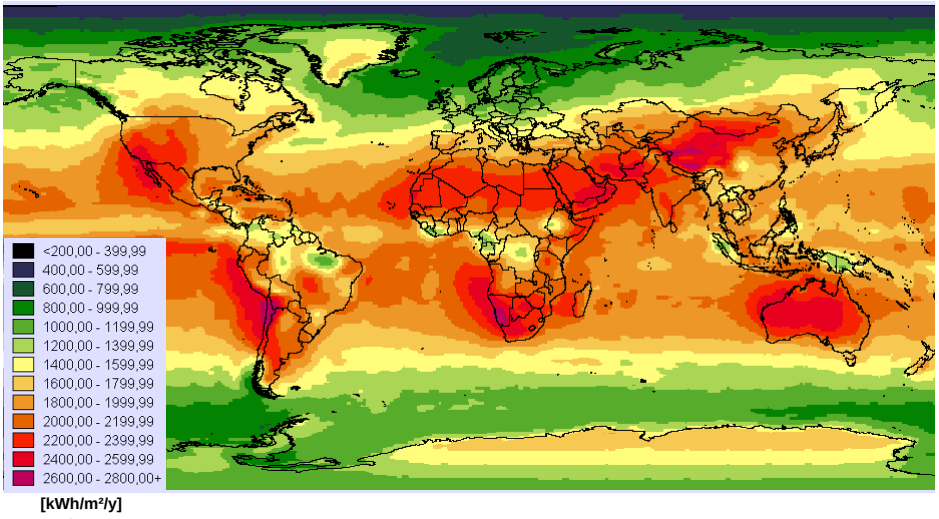
Model Parameter:
$CF_{PV} = f(t,GTI)$

Assumptions:

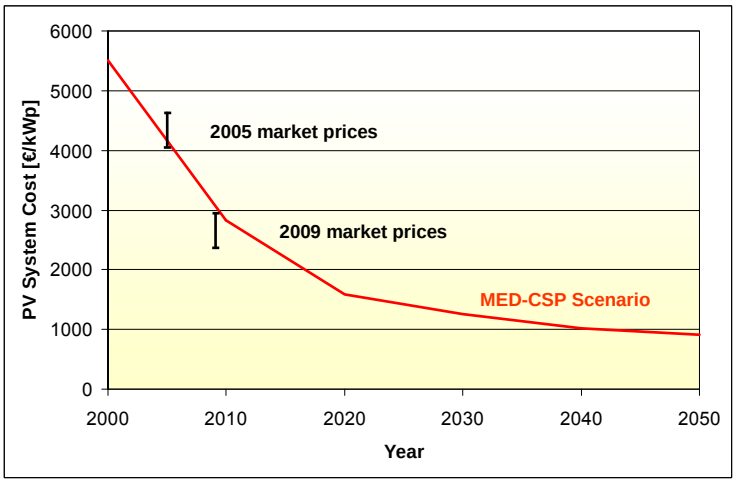
η_{PV} Initial PV standard system efficiency = 10%

A_{PV} Design collector area for standard efficiency = 10 m²/kW

Annual Global Irradiance for Fix Tilted PV Systems



Photovoltaic System Cost Perspectives

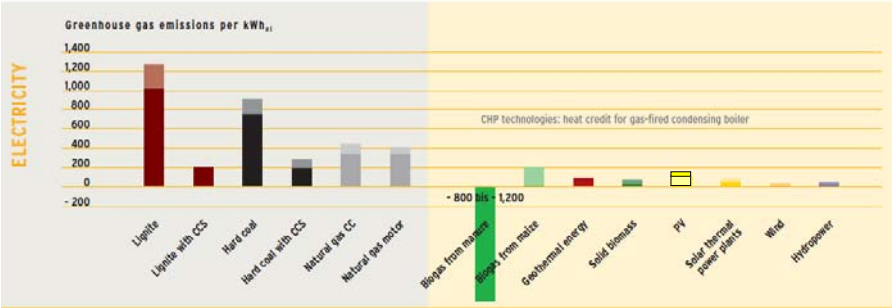


MED-CSP 2005, LBBW 2009

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

Wind Power

Wind Power Applications

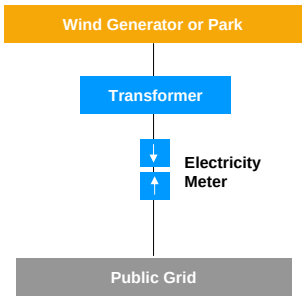
On-Shore Wind Park

Off-Shore Wind Park

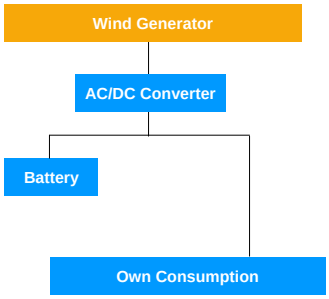
Stand-alone Devices

Rural Power & Pumping

Grid Connected Wind Power Systems



Stand-alone Wind Power Systems



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.

$$v(h) = v(h_0) \cdot \ln(h/z_0) / \ln(h_0/z_0)$$

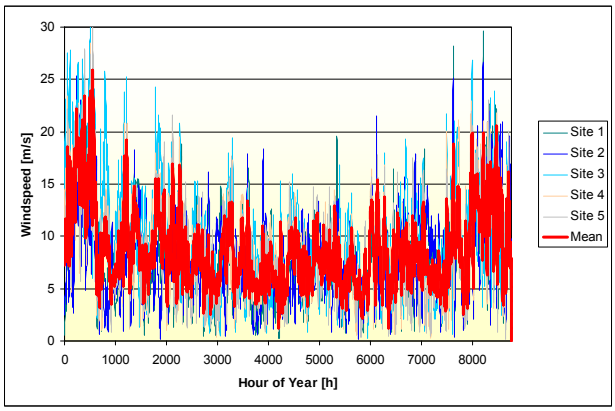
$v(h)$	wind speed at shaft height h
$v(h_0)$	wind speed at measured height h_0
z_0	ground roughness at site
ln	natural logarithm

wind speed in units of m/s

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

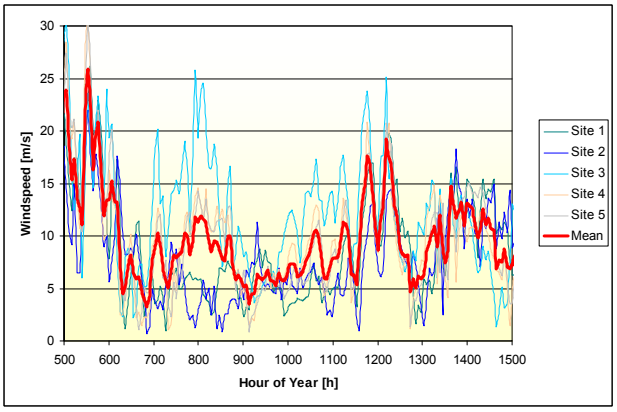
Brischke 2005

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 < 30% (8-12%)

Capacity Factor = Average annual utilization of the system *

➔ Depends on the technology and annual average wind speed

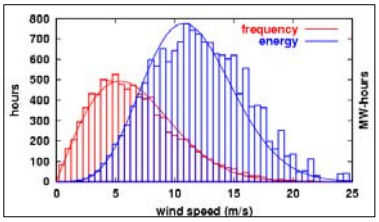
Fluctuating Primary Energy:

