



Part 2: Renewable Energy Technologies

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MBA Energy Management, Vienna, September 9-10, 2010



Photovoltaics





Photovoltaic Applications



grid connected rooftop



grid connected power station



façades

stand
alone
rural



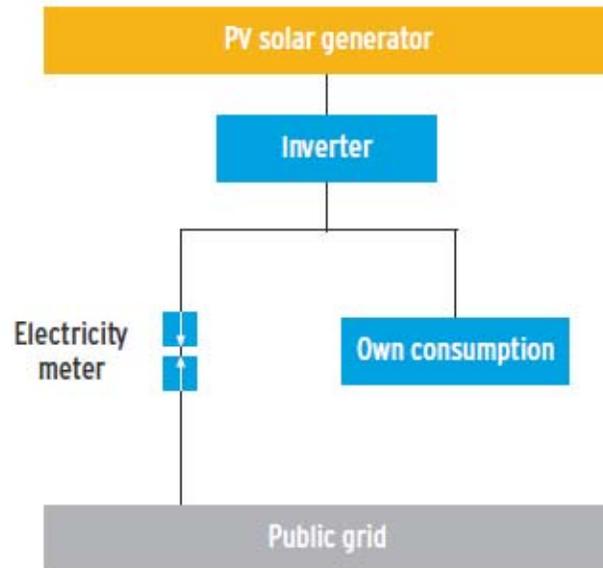
stand alone devices



transport

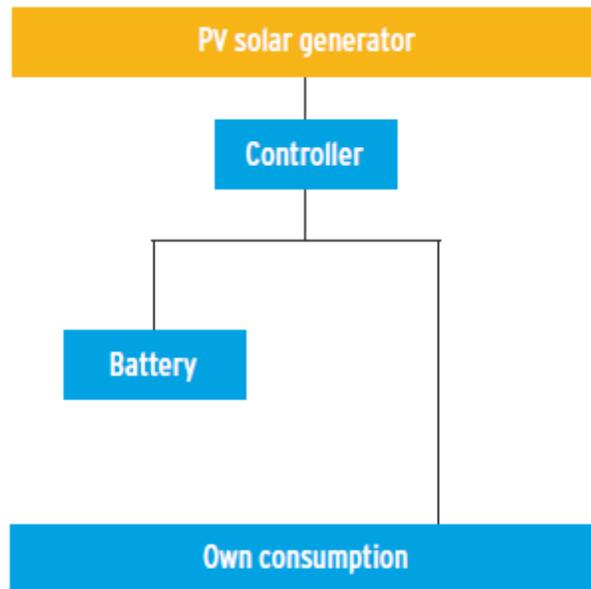


Grid-Connected Photovoltaic System





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)

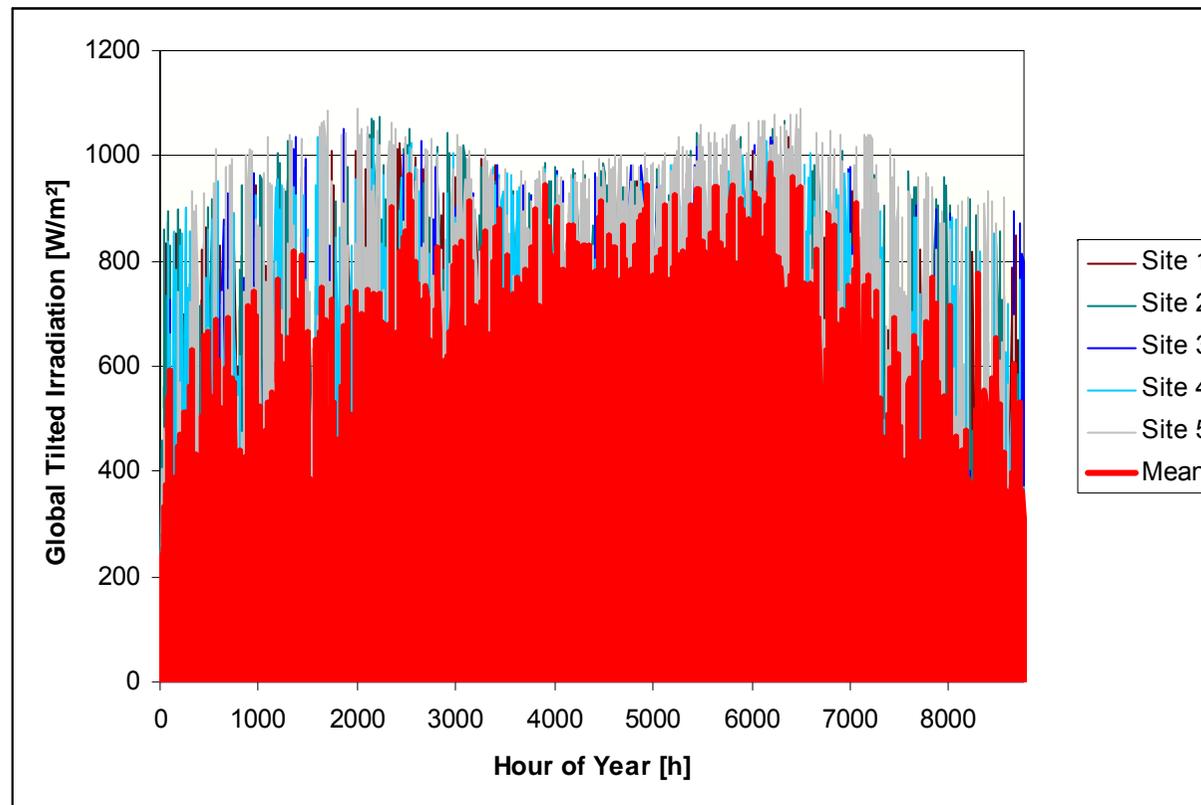
Fixed Horizontal Array

→ Global Horizontal Irradiance (GHI)





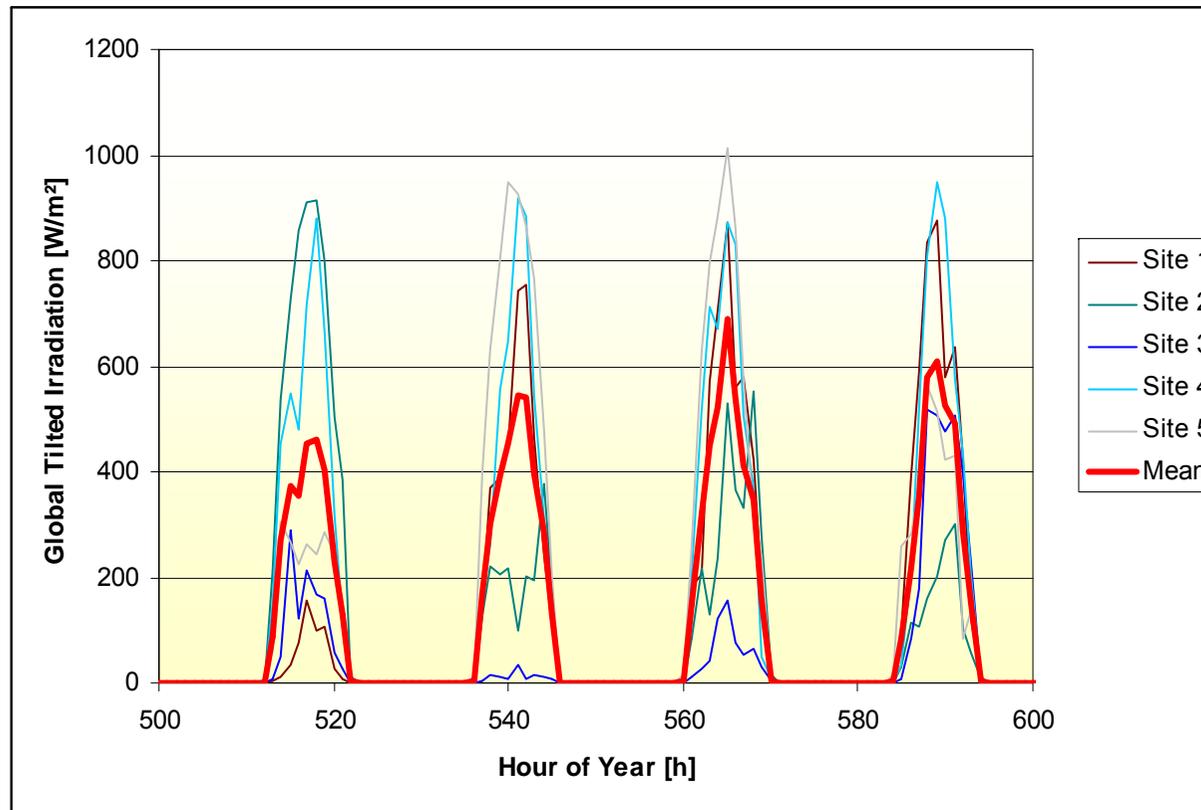
Photovoltaic Energy Resources



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

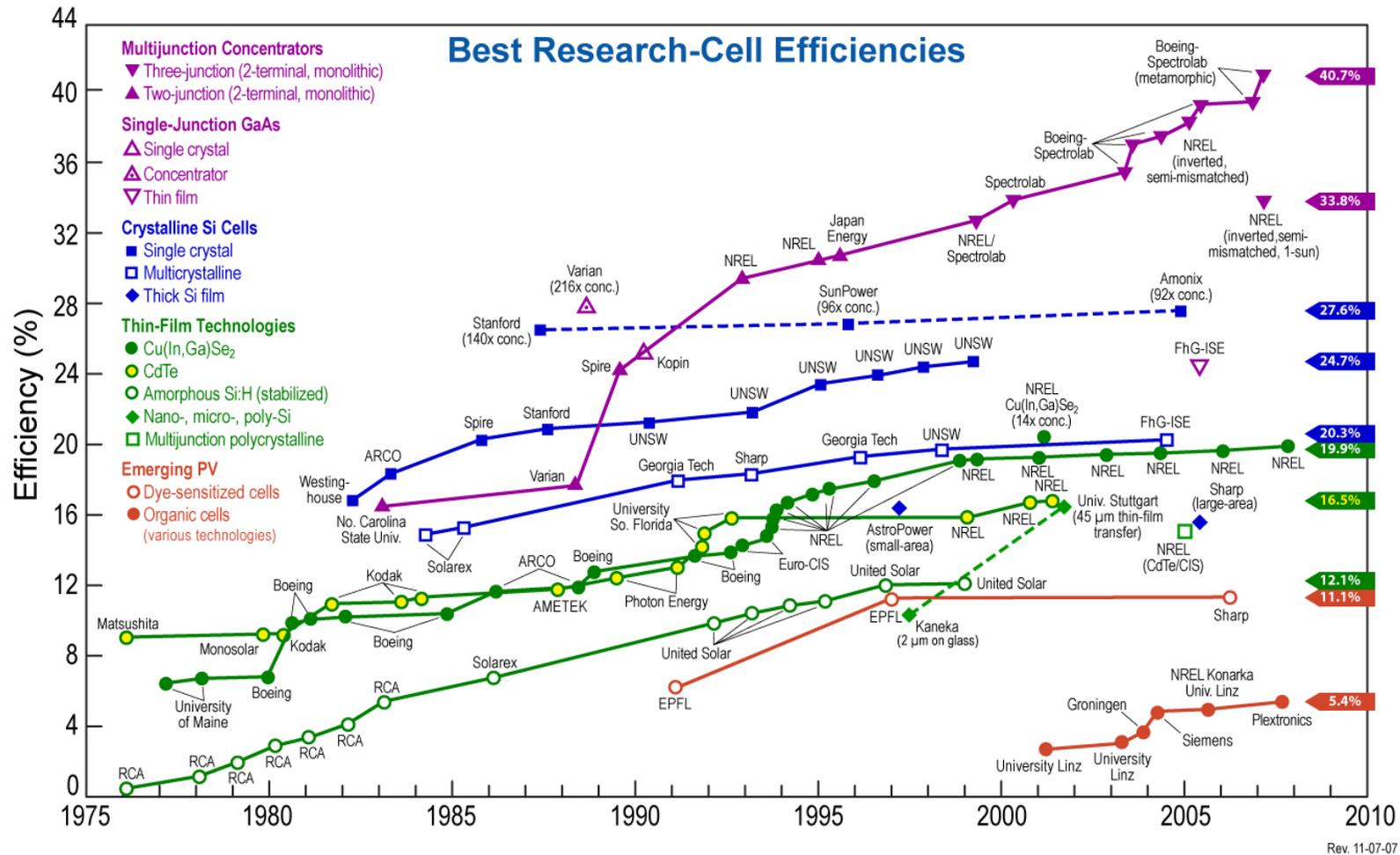
Fluctuating Primary Energy:

Photons cannot be stored → Storage only through electricity

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



Photovoltaic Cells Efficiency





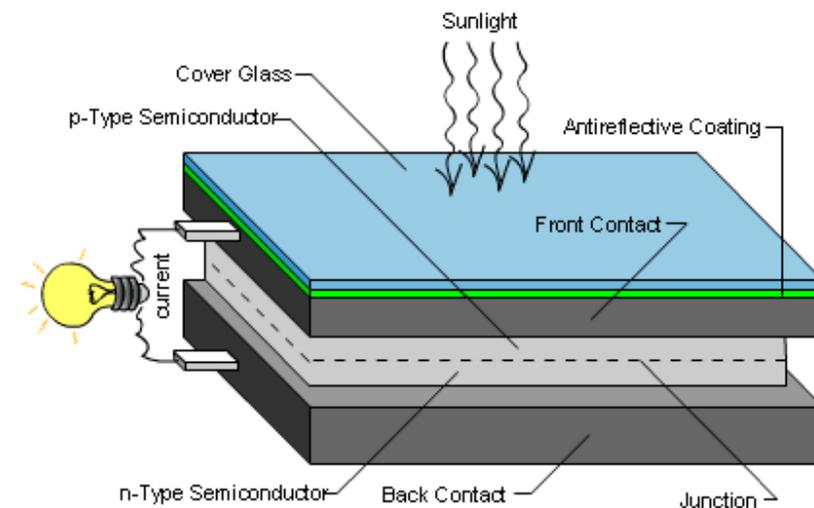
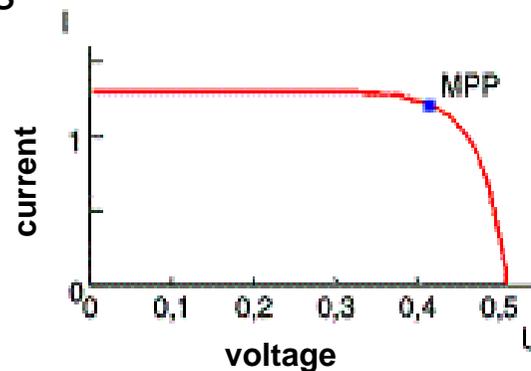
Photovoltaic Systems Efficiency Examples

| System Component | Non-Conc. MSi | Conc. MJ |
|--|---------------|------------|
| Cell at standard conditions 25°C, 1000 W/m ² , 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 [$kWh/m^2/y$]

η_{PV} PV system standard design efficiency

A_{PV} Design collector area for standard efficiency [m^2/kW_p]

8760 represents the total hours per year [h/y]