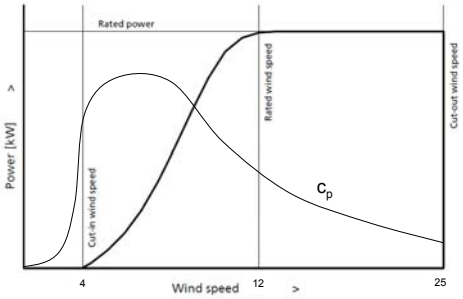
Wind cannot be stored ➔ Storage only through electricity

* 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

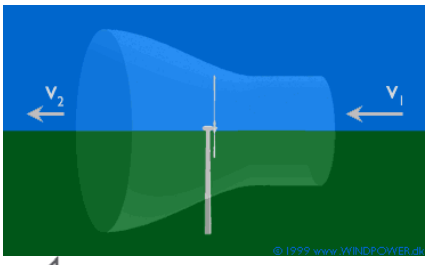
Electric Power from Wind [MW]:

$$P_{el} = c_p \cdot ½ \cdot \rho_{air} \cdot A \cdot v^3 \cdot k_e$$

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 $k_e = 1 + 0.28 \cdot v^{(-0.87)}$
ρ_{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%



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

Simple Wind Performance Model

E_{wind} = $P_{wind} \cdot CF_{wind} \cdot 8760$ h/y

CF_{wind} = $0.07 \cdot v_{wind} - 0.2155$

CC_{wind} = $0.0613 \cdot v_{wind} - 0.304$

v_{wind} Average annual wind speed [m/s]

E_{wind} Annual electricity yield from wind power [MWh/y]

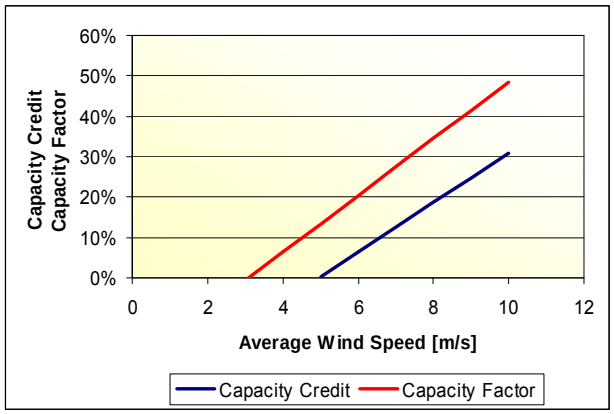
CF_{wind} Capacity Factor as function of the average annual wind speed

CC_{wind} Capacity Credit as function of the average annual wind speed

P_{wind} Installed nominal wind power capacity [MW]

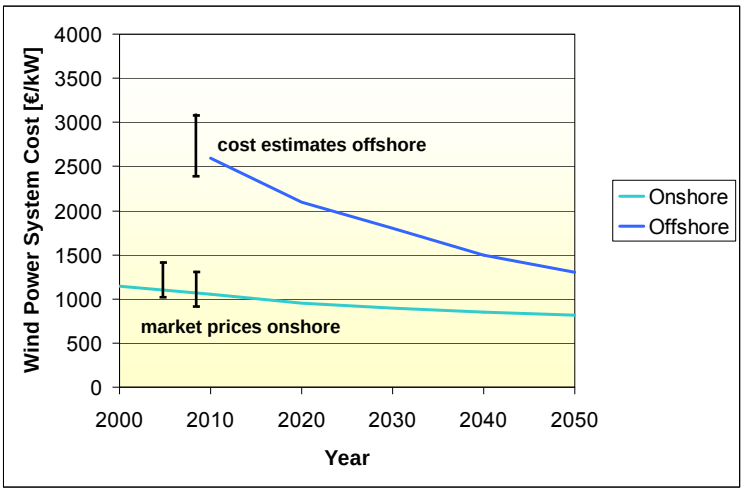
8760 Total hours per year [h]

Simple Wind Performance Model



Estimate for large regions with several wind parks

Wind Power System Cost Perspectives



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MED-CSP 2005, ECOFYS 2009, Lead Study 2009

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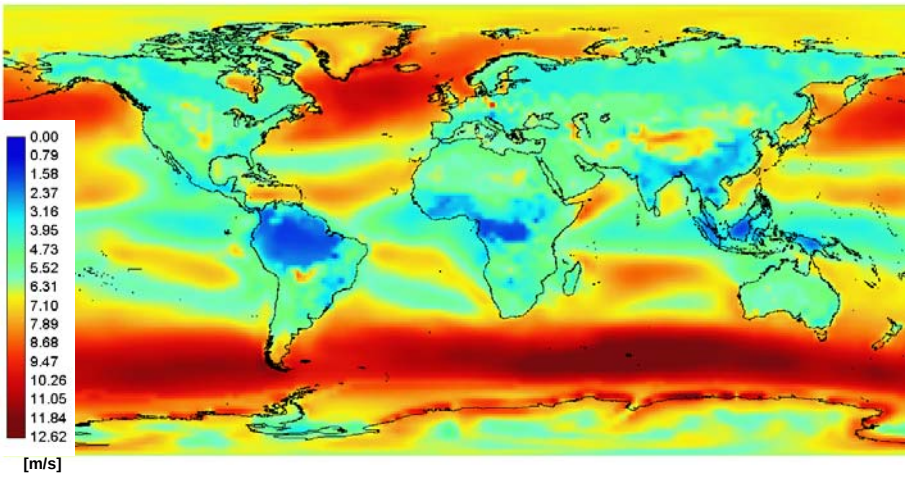
Annual Average Wind Speed at 50 m Height



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http://eosweb.larc.nasa.gov/sse/

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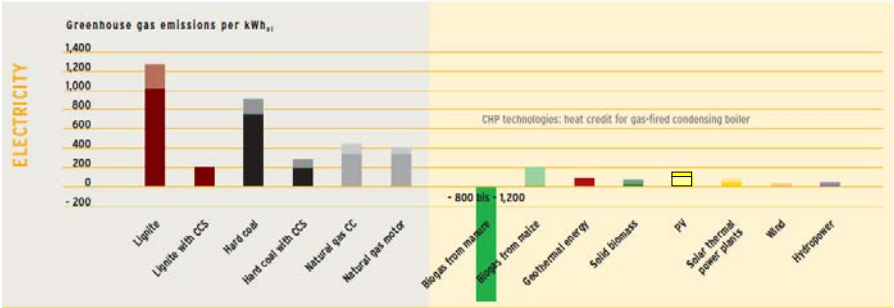
Environmental Impacts of Wind Power Systems

- 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

Wind Power Life Cycle Carbon Emissions



GHG Emissions: 10 - 20 g/kWh
Energy Payback Time: 3 - 7 months

Concentrating Solar Thermal Power

Concentrating Solar Power Applications

Grid Connected

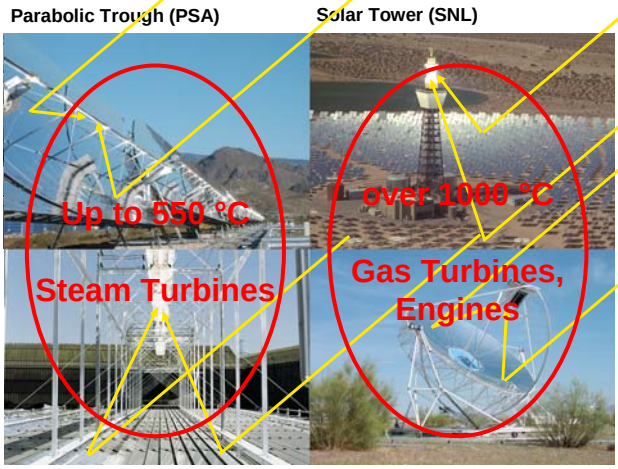
Grid Connected with Storage

Stand Alone

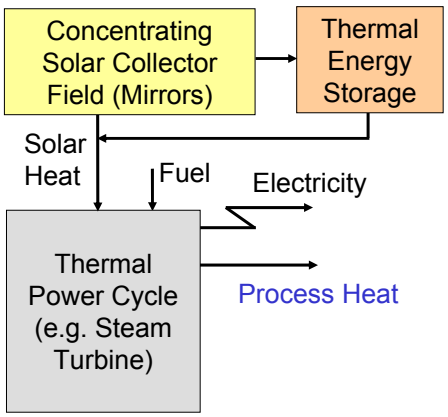
Multi Purpose

WIKI Wind 2009, BMU 2009

Concentrating Solar Thermal Collectors

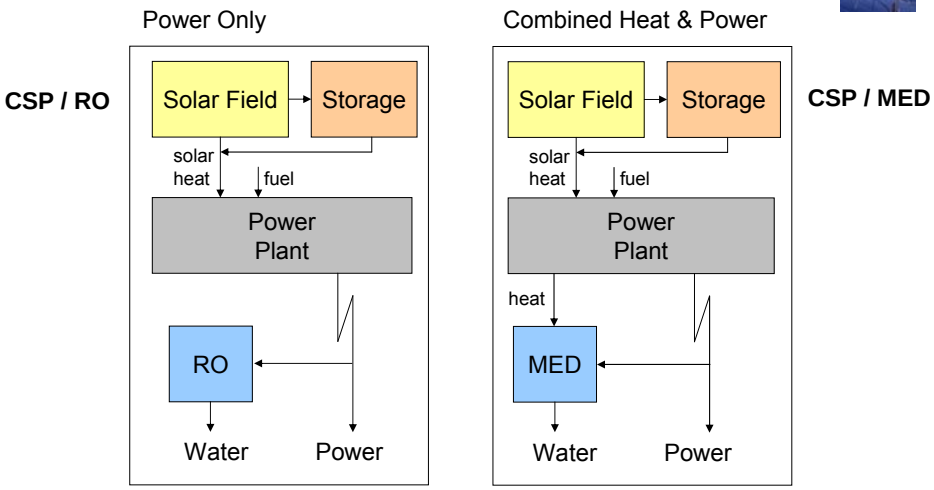


Principle of a Concentrating Solar Thermal Power Plant



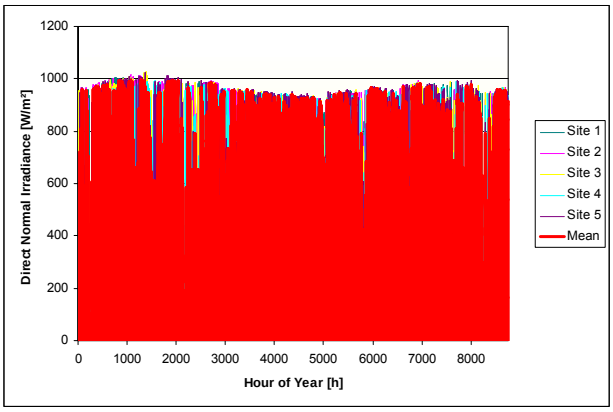
- concentrated, easily storable solar thermal energy as fuel saver
- spinning reserve
- firm capacity, power on demand
- combined generation of process heat for cooling, industry, desalination, etc.

Configurations of CSP Desalination Plants



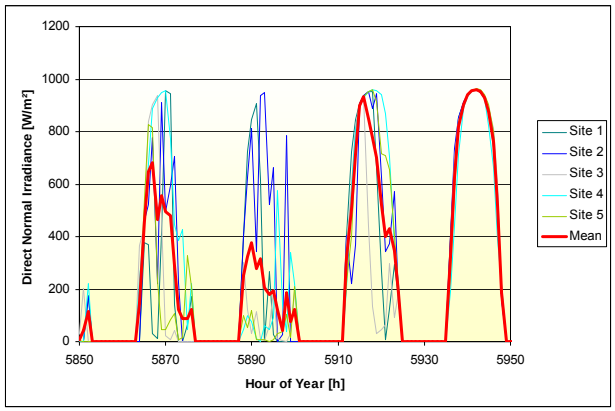
MED: Multi-Effect-Distillation
RO: Reverse Osmosis Membrane Desalination

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

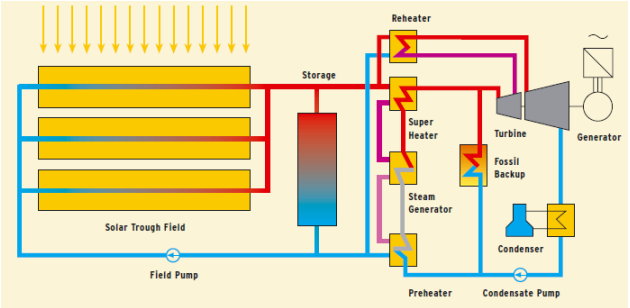
* can also be expressed as: equivalent full load hours / total hours per year

CSP Systems Efficiency Example

Component Efficiency	Nominal	Annual
Geometrical Efficiency (cosine, shading, etc.)	92%	70%
Optical Efficiency (transparancy, absorptivity, reflectancy)	90%	90%
Thermal Efficiency (infrared emissivity, insulation, transport, storage)	75%	75%
Power Block Efficiency (Steam Cycle)	37%	34%
Parasitics (tracking, pumps, etc.)	93%	93%
Average Total System Efficiency	**21%**	**15%**

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

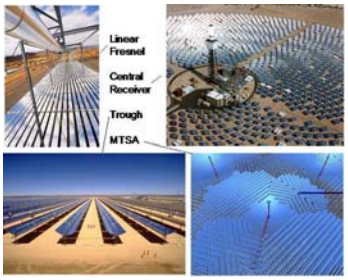
Average Land Use Efficiency (LUE)

= Solar-Electric-Efficiency (12%)

x Land Use Factor (37%)

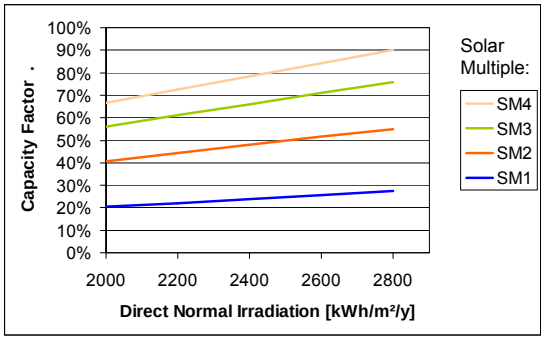
= 4.5% for parabolic trough steam cycle

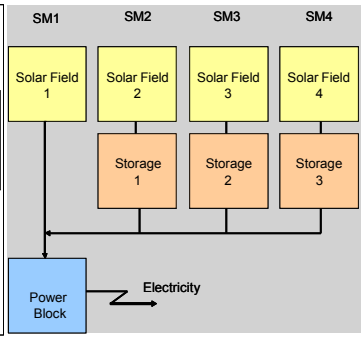
with dry cooling tower



Collector & Power Cycle Technology	Solar-Electric Aperture Related Efficiency	Land Use Factor	Land Use Efficiency
Parabolic Trough Steam Cycle	11 - 16%	25 - 40%	3.5 - 5.6%
Central Receiver Steam Cycle	12 - 16%	20 – 25%	2.5 – 4.0%
Linear Fresnel Steam Cycle	8 - 12%	60 - 80%	4.8 - 9.6%
Central Receiver Combined Cycle*	20 - 25%	20 - 25%	4.0 – 6.3%
Multi-Tower Solar Array Steam or Combined Cycle*	15 - 25%	60 - 80%	9.0 – 20.0%