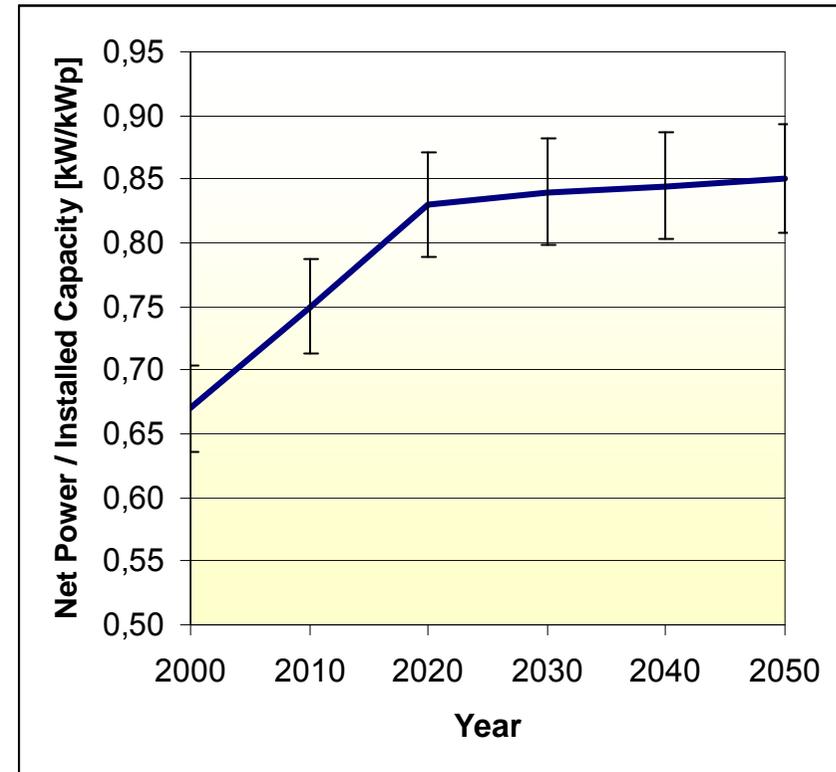


Photovoltaic Scenario Model

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

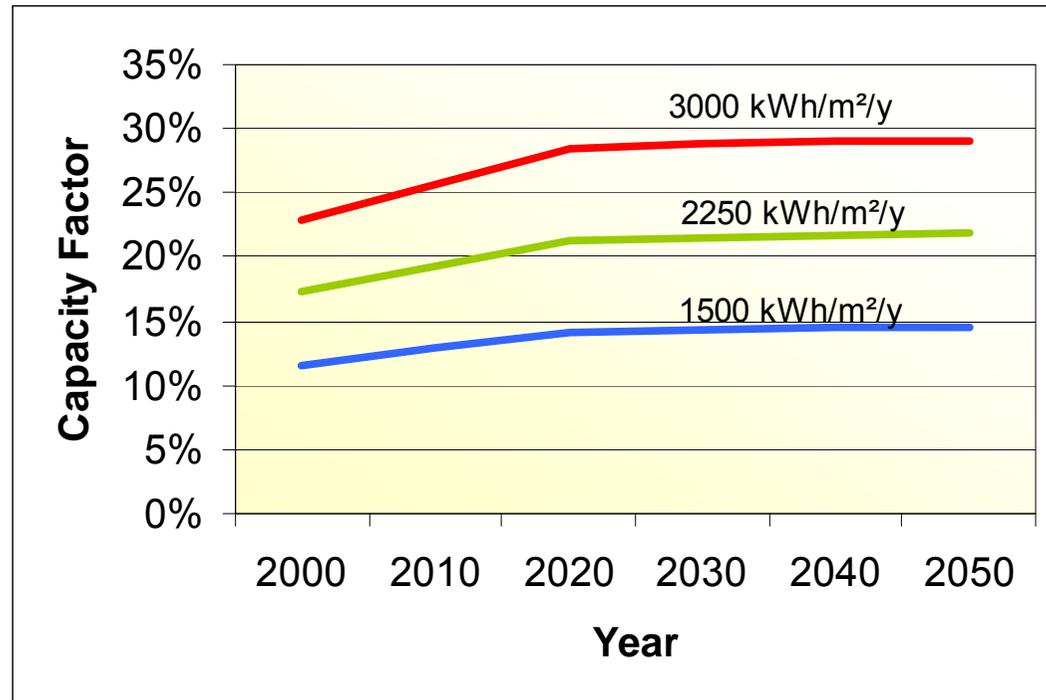
The capacity factor of a PV system varies according to the annual solar irradiation and to system performance which will increase as technology is improved.

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

Assumptions:

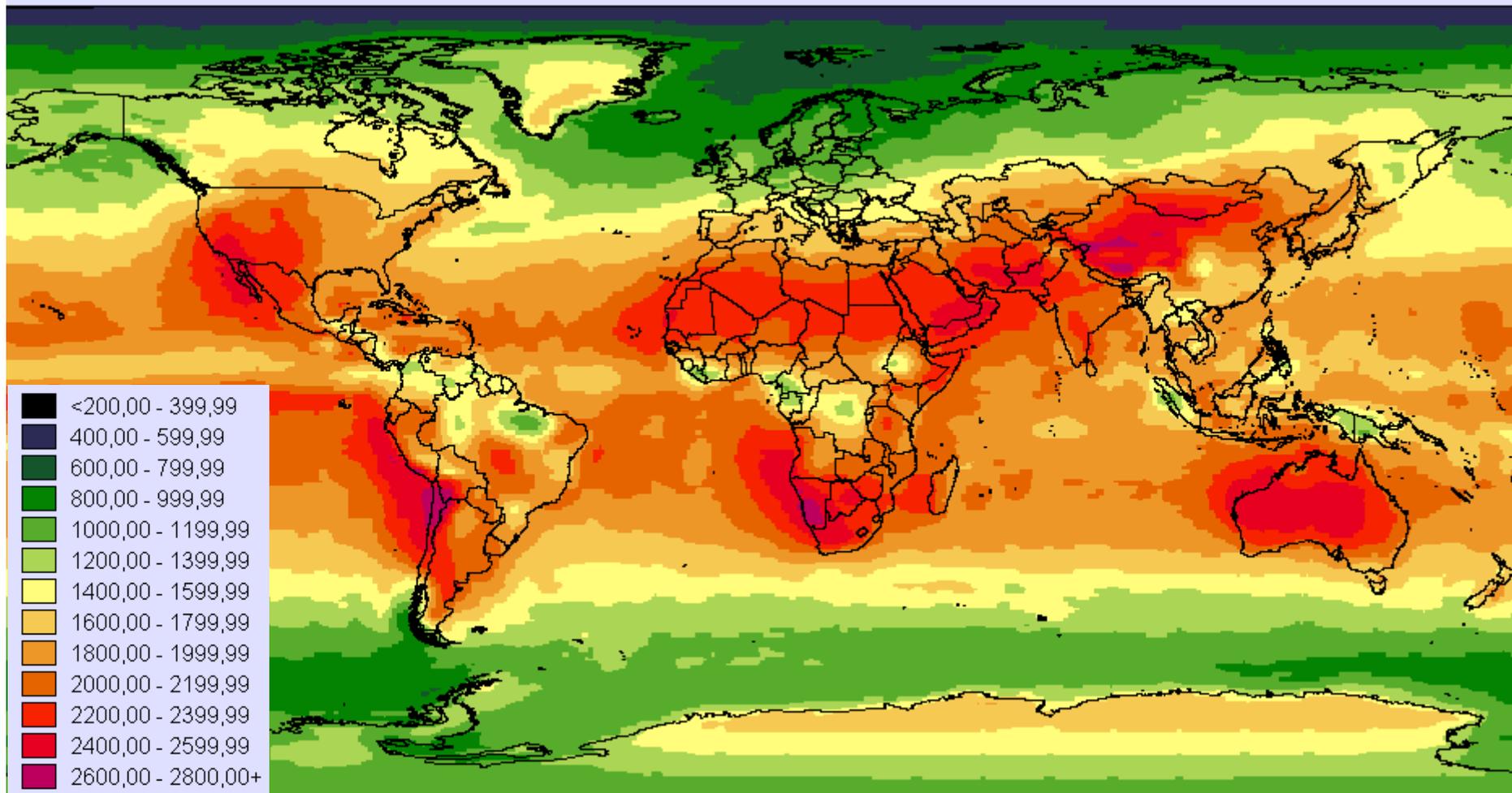
η_{PV} Initial PV standard system efficiency = 10%

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





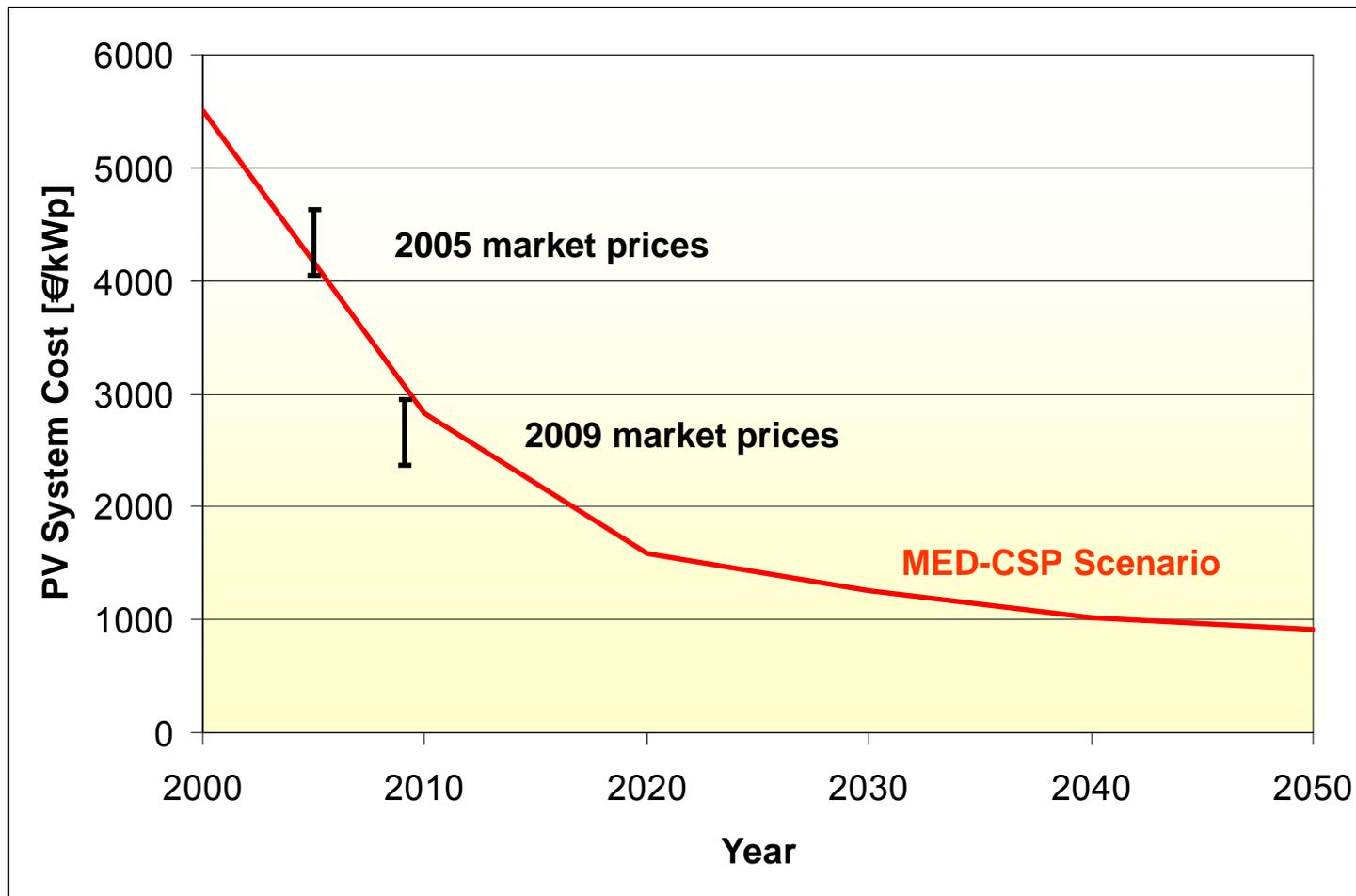
Annual Global Irradiance for Fix Tilted PV Systems



[kWh/m²/y]



Photovoltaic System Cost Perspectives



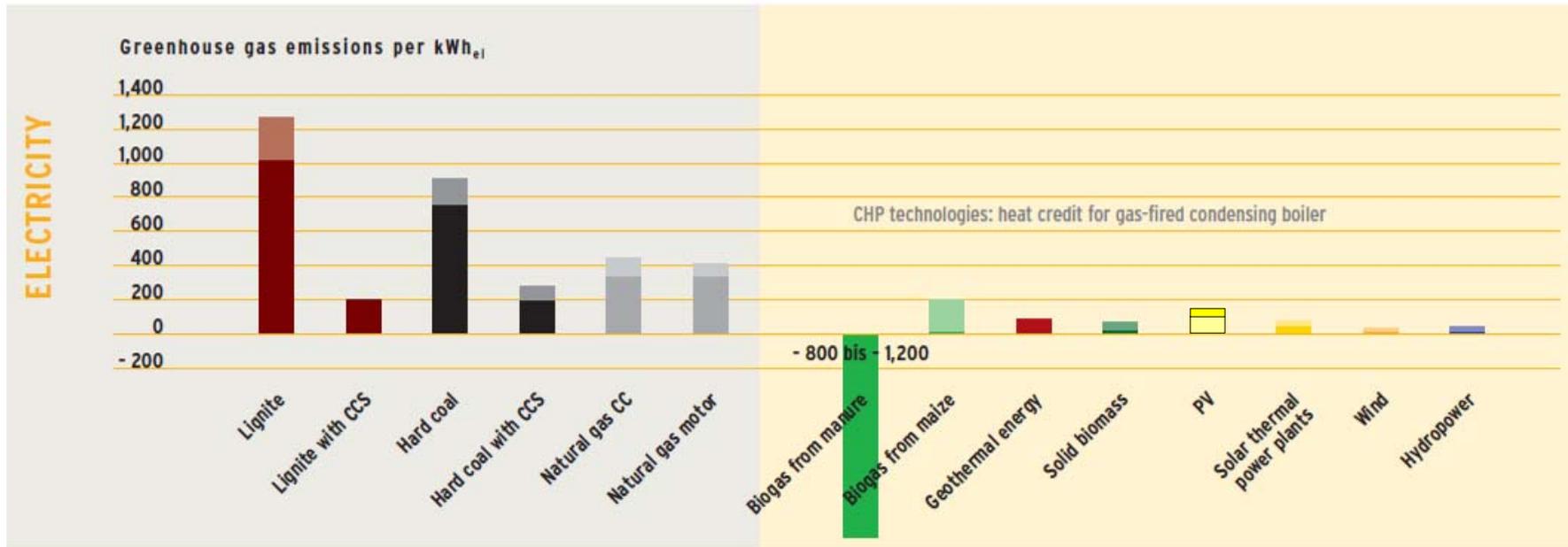


Environmental Impacts of Photovoltaic Systems

- 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



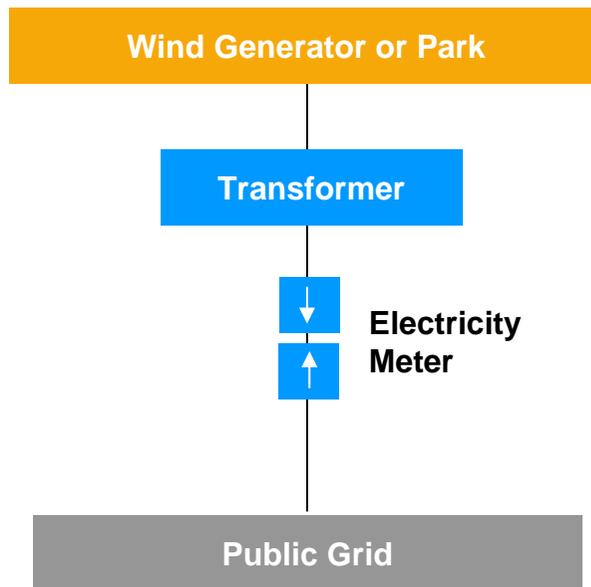
Stand-alone
Devices



Rural
Power &
Pumping

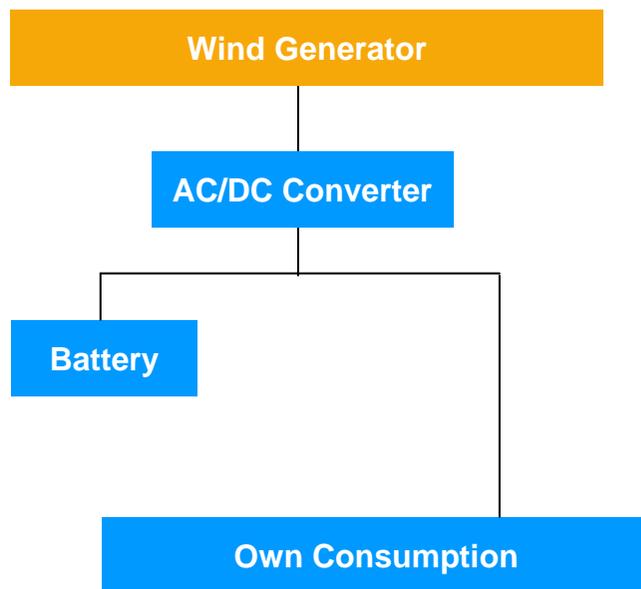


Grid Connected Wind Power Systems





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.