Effect of Thermal Energy Storage on the Availability of CSP





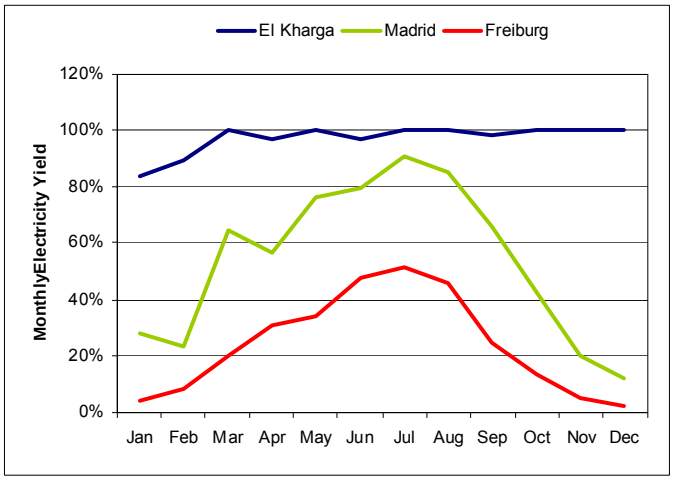
SM = Solar Multiple
1 Solar Field = 6000 m²/MW
1 Storage = 6 hours (full load)

CF Capacity Factor
DNI Annual Direct Normal Irradiance [kWh/m²/y]

$$CF = (2.5717 \cdot DNI + 694) \cdot (-0.0371 \cdot SM^2 + 0.4171 \cdot SM - 0.0744)/8760$$

Effect of Site Conditions on the Availability of CSP

SM = 4

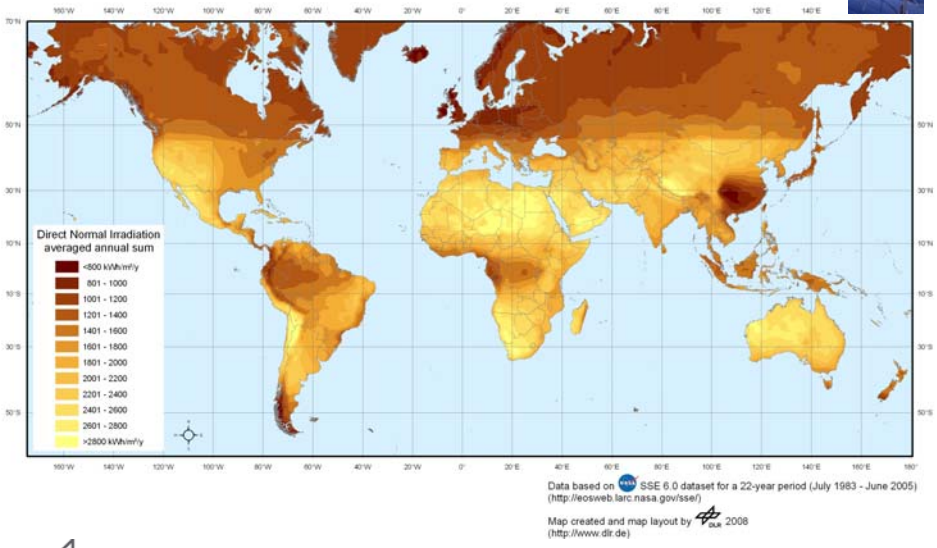


Simple CSP Performance Model

$$E_{CSP} = P_{CSP} \cdot (CF_{solar} + CF_{fuel}) \cdot 8760 = E_{solar} + E_{fuel}$$

E_{CSP}	Annual electricity yield [MWh/y]
E_{solar}	Annual solar electricity yield [MWh/y]
E_{fuel}	Annual fossil electricity yield [MWh/y]
CF_{solar}	Capacity factor as function of Solar Multiple and DNI
CF_{fuel}	Capacity factor complementing supply and demand by fuel
P_{CSP}	Installed capacity [MW]
8760	represents the total hours per year

CSP Resource: Direct Normal Irradiation (DNI)



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www.dlr.de/tt/csp-resources

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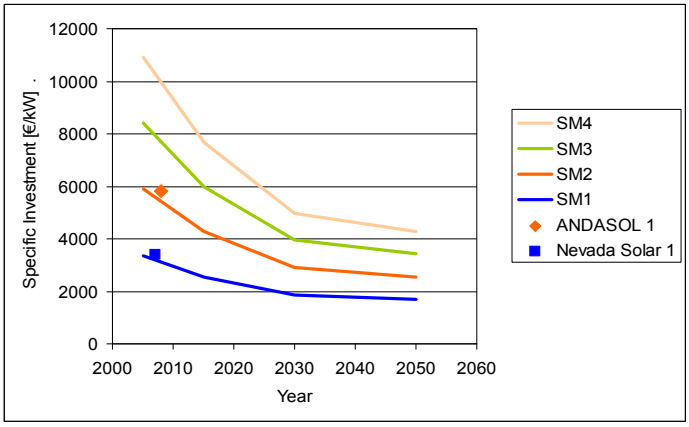
CSP Investment Cost Perspectives

Year	*PR*	2005	2015	2030	2050	Unit
World CSP Capacity		354	5000	150000	500000	MW
Solar Field	90%	360	241	144	120	€/m²
Power Block	98%	1200	1111	1006	971	€/kW
Storage	92%	60	44	29	25	€/kWh