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

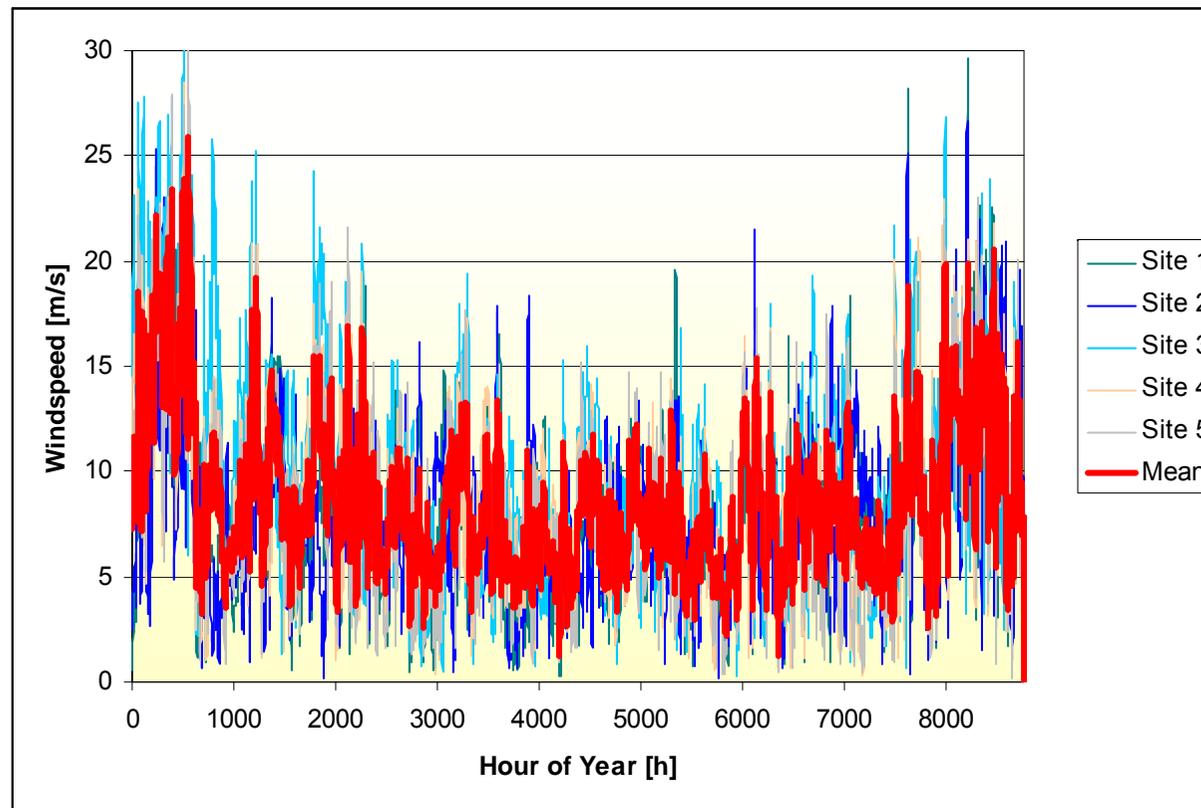
- $v(h)$ wind speed at shaft height h
- $v(h_0)$ wind speed at measured height h_0
- z_0 ground roughness at site
- \ln natural logarithm

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 |



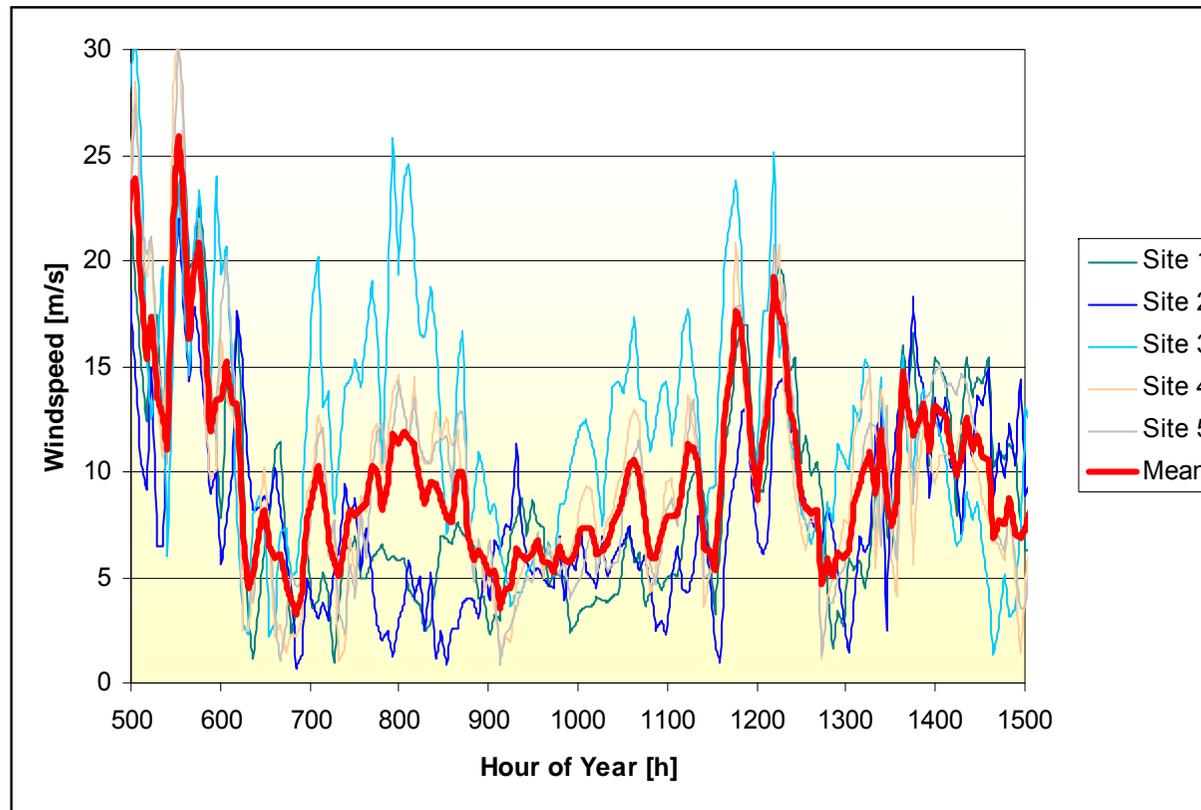
Wind Energy Resources



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:

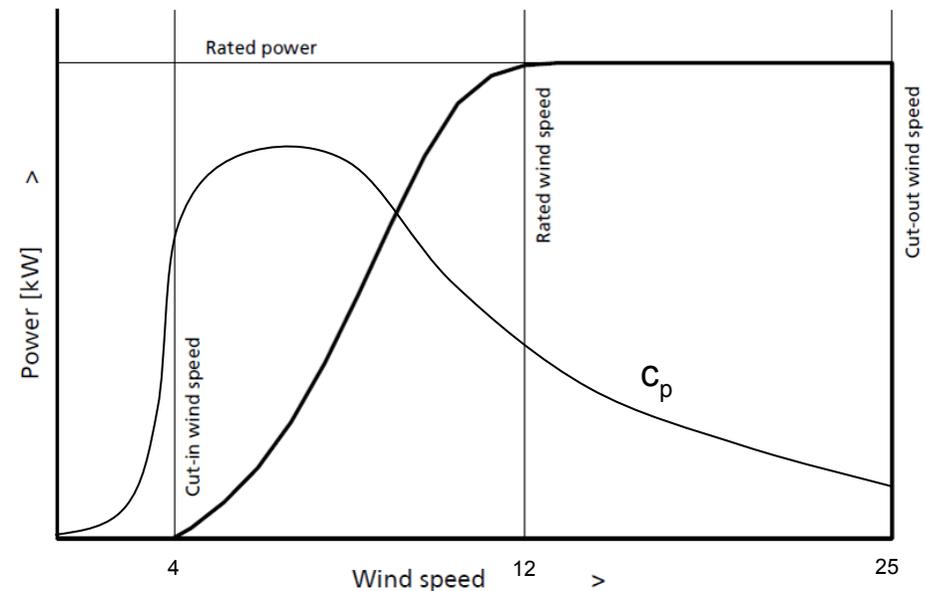
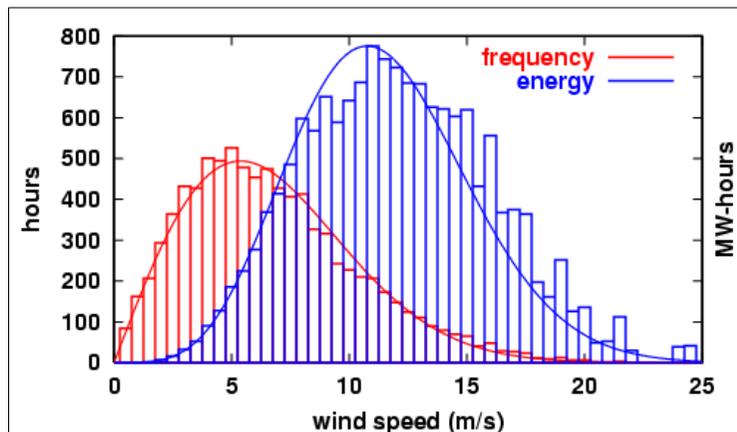
Wind cannot be stored → Storage only through electricity

* 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]:

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

v Wind Speed [m/s]

A Rotor Area [m²]

c_p Power Coefficient (depends on turbine type and wind speed)

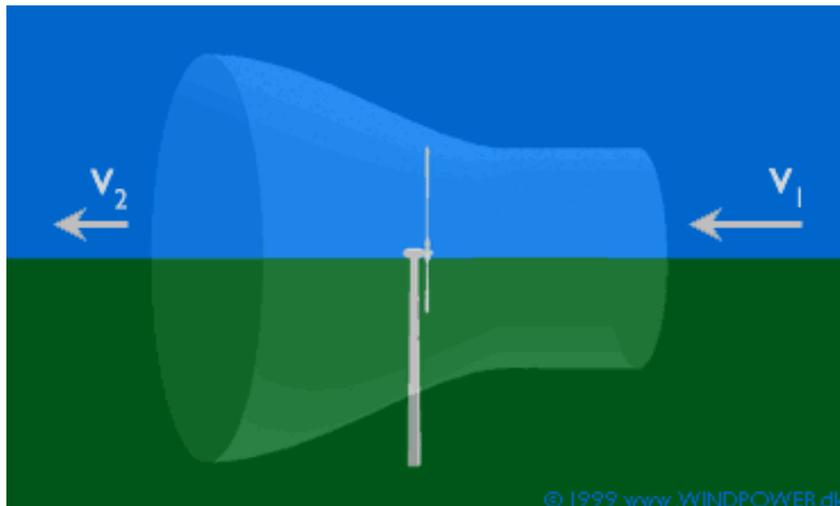
k_e Energy Pattern Factor $k_e = 1 + 0.28 \cdot v^{(-0.87)}$

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

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

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

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

v_{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

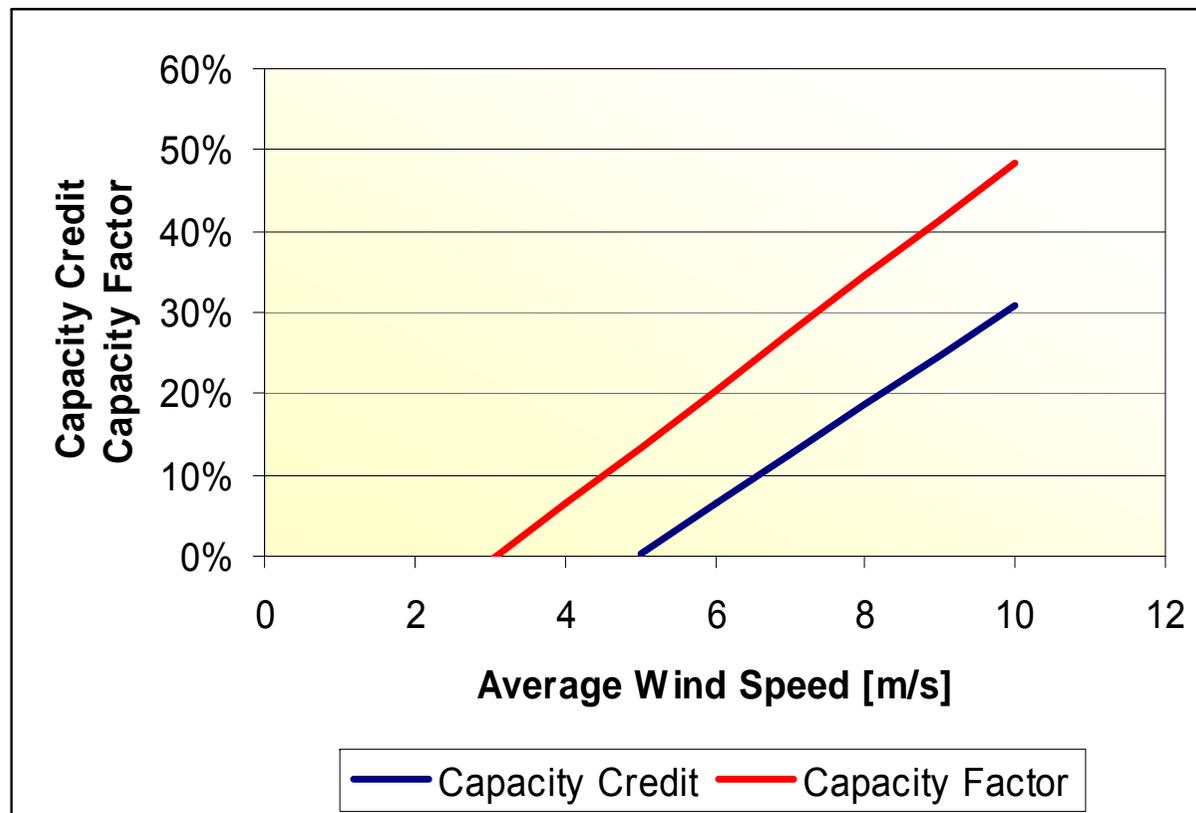
CC_{wind} Capacity Credit as function of the average annual wind speed

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

8760 Total hours per year [h]



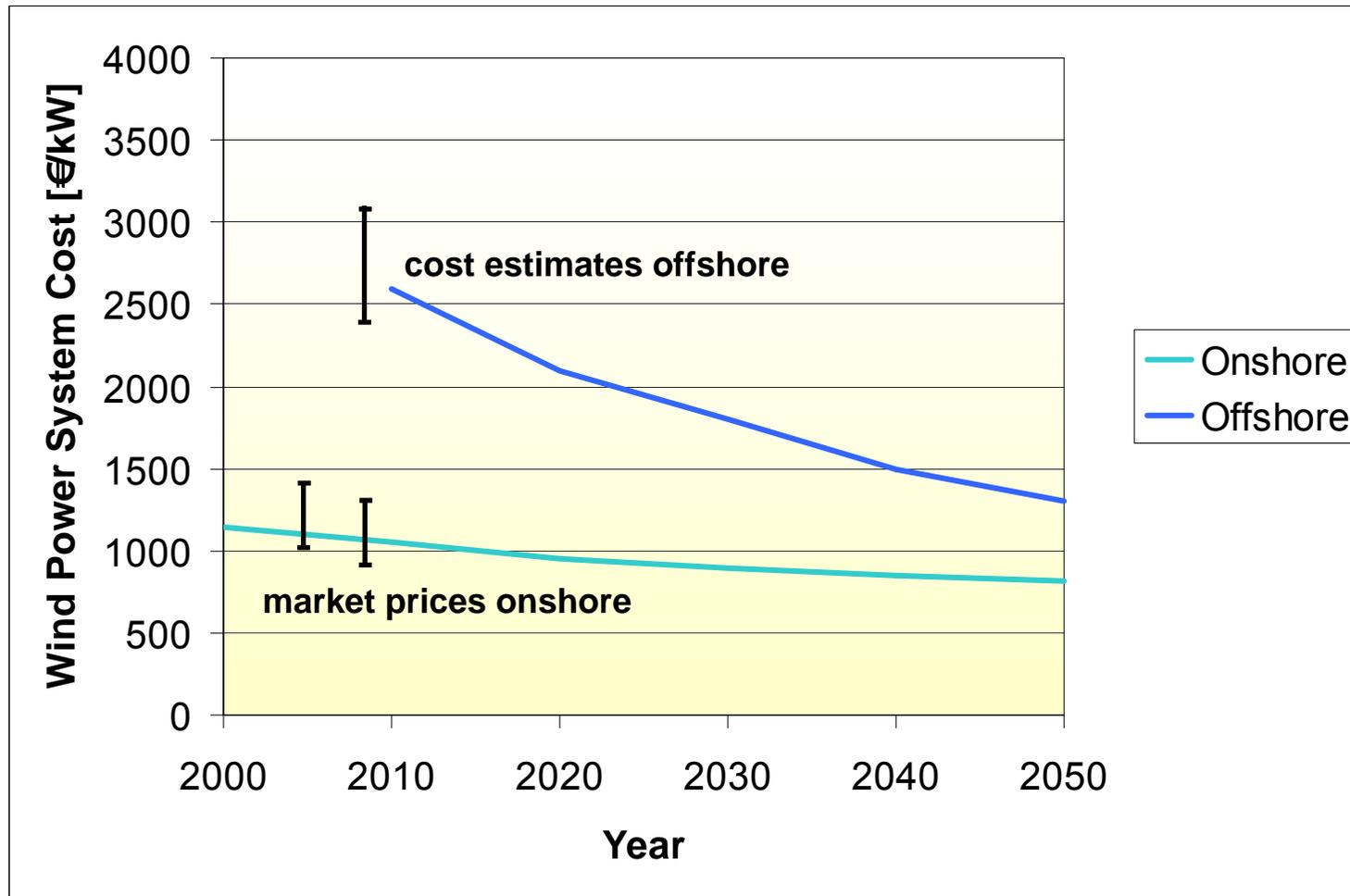
Simple Wind Performance Model



Estimate for large regions with several wind parks

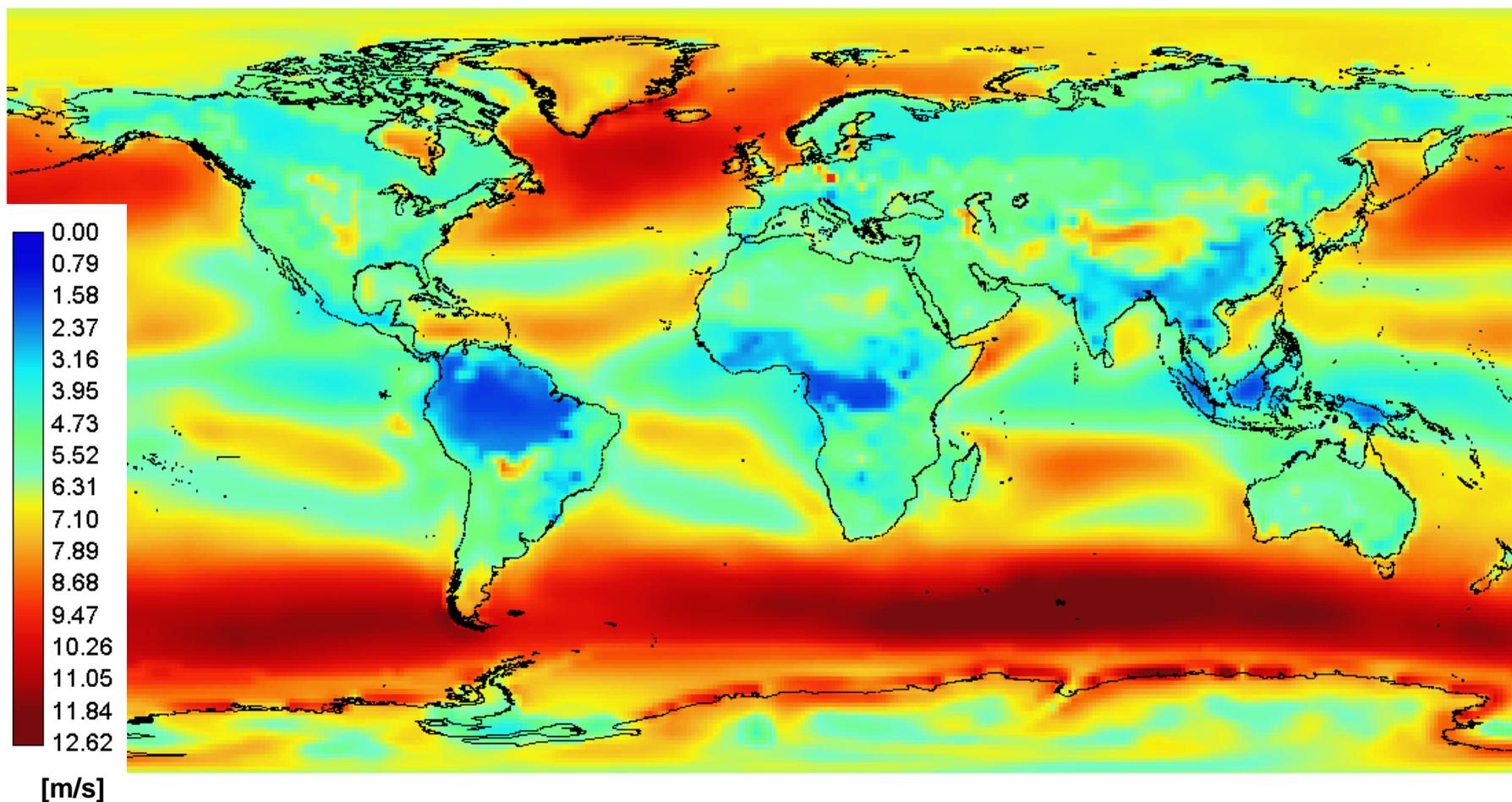


Wind Power System Cost Perspectives





Annual Average Wind Speed at 50 m Height



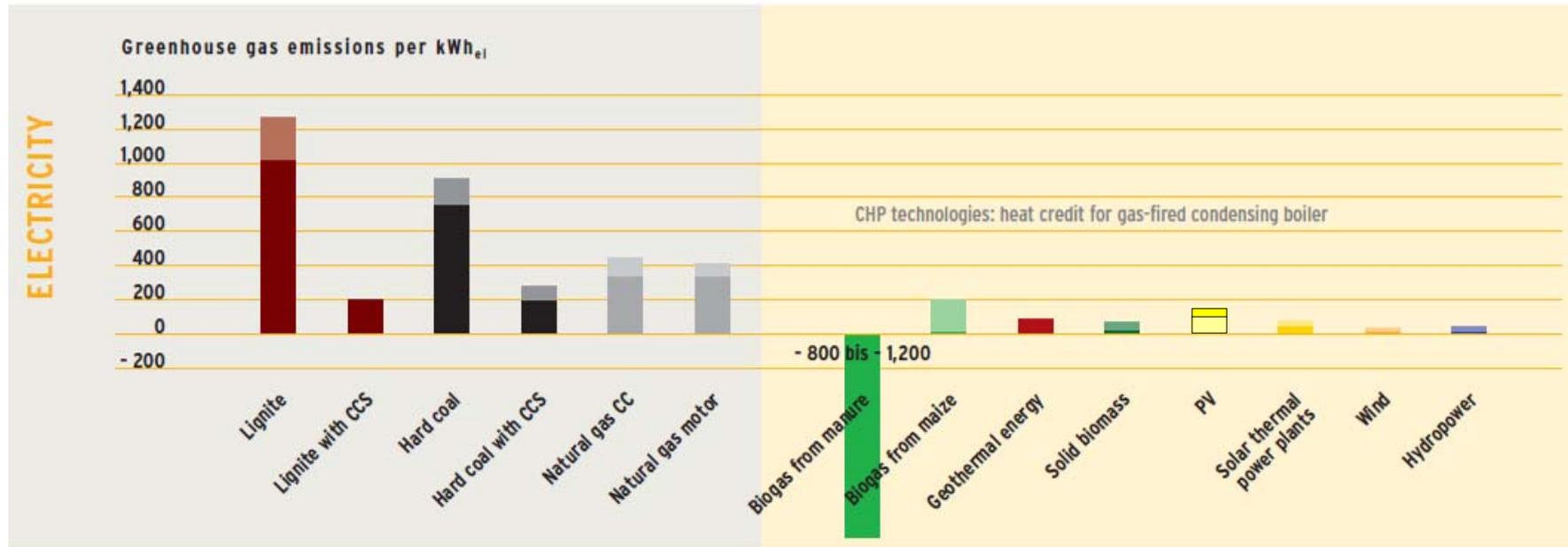


Environmental Impacts of Wind Power Systems

- 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





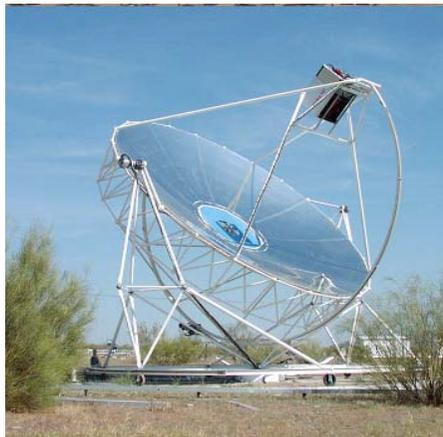
Concentrating Solar Power Applications



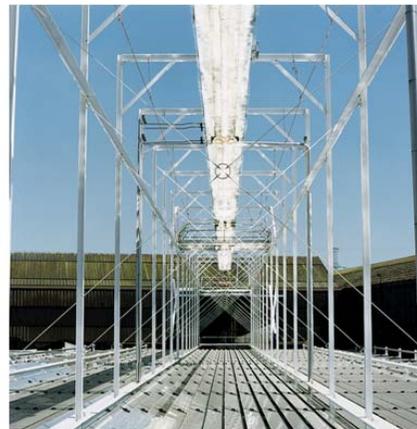
Grid Connected



Grid Connected with Storage

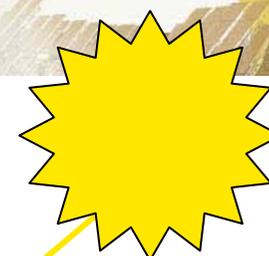


Stand Alone



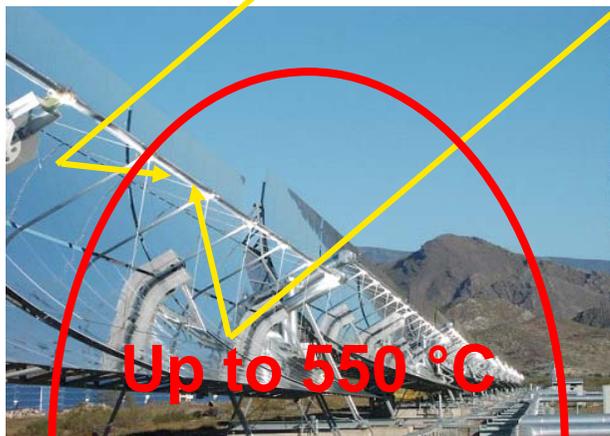
Multi Purpose

Concentrating Solar Thermal Collectors

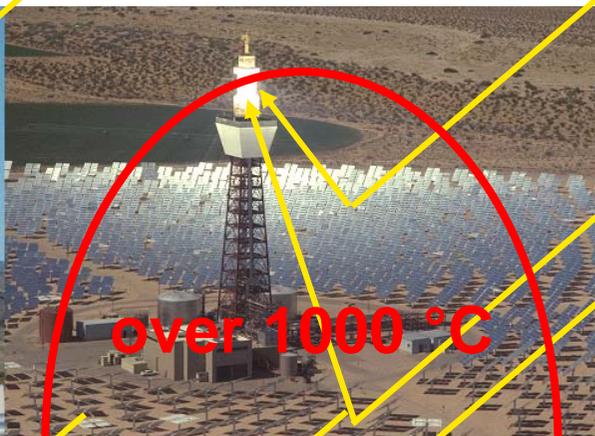


Parabolic Trough (PSA)

Solar Tower (SNL)



Up to 550 °C



over 1000 °C



Steam Turbines



Gas Turbines,
Engines

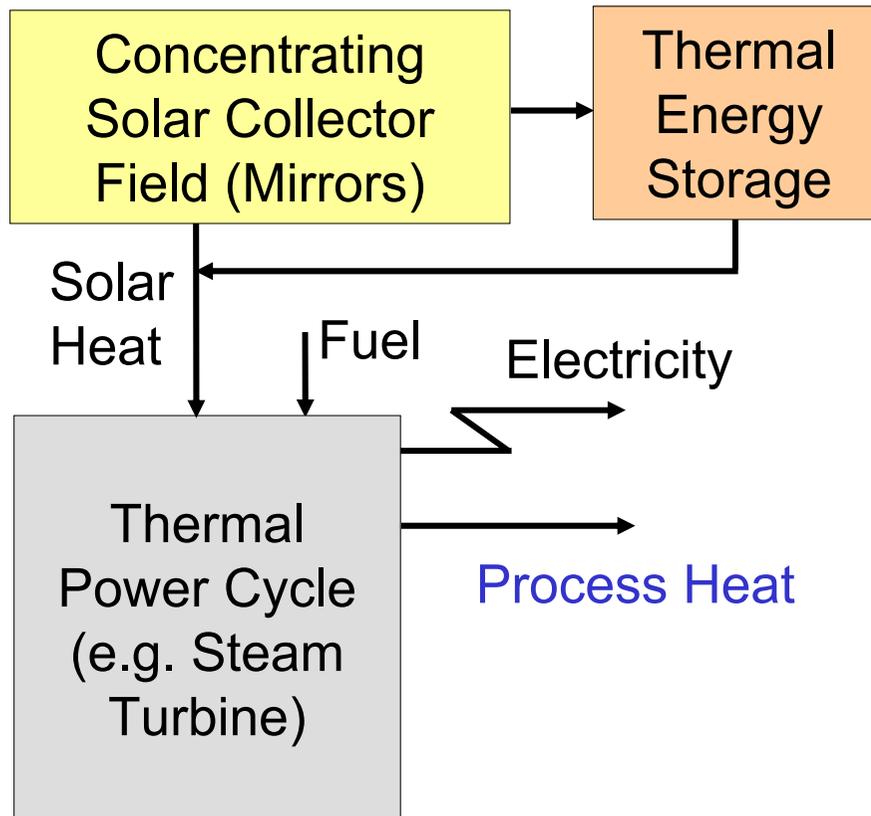
Linear Fresnel (MAN/SPG)

Dish-Stirling (SBP)





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.