$$c_x = c_0 \cdot \left(\frac{P_x}{P_0}\right)^{\frac{\log PR}{\log 2}}$$

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

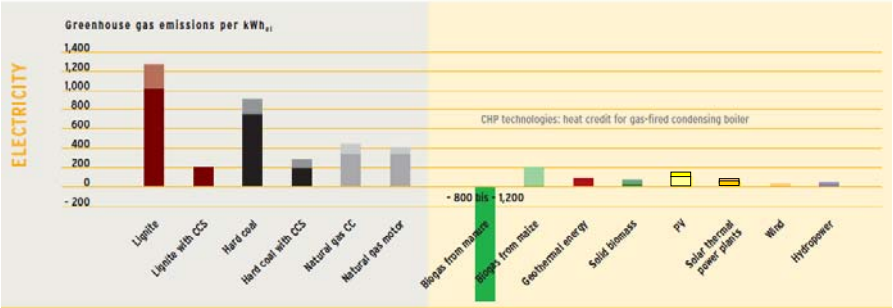
www.dlr.de/tt/csp-resources

Slide 52
Trieb

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

CSP Life Cycle Carbon Emissions



GHG Emissions: 20 - 30 g/kWh
Energy Payback Time: 4 - 8 months

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Hydropower

Hydropower Applications

Storage Dam

Micro Hydropower

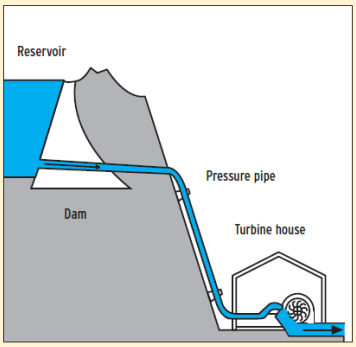
River Runoff

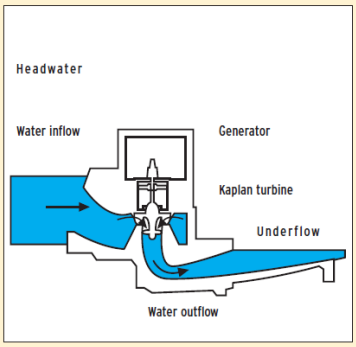
Pump Storage

Hydropower Systems

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

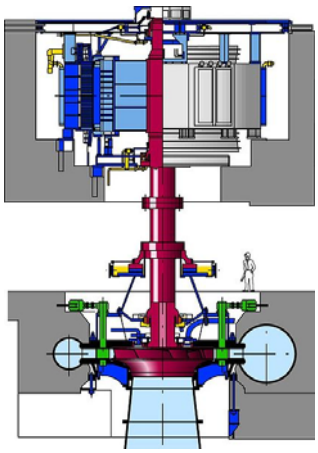
Sources: Tauernkraft/Verbund und ExpoStadt



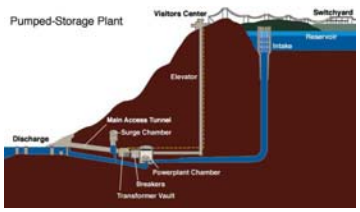


Principle of a dam storage power plant and of a run-of-river power plant

Hydropower Systems

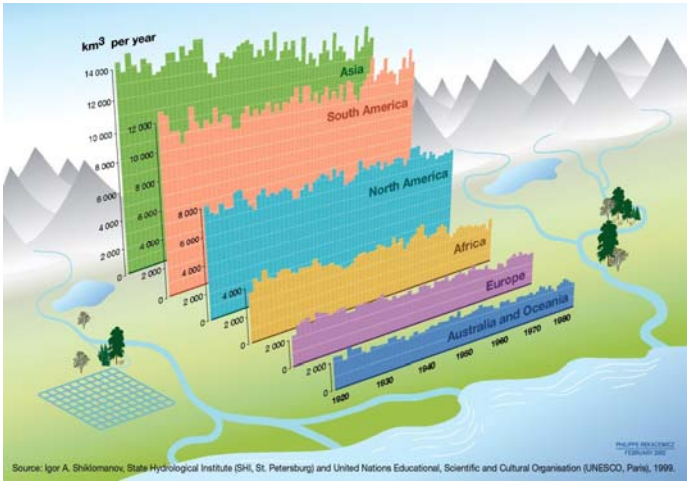


Goldisthal Pump Turbine Cross Section

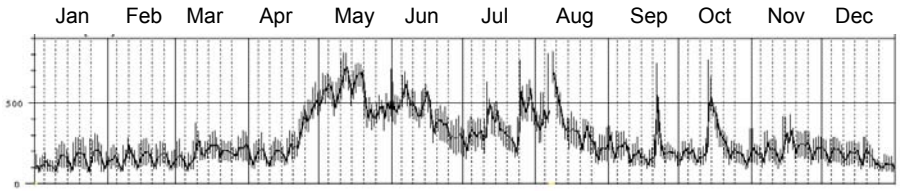


Hohenwarte an der Saale pump-storage hydropower station

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%
- parasitics, transformers 1-4%
- overall hydropower efficiency 80-90%
- overall pump storage efficiency 70-80%

Hydropower Performance Model

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

P	power capacity [W]
g	acceleration by gravity = 9.81 [m/s²]
h	height [m]
Q	volumetric flow through turbine as part of total river runoff [m³/s]
ρ	density of water [kg/m³]
ζ	piping losses as function of pipe length and fittings [%]
Φ	parasitics and transformation losses [%]
$\eta_{turbine}$	turbine efficiency as function of load [%]
$\eta_{generator}$	generator efficiency as function of load [%]

Hydropower Scenario Model

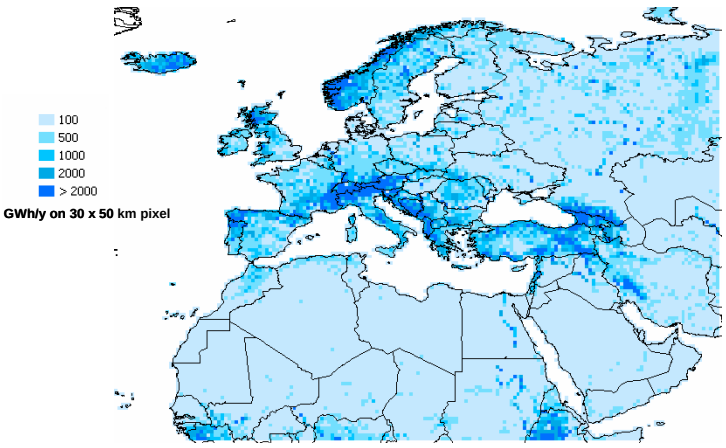
The statistics on hydropower plants world wide are rather reliable. Assuming that hydropower plants will have a similar performance as similar plants in the same region, the capacity factor CF_{hydro} can be estimated from documented hydropower generation (E_{hydro}) and installed capacity (P_{hydro}).

$$CF_{hydro} = E_{hydro} / P_{hydro} / 8760$$

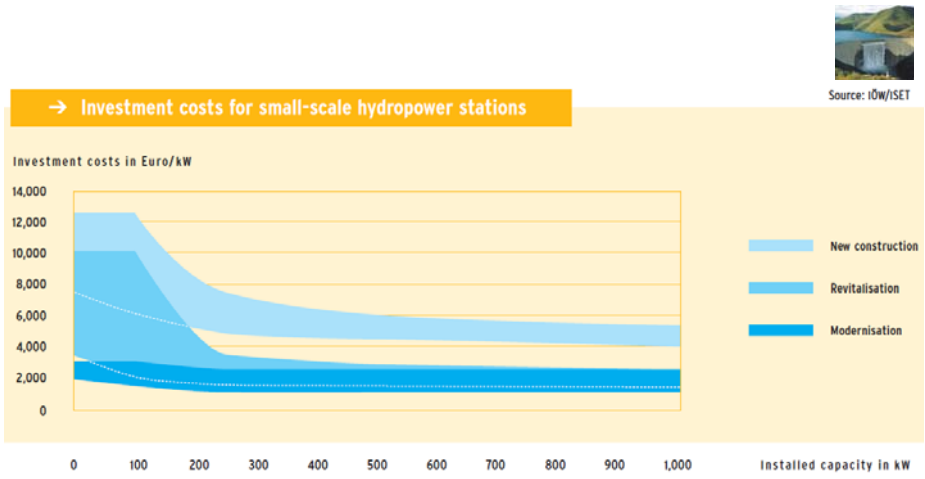
CF_{hydro}	capacity factor
E_{hydro}	annual electricity [MWh/y]
P_{hydro}	installed capacity [MW]