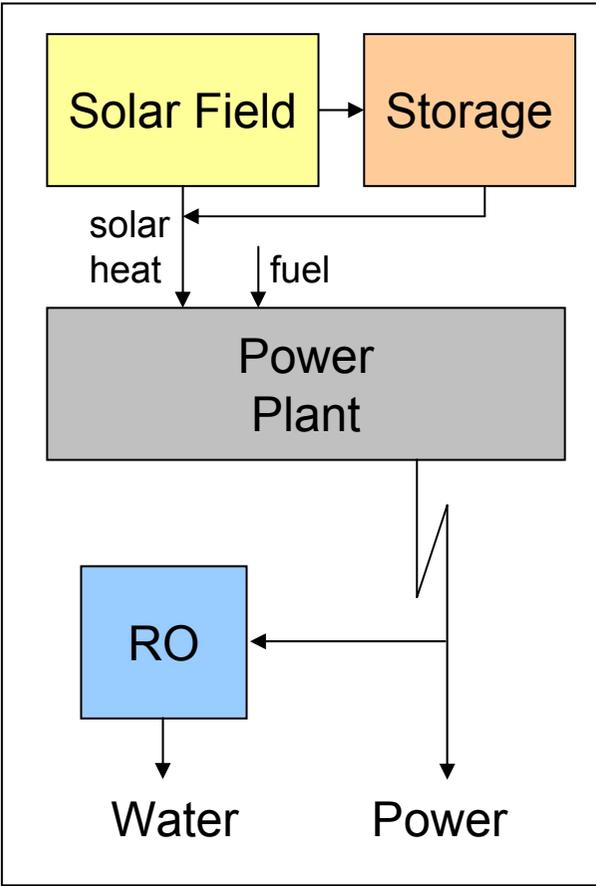
Configurations of CSP Desalination Plants



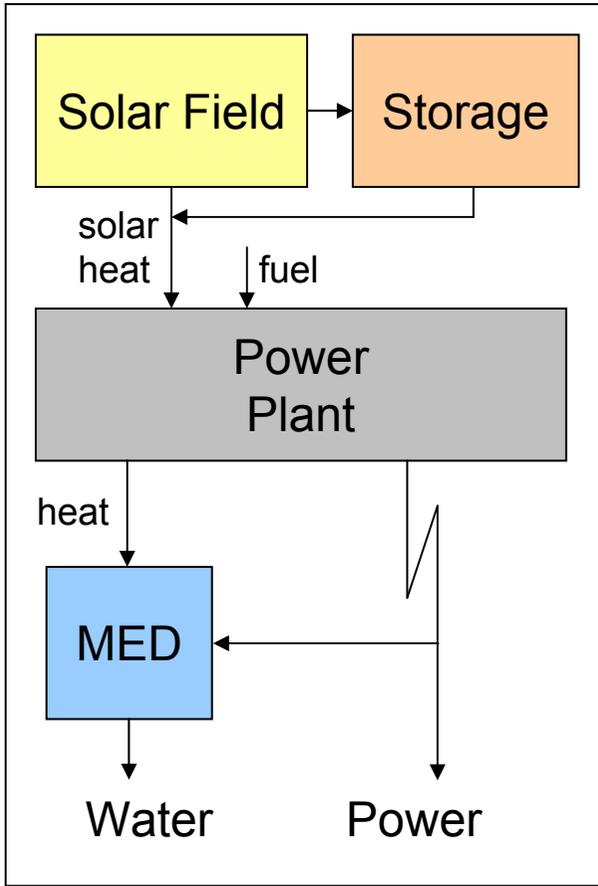
Power Only

Combined Heat & Power

CSP / RO



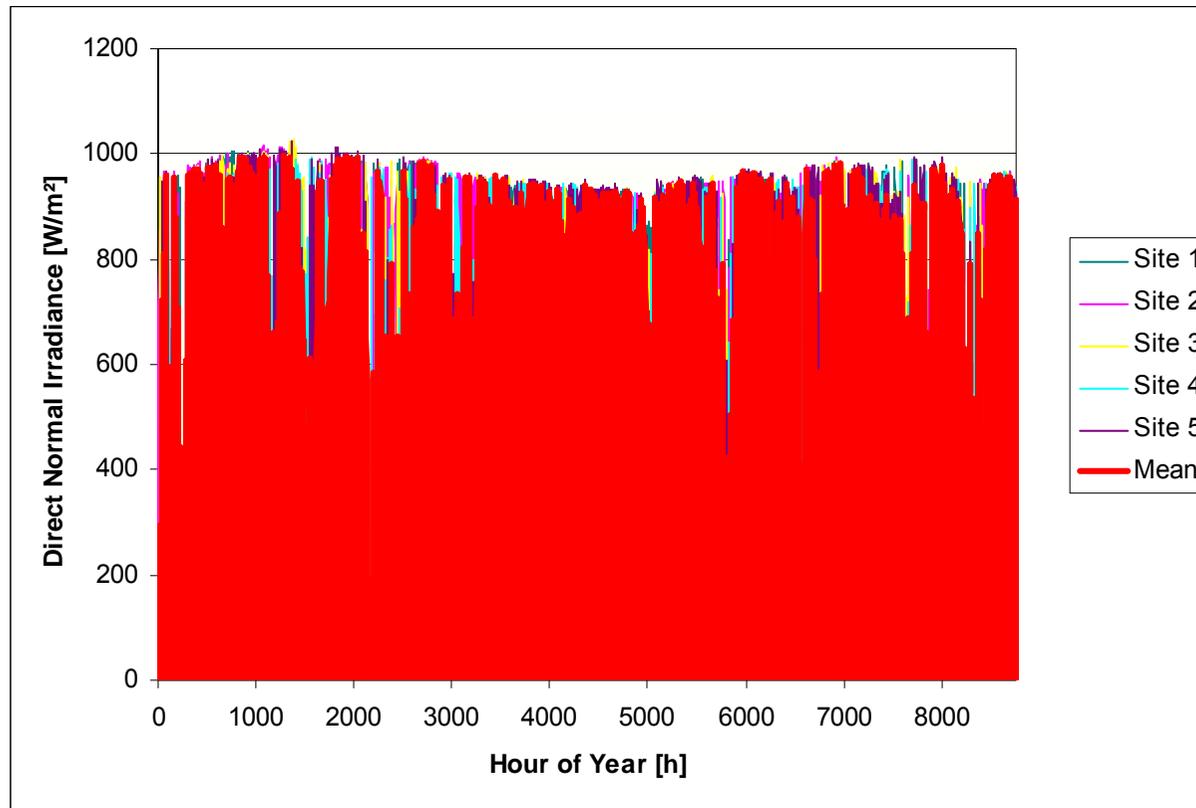
CSP / MED



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



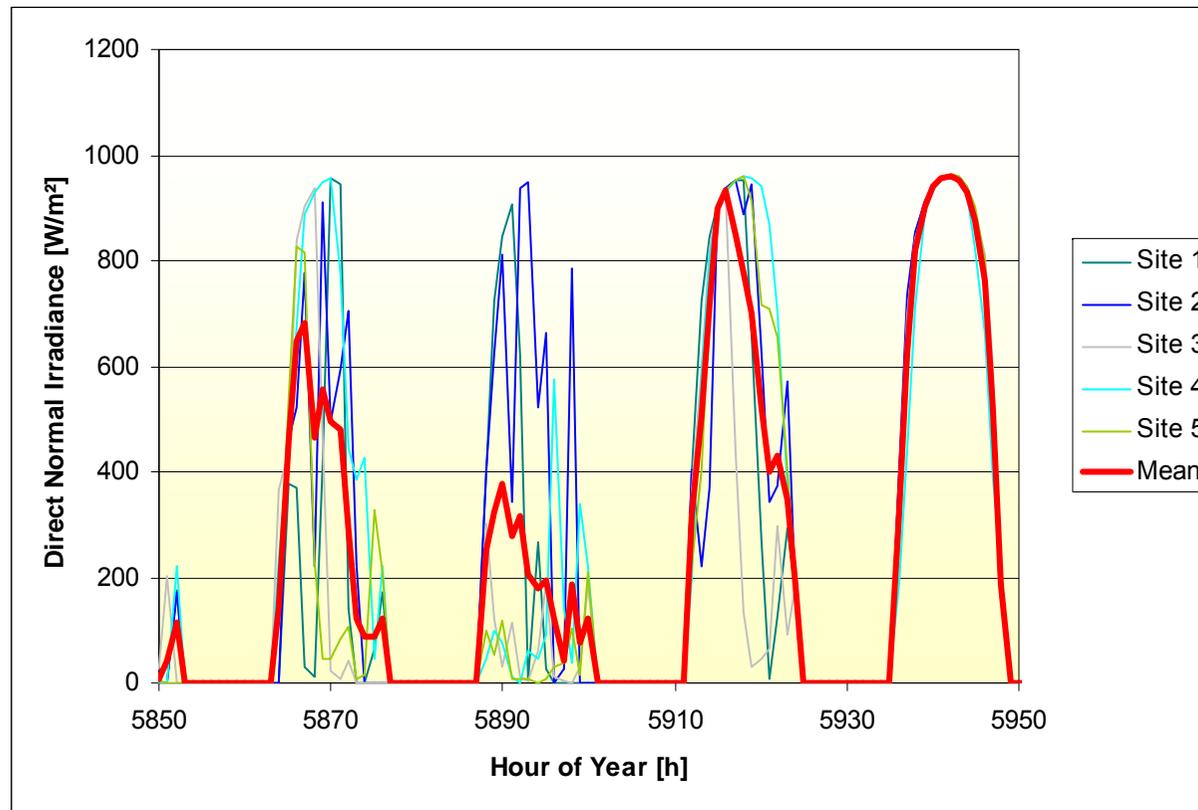
CSP Energy Resources



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



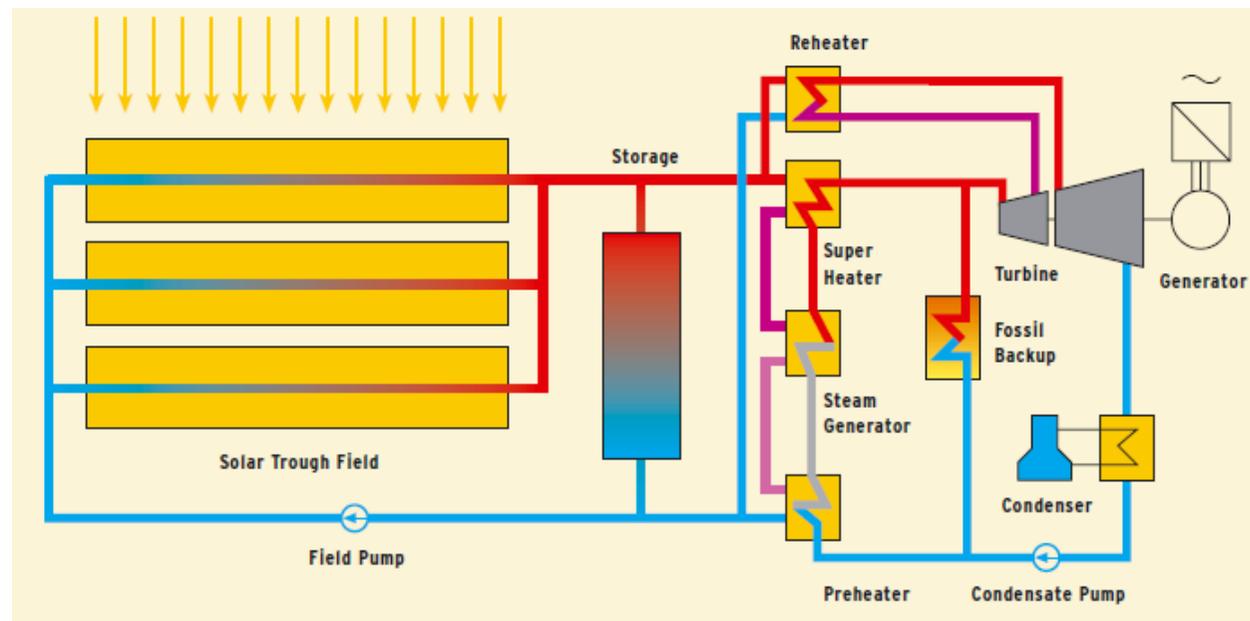
CSP Systems Efficiency Example

| Component Efficiency | Nominal | Annual |
|--|----------------|---------------|
| Geometrical Efficiency (cosine, shading, etc.) | 92% | 70% |
| Optical Efficiency (transparency, 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

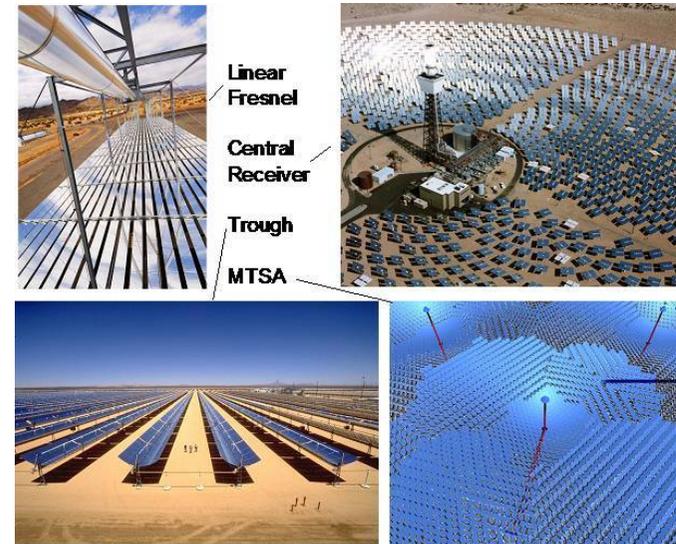
- time series of direct normal irradiance (minimum hourly)
- geometrical relation of sun and collectors (cosine losses, concentration)
- reflectancy, transparency, absorptivity and other optical losses
- insulation, heat transport and storage
- power cycle
- parasitics





CSP Performance Model

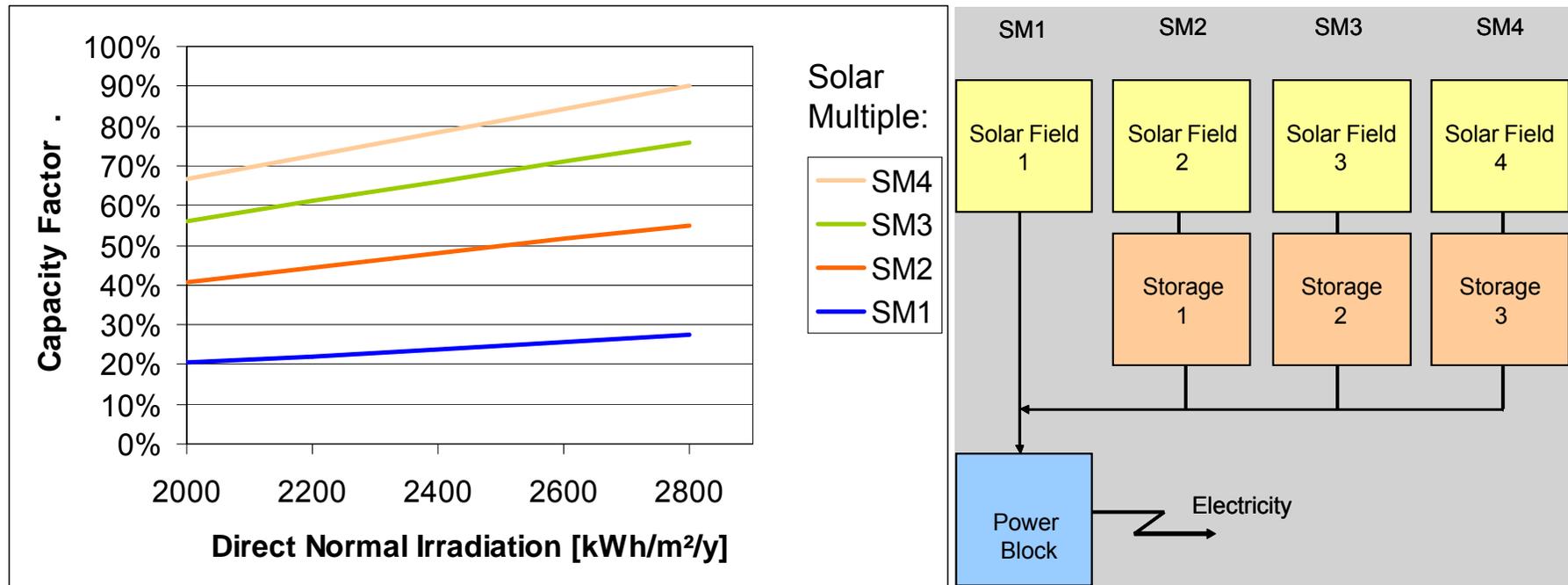
Average Land Use Efficiency (LUE)
 = Solar-Electric-Efficiency (12%)
 x Land Use Factor (37%)
 = 4.5% for parabolic trough steam cycle
 with dry cooling tower



| 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]