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

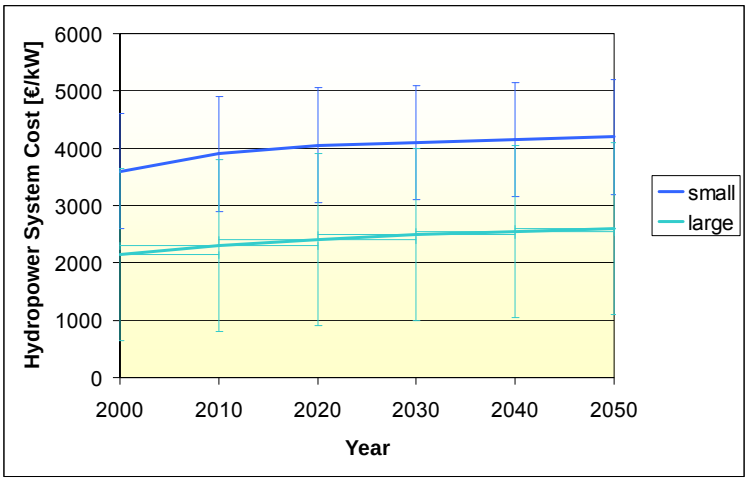
Hydropower Resources



Gross Hydropower Potentials adapted from /Lehner et al. 2005/



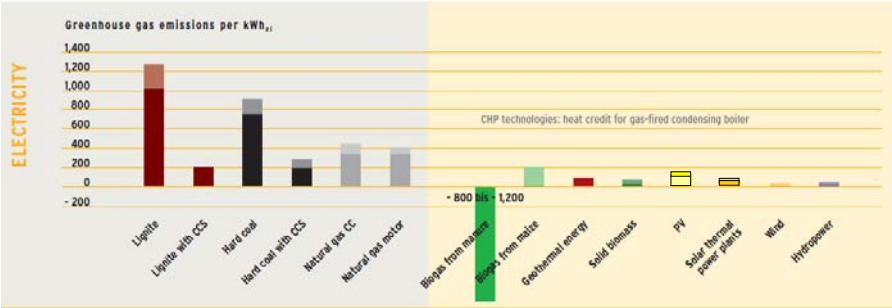
Hydropower Investment Cost Perspectives



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

Biomass

Biomass Applications

Biogas

Biofuel

Combustion & Gasification of Solid Biomass

→ Generating electricity from biomass

SOLID BIOMASS

- Combustion
- Gasification
- Liquefaction

	Electrical efficiency
>> Coal- or gas-fired power plant	30 - 40 %
> Steam turbine or engine	15 - 30 %
> Stirling engine	10 - 15 %*
> Gas turbine / Gas-and-steam plant	20 (GT) - 30 %
>> Reciprocating engine	ca. 25 %
>> Fuel cell	30 - 45 %**

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

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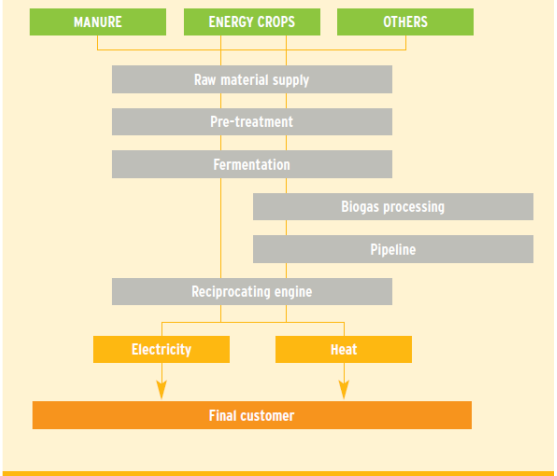
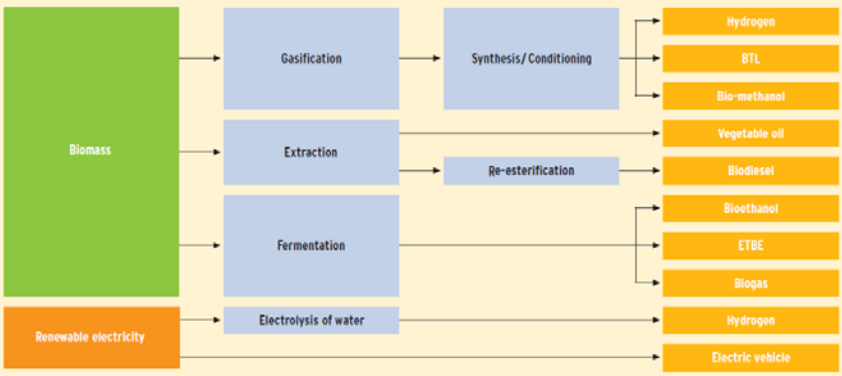
→ Biogas system

Source: IFEU



From raw material to useful energy

→ Fuel production paths

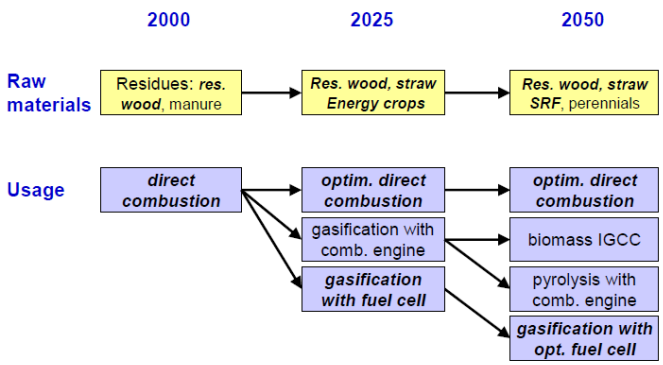


Some of the possible pathways to produce fuels from renewable energy carriers

Energy Yield from One Hectare (ha) of Energy Crops

	Biomass yield in tons	Yield of final energy in GJ
Solid biofuels		
Short rotation poplar	20	180
Triticale (whole plant)	14	170
Miscanthus × giganteus	16	180
Liquid biofuels		
Sugar beet ethanol	56	110
Wheat ethanol	7 (grains)	55
Rapeseed oil	3.5 (seeds)	40
Biodiesel from rapeseed oil	3.5 (seeds)	40
Biomass-to-liquid diesel (BTL) from poplar	20	90
Gaseous biofuel		
Biogas from corn	45	120
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

$E_{bio} = E_{mun} + E_{agr} + E_{wood}$

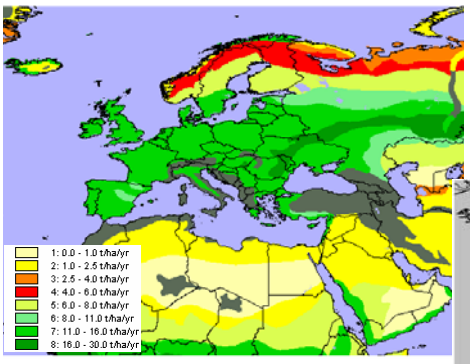
$E_{mun} = N \cdot w_{mun} \cdot e_{bio}$

$E_{agr} = w_{agr} \cdot e_{bio}$

$E_{wood} = p_{wood} \cdot A_{forest} \cdot e_{bio}$

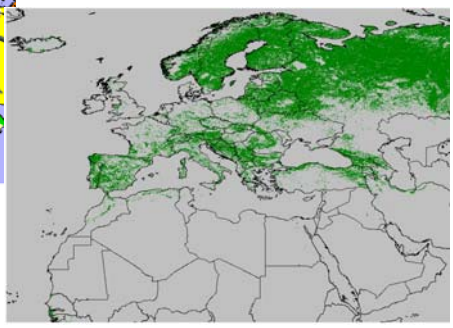
E_{bio}	Electricity from biomass [MWh/y]
E_{mun}	Electricity from municipal waste [MWh/y]
E_{agr}	Electricity from agricultural residues [MWh/y]
E_{wood}	Electricity from wood [MWh/y]
e_{bio}	Specific electricity yield from biomass [MWh/ton] ~ 0.5 - 1.0 MWh/ton
w_{mun}	Specific municipal waste production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