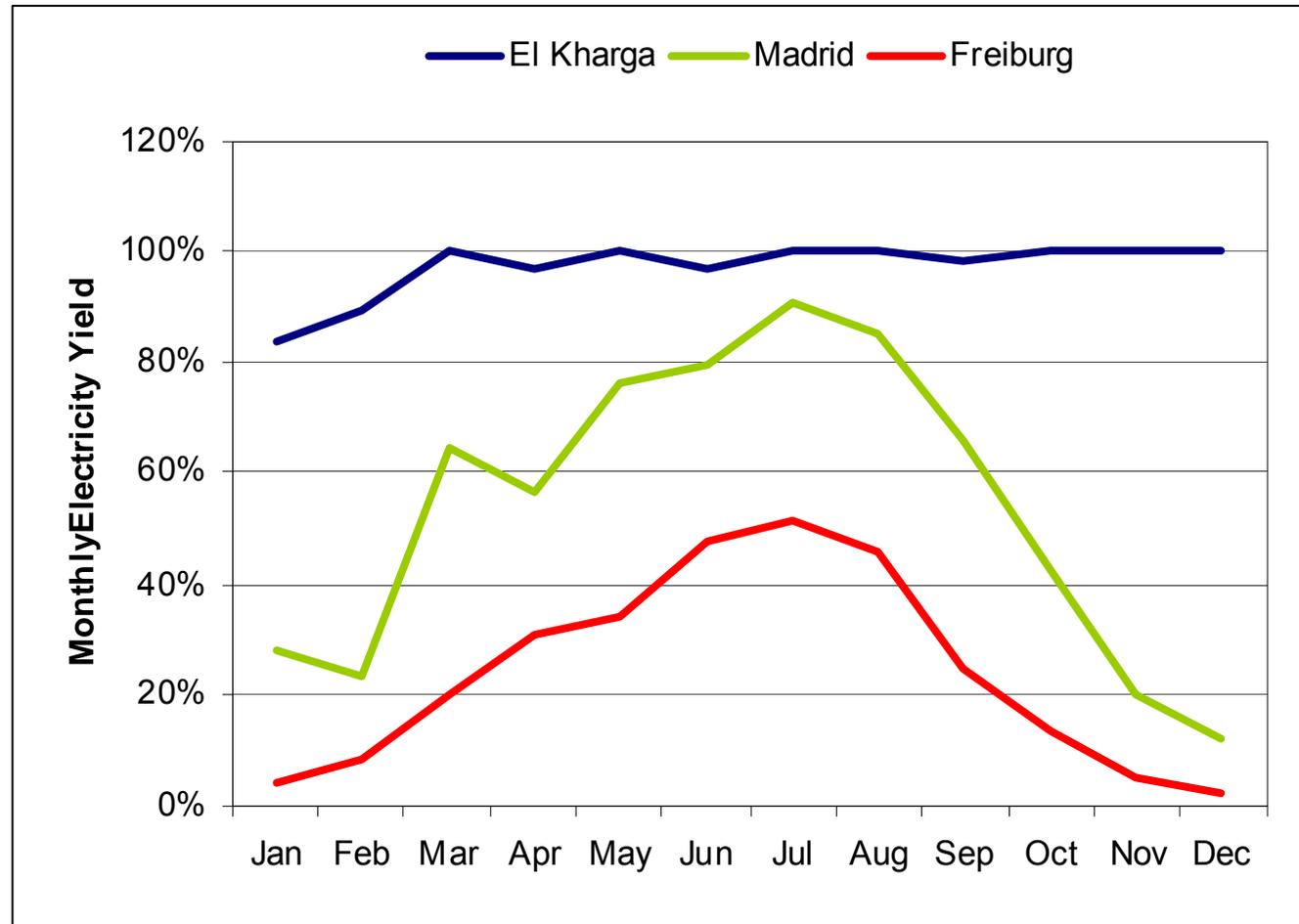
$$CF = (2.5717 \cdot DNI + 694) \cdot (-0.0371 \cdot SM^2 + 0.4171 \cdot SM - 0.0744) / 8760$$



Effect of Site Conditions on the Availability of CSP



SM = 4





Simple CSP Performance Model

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

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

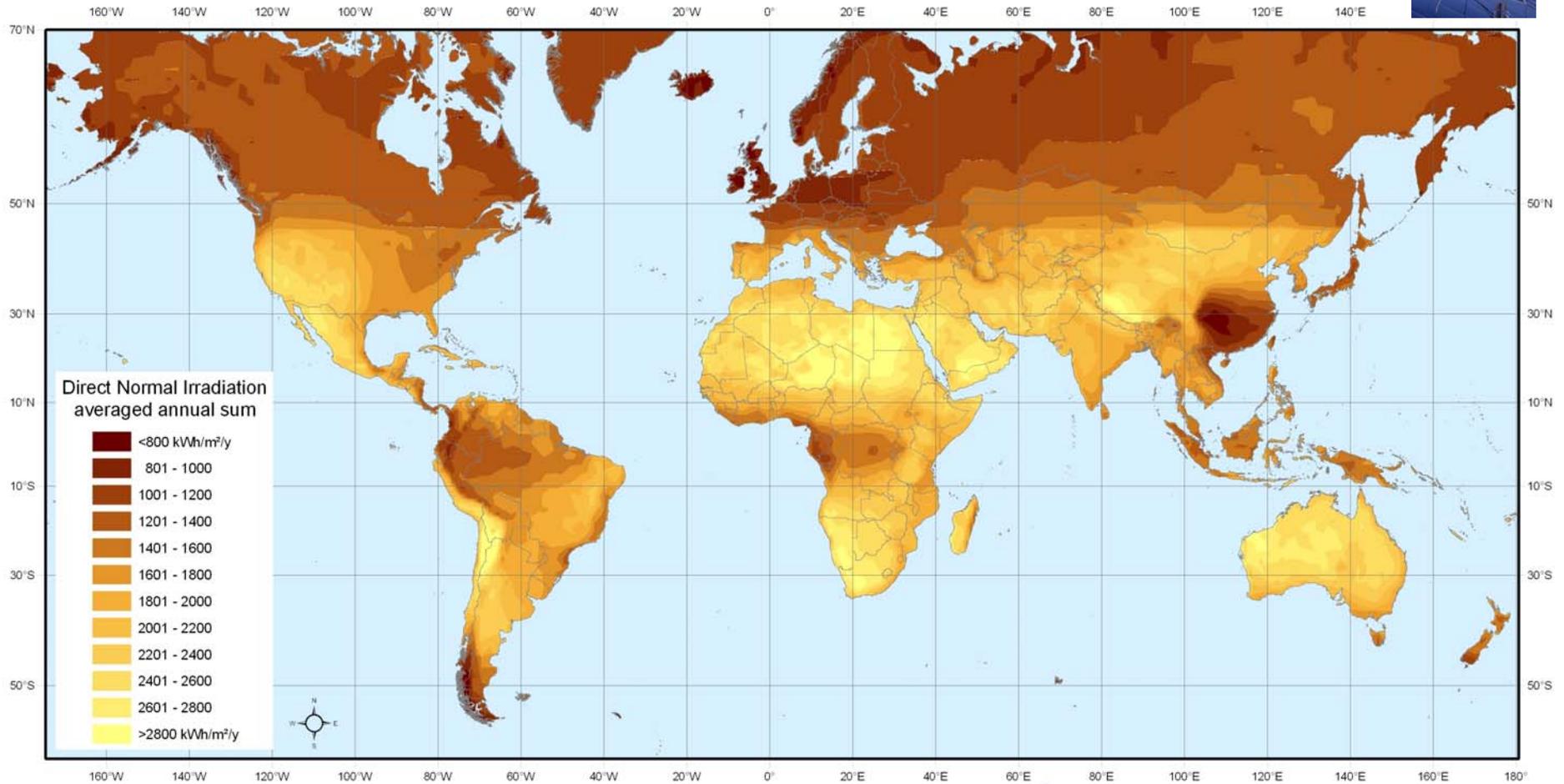
CF_{fuel} Capacity factor complementing supply and demand by fuel

P_{CSP} Installed capacity [MW]

8760 represents the total hours per year



CSP Resource: Direct Normal Irradiation (DNI)



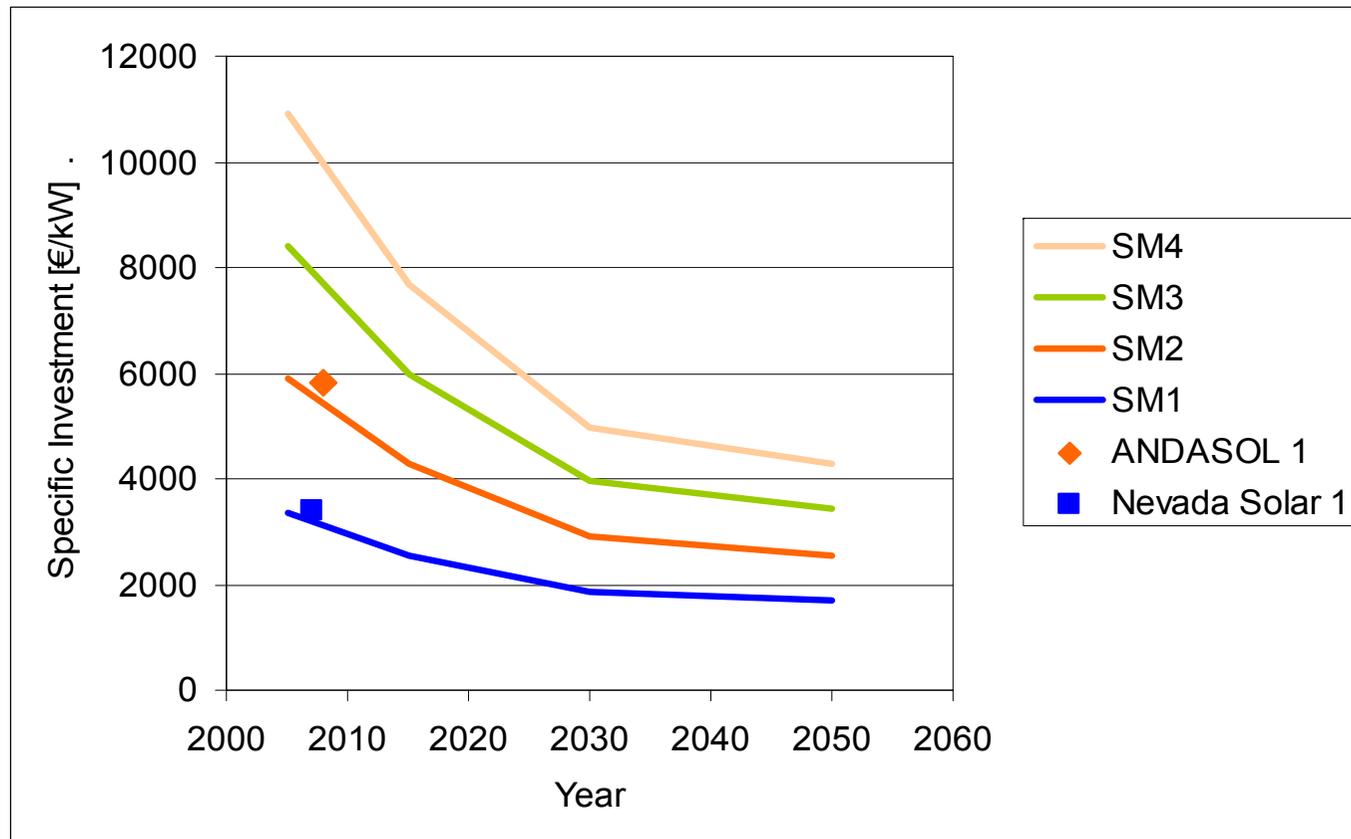
Data based on NASA SSE 6.0 dataset for a 22-year period (July 1983 - June 2005)
(<http://eosweb.larc.nasa.gov/sse/>)

Map created and map layout by DLR 2008
(<http://www.dlr.de>)



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 | €/m ² |
| Power Block | 98% | 1200 | 1111 | 1006 | 971 | €/kW |
| Storage | 92% | 60 | 44 | 29 | 25 | €/kWh |



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

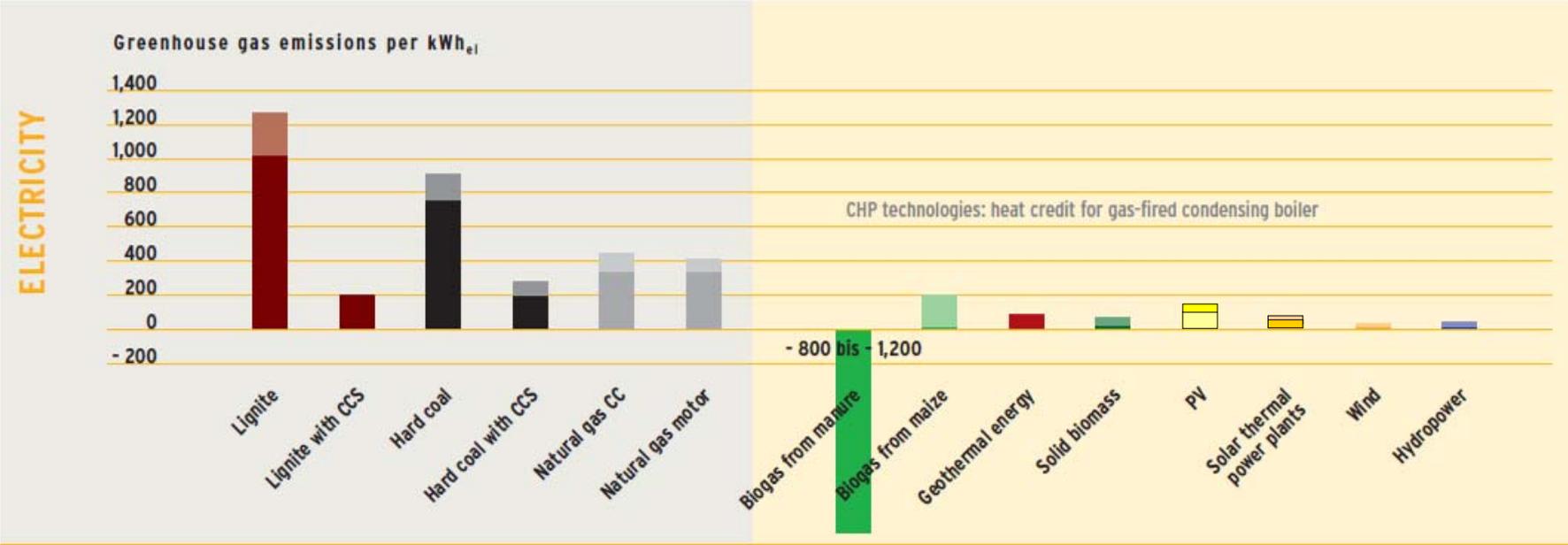


Concentrating Solar Power Impacts on Environment

- 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



Hydropower





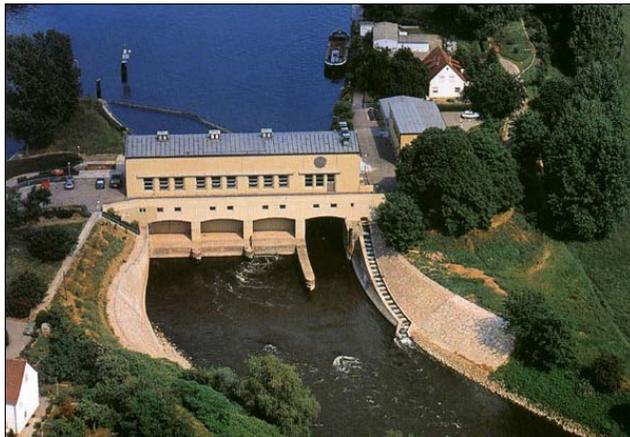
Hydropower Applications



Storage Dam



Micro Hydropower



River Runoff



Pump Storage

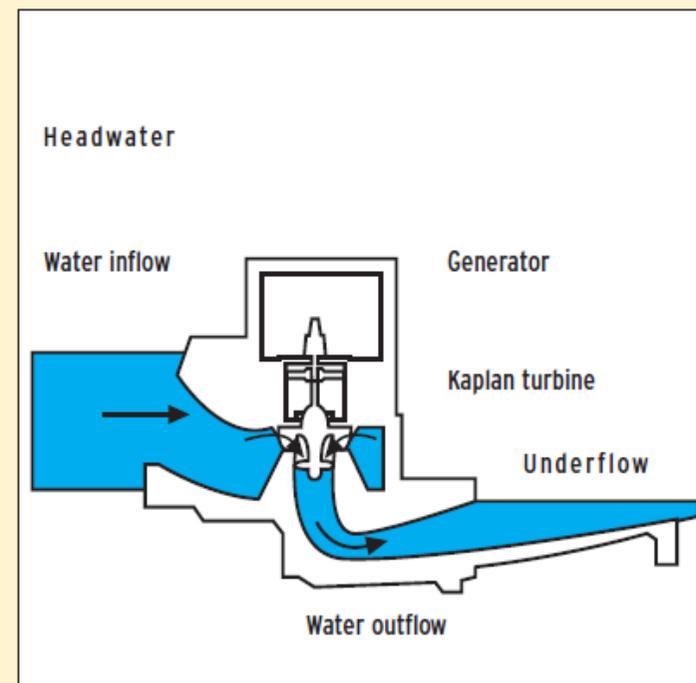
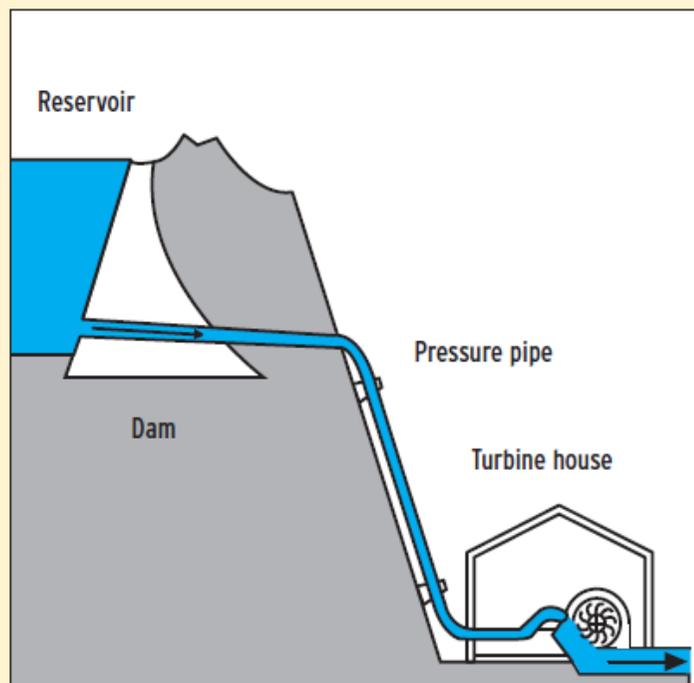


Hydropower Systems



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

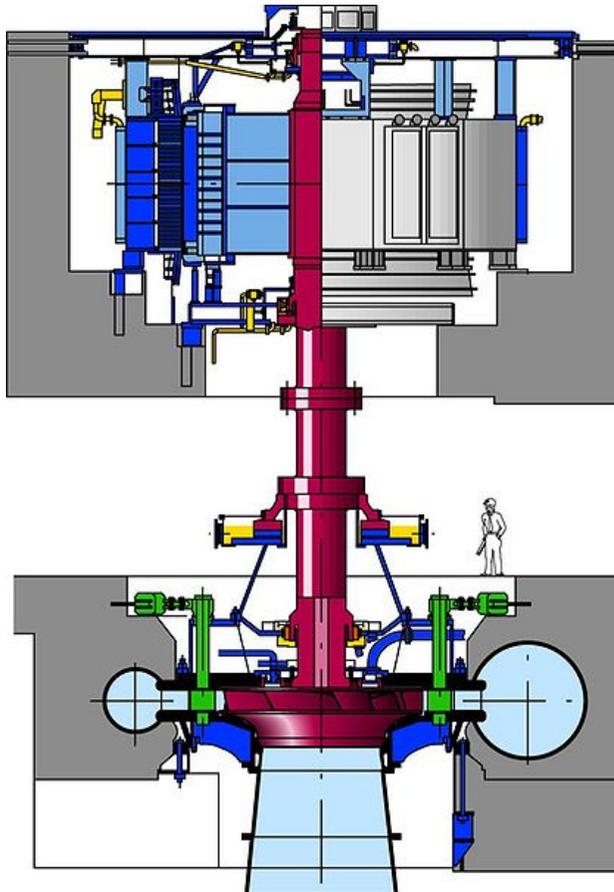
Sources: Tauernkraft/Verbund und ExpoStadt



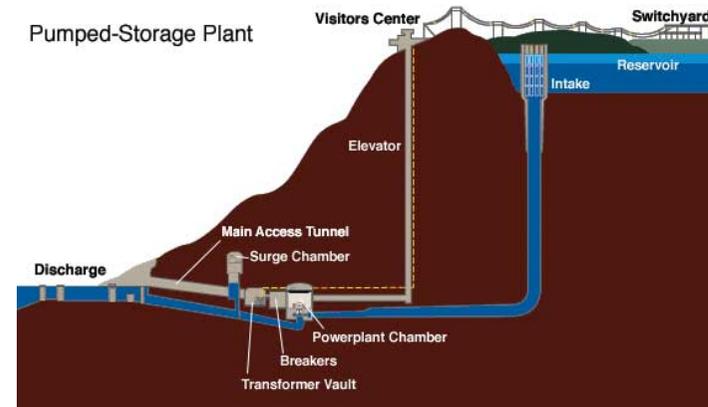
Principle of a dam storage power plant and of a run-of-river power plant



Hydropower Systems



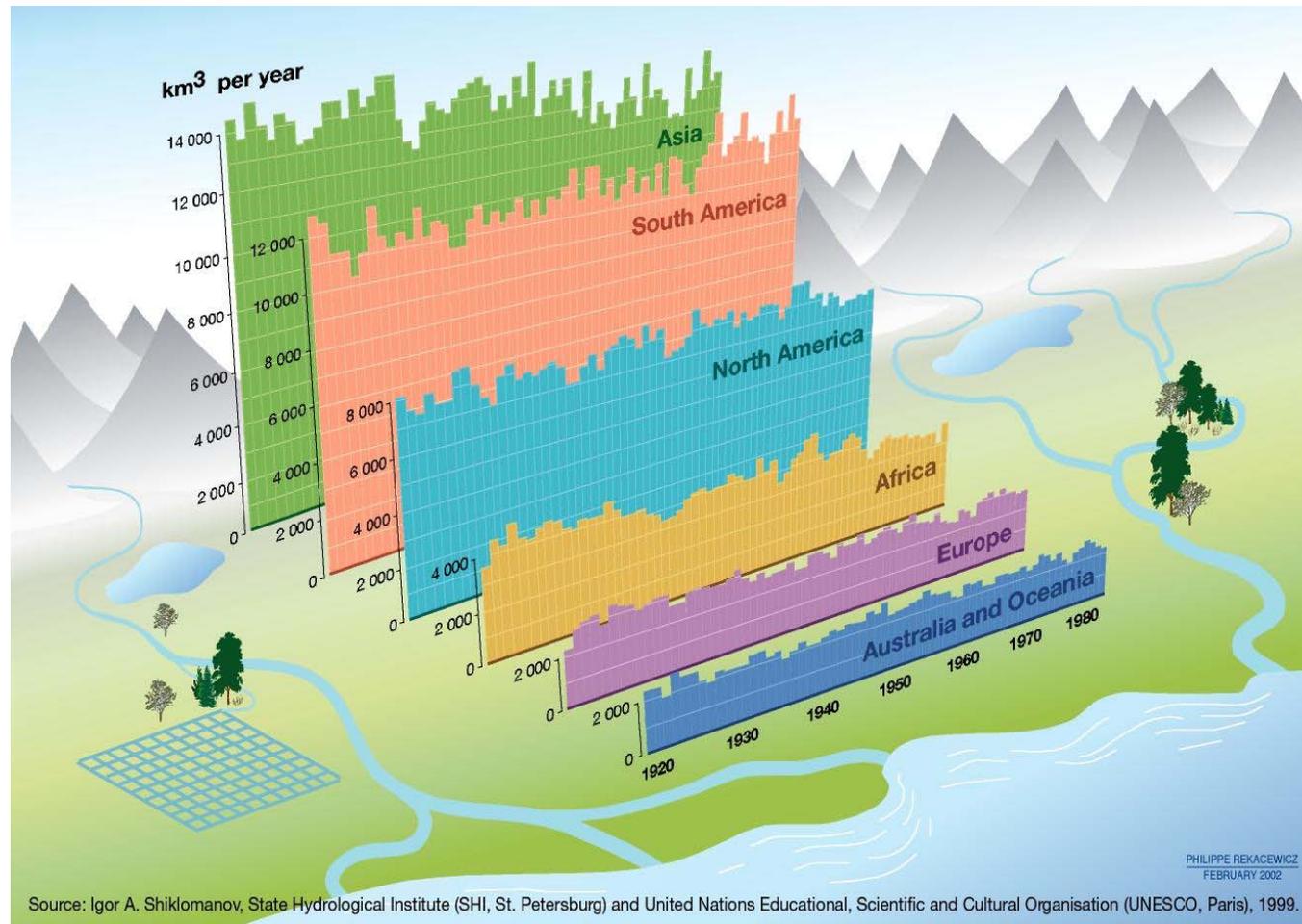
Goldisthal Pump Turbine Cross Section



Hohenwarte an der Saale pump-storage hydropower station

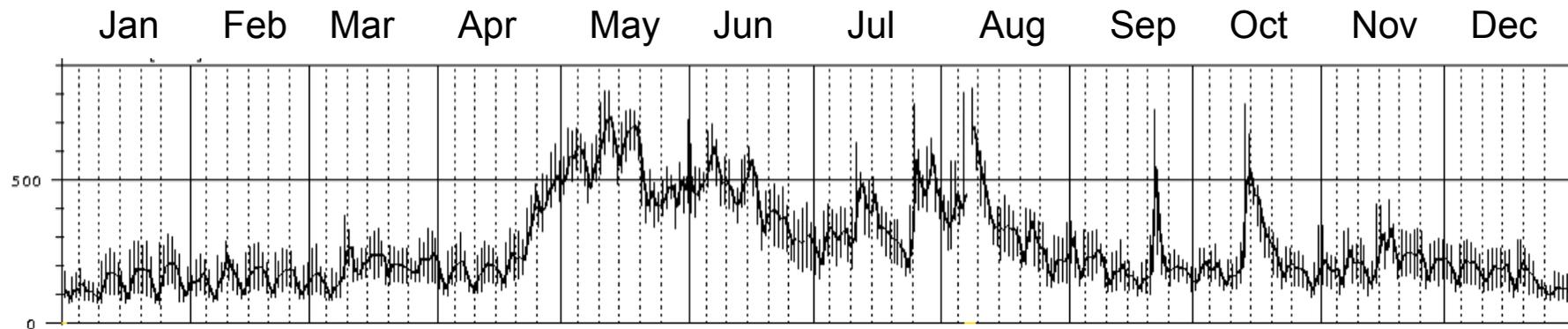


Hydropower Resources (River Runoff)





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

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

- 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 [%]
- η_{turbine} turbine efficiency as function of load [%]
- $\eta_{\text{generator}}$ 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}).

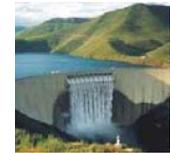
$$CF_{\text{hydro}} = E_{\text{hydro}} / P_{\text{hydro}} / 8760$$

CF_{hydro} capacity factor

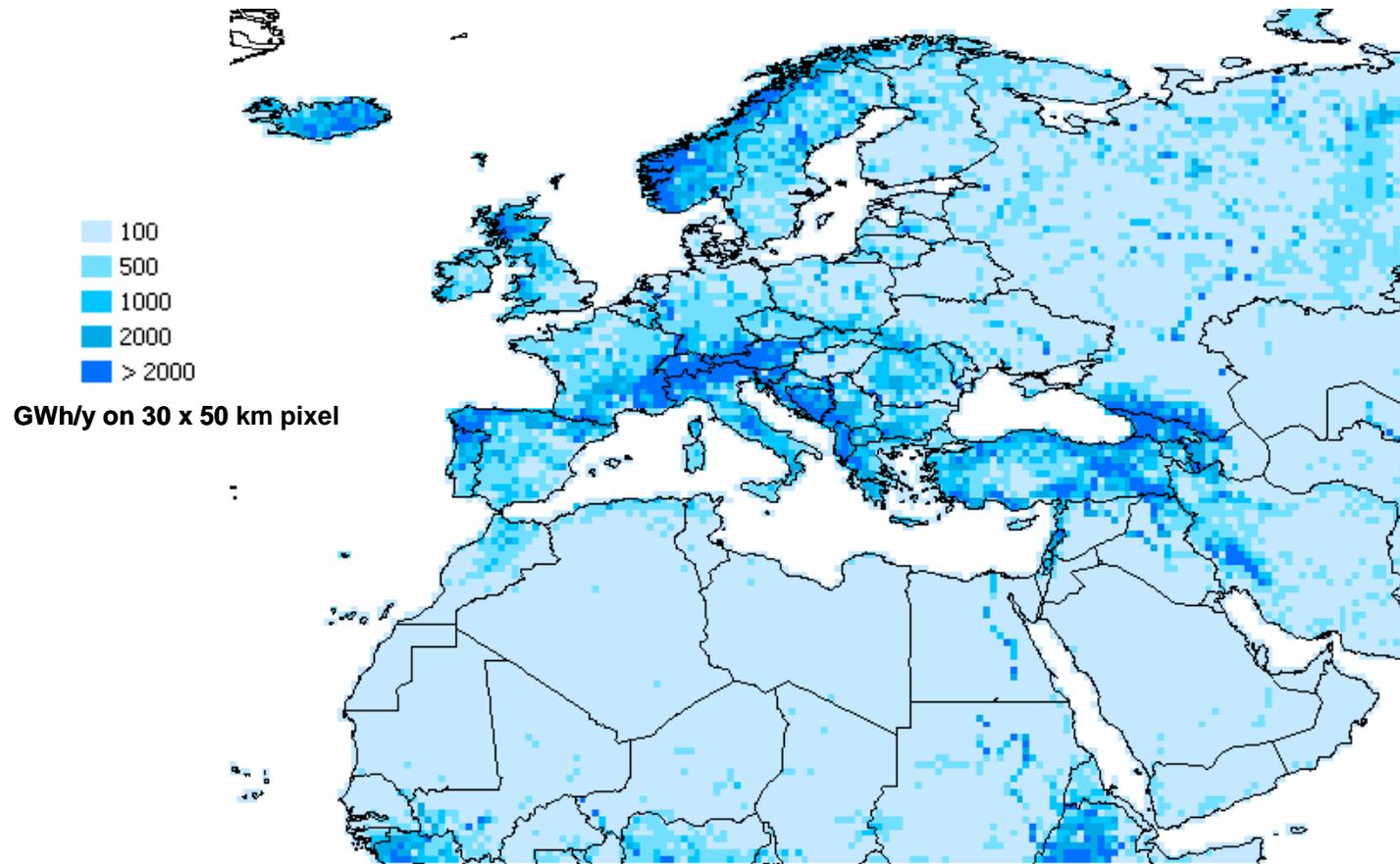
E_{hydro} annual electricity [MWh/y]

P_{hydro} installed capacity [MW]