Biomass Resources

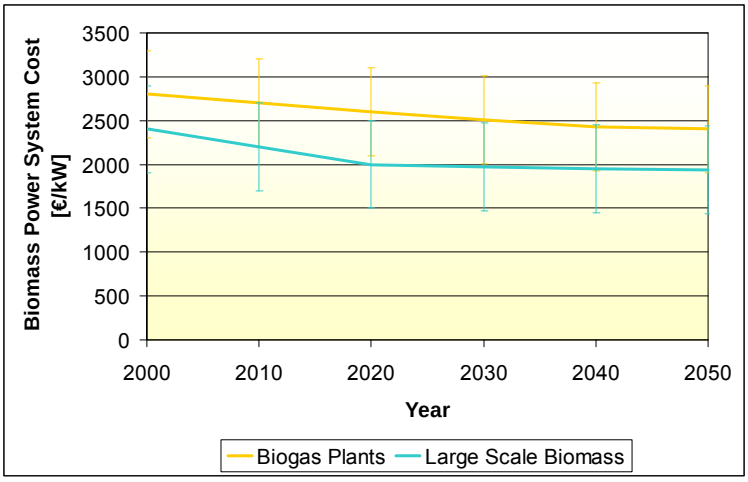


Map of biomass productivity /Bazilevich 1994/

Map of forest areas /USGS 2002



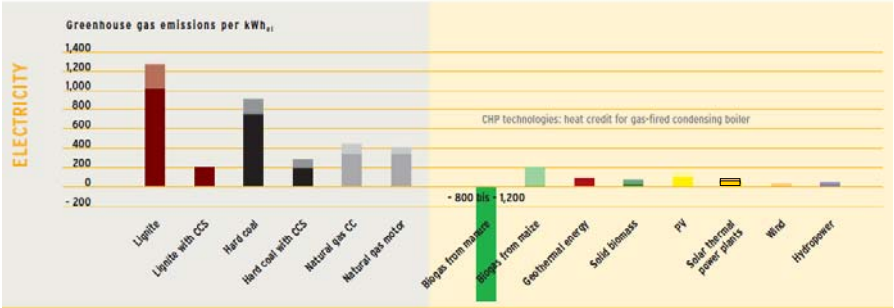
Biomass Investment Cost Perspectives



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

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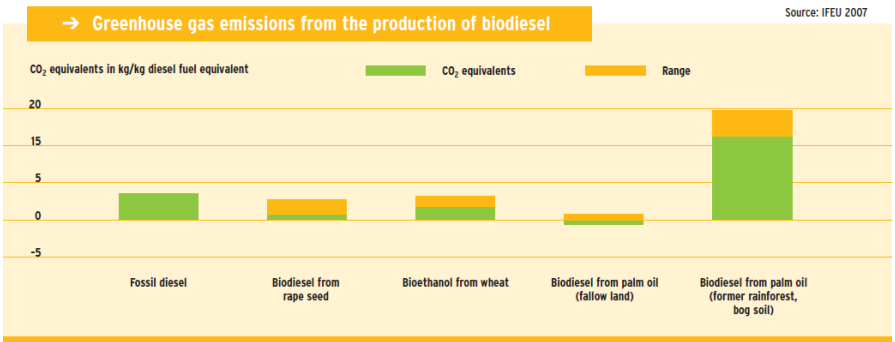
Biodiesel Life Cycle Carbon Emissions



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.

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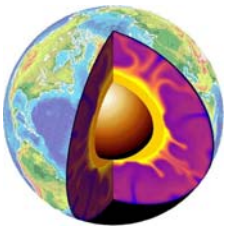
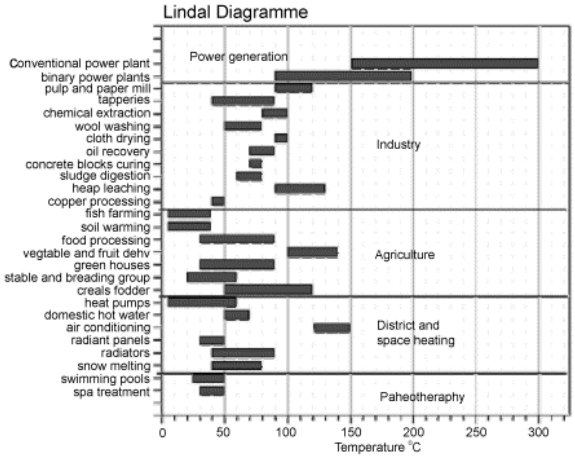
Geothermal Power



Geothermal Heat Applications



Geothermal Power Options

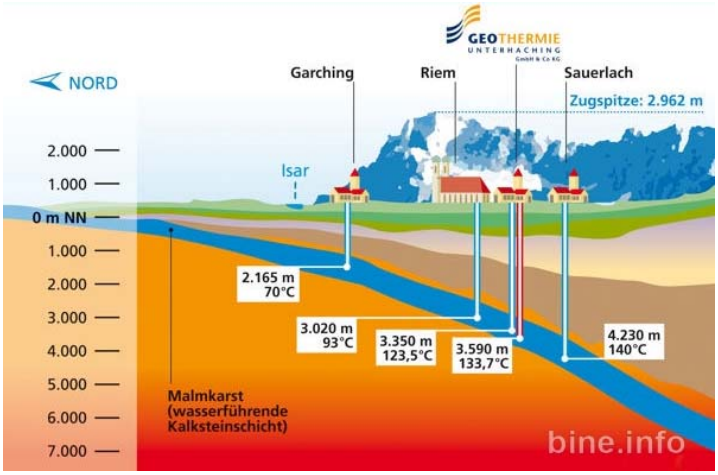
Hydrothermal Power Plant

Blue Lagoon, Reikjawik, Island

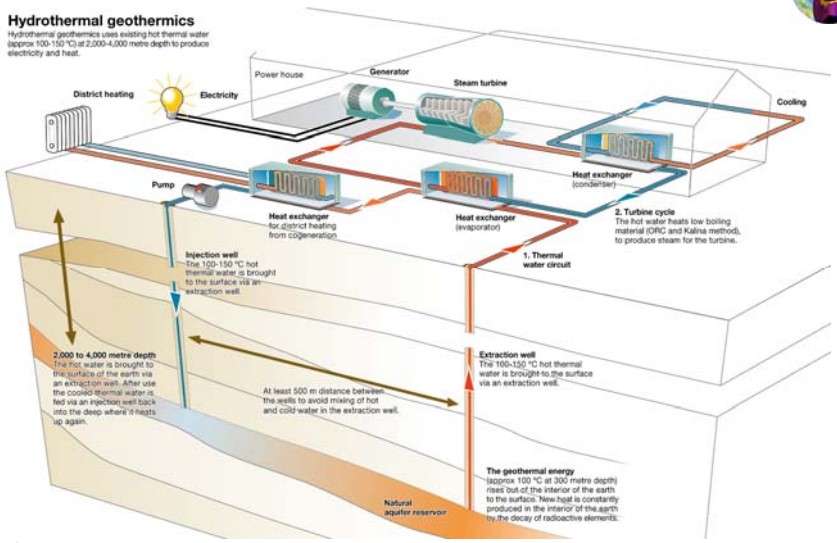
Power from
Deep Hot Dry Rock

HDR Drilling in Basel, Switzerland

Hydrothermal Systems

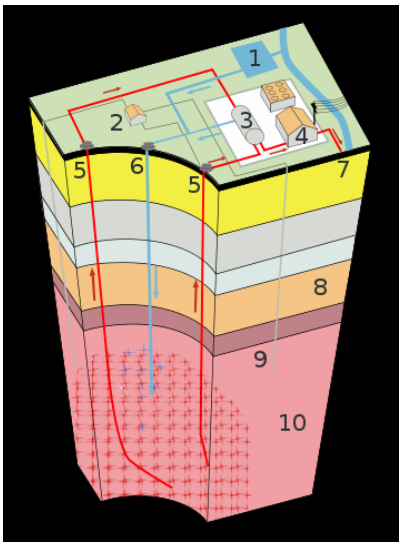


Hydrothermal System for Heat & Power



Hot Dry Rock System for Heat & Power

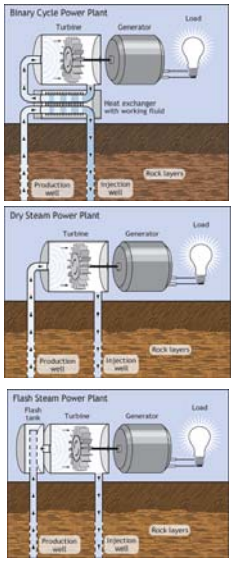
1: Reservoir
2: Pump house
3: Heat exchanger
4: Turbine hall
5: Production well
6: Injection well
7: Hot water to district heating
8: Porous sediments
9: Observation well
10: Crystalline bedrock



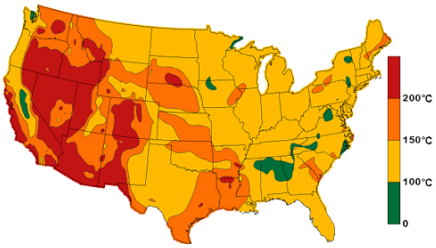
Geothermal Power Cycles

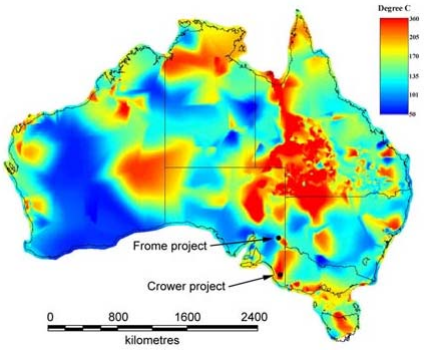
A binary cycle power plant is a type of geothermal power plant that allows cooler geothermal reservoirs to be used than with dry steam and flash steam plants. They are used when the temperature of the water is less than 175 °C. With binary cycle geothermal power plants, pumps are used to pump hot water from a geothermal well, through a heat exchanger, and the cooled water is returned to the underground reservoir. A second "working" or "binary" fluid with a low boiling point, typically a butane or pentane hydrocarbon, is pumped at high pressure through the heat exchanger, where it is vaporized and then directed through a turbine. The vapor exiting the turbine is then condensed by cold air radiators or cold water and cycled back through the heat exchanger. Examples of binary cycle geothermal plants can be found at Mammoth Lakes, California, Steamboat Springs, Nevada and Hilo, Hawaii.

Binary power plants have a cycle efficiency of 10-13%



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 (η)	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]
ρ_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]
η :	Efficiency [1]

Jung et al. 2005

Geothermal Power Model Parameters

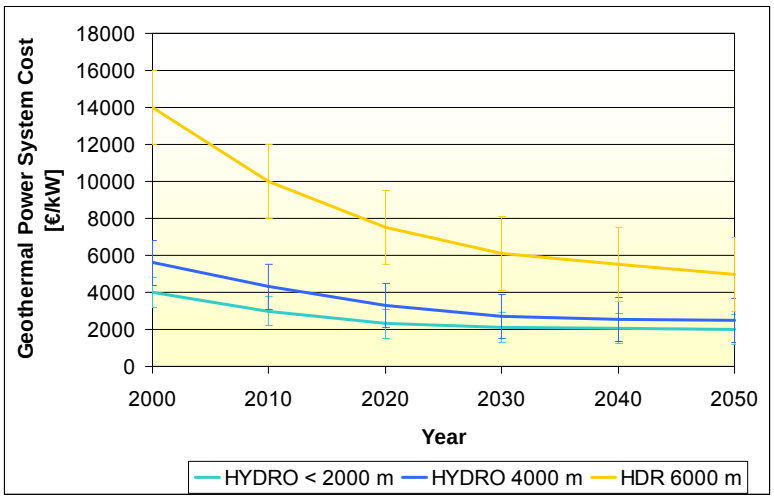
	Hot water aquifer			Faults, Crystalline rock			
	R			R			η
Temp.-class [°C]	Power	CHP	CHP-H	Power	CHP	CHP-H	
100-130	14	20	27	2,4	2,9	3,2	10,3
130-160	18	23	28	4,0	4,9	5,3	11,7
160-190	21	25	29	4,6	5,5	6,4	12,6
190-220				5,0	5,8	6,5	13,1
220-250				5,3	6,0	6,6	13,5

Recovery factors R [%] and efficiencies η [%]. CHP: Combined Heat and Power Production, CHP-W: Combined Heat and Power Production with heat pump

rock density ρ_R = 2600 kg/m³
specific heat c_R = 840 J/kg
electricity $E_{geo} = H_{el} / (t_{exploit} \cdot 3.6 \cdot 10^{12})$ [GWh/y]
Exploitation time $t_{exploit}$ = 100 years

Jung et al. 2005

Geothermal Power Investment Cost Perspectives

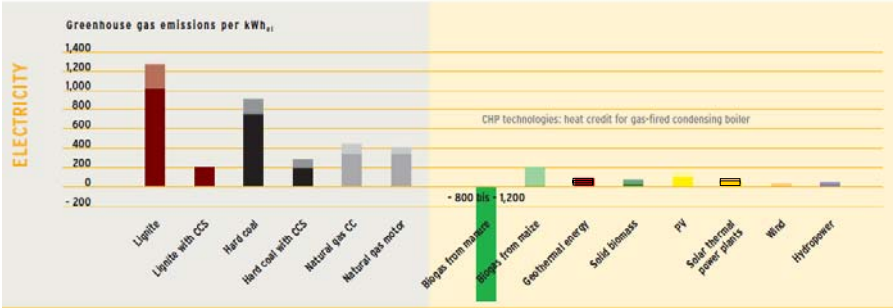


ECOFYS 2009, own estimates

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
- 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

BMU 2009

Sources and Literature

BMU 2009	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) Dr. M. Pehnt (IFEU/coordination) with D. Jessing, P. Otter, R. Vogt, G. Reinhardt (IFEU) Dr. W. Krewitt, M. Nast, Dr. J. Nitsch, Dr. F. Trieb (DLR) Renewable Energies - Innovations for a Sustainable Energy Future Berlin 2009 http://www.erneuerbare-energien.de/inhalt/44744/4590/
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