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



Hydropower Resources



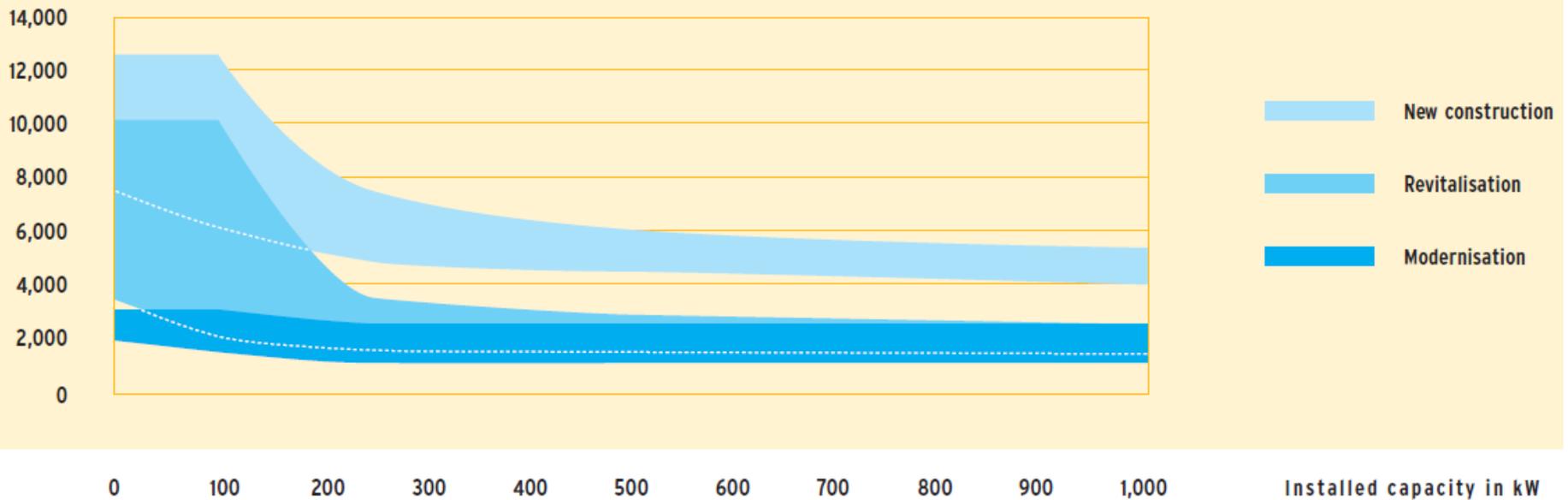
Gross Hydropower Potentials adapted from /Lehner et al. 2005/



Source: IÖW/ISET

→ Investment costs for small-scale hydropower stations

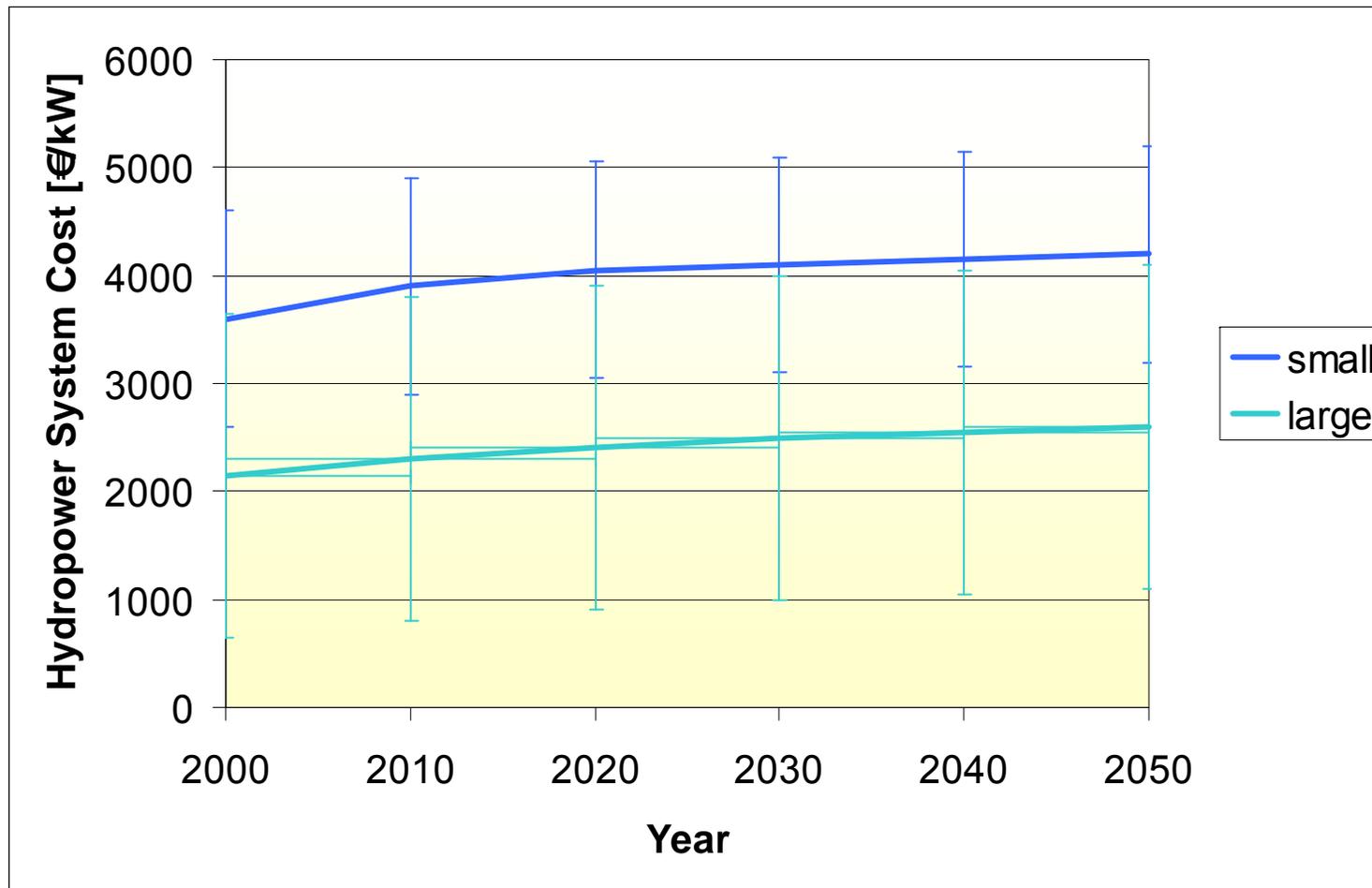
Investment costs in Euro/kW



Investment costs for new and reactivated small-scale hydropower stations as a function of the installed capacity.



Hydropower Investment Cost Perspectives



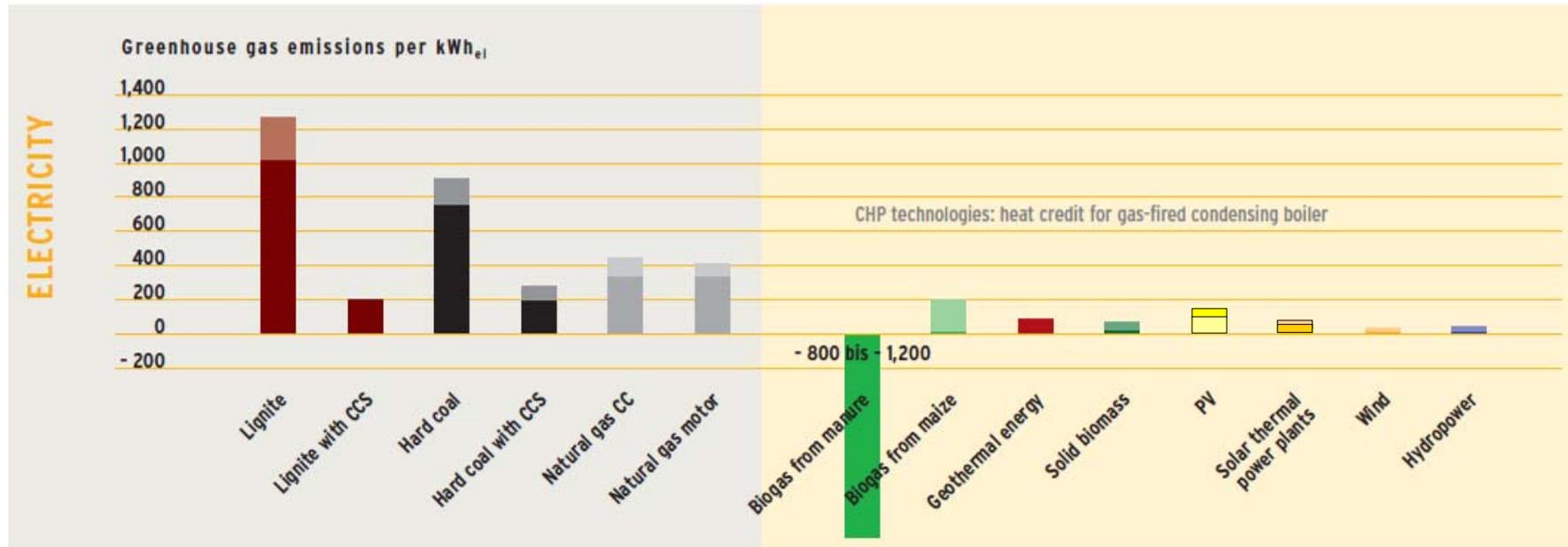


Environmental Impacts of Hydropower

- 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



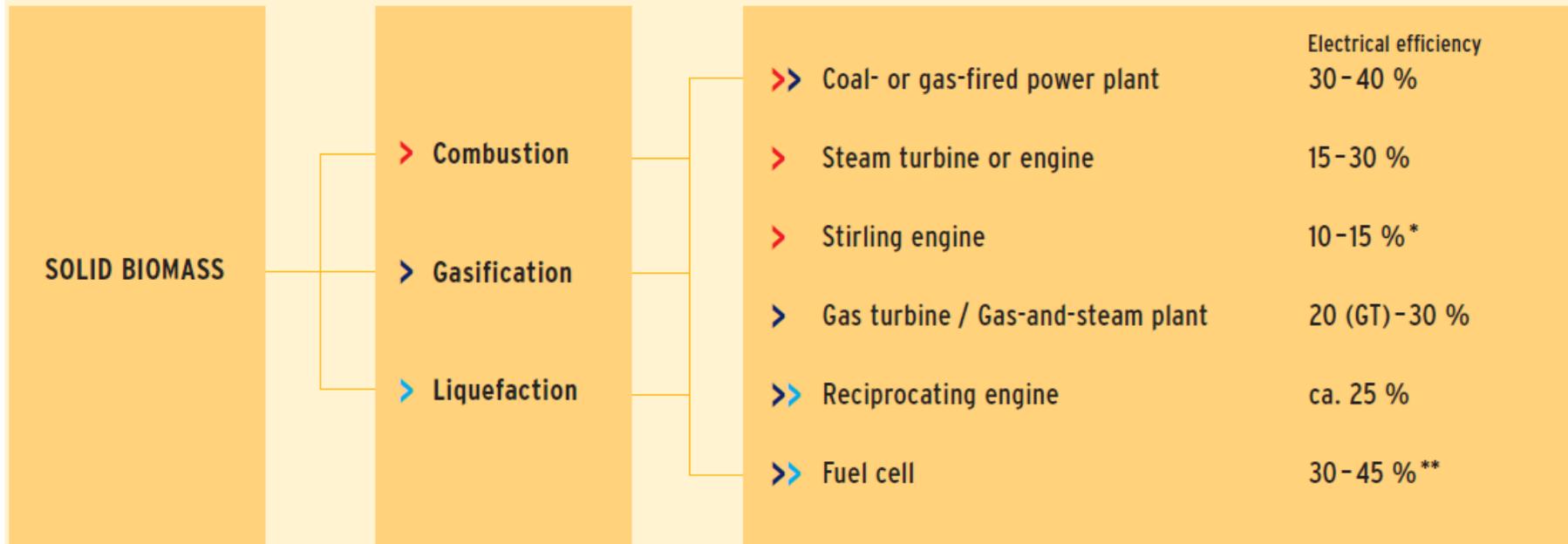
Combustion & Gasification of Solid Biomass



Biofuel



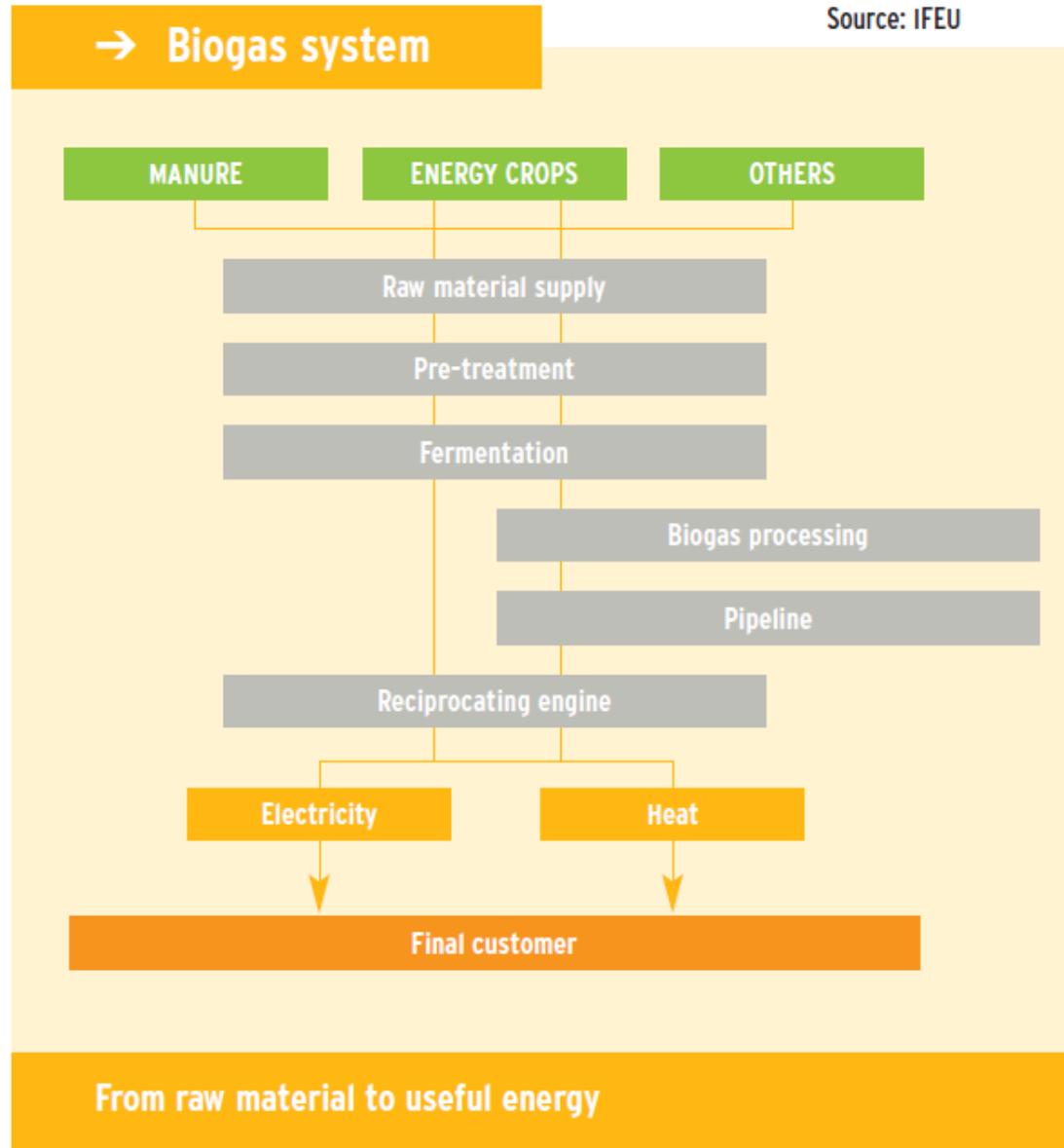
→ Generating electricity from biomass



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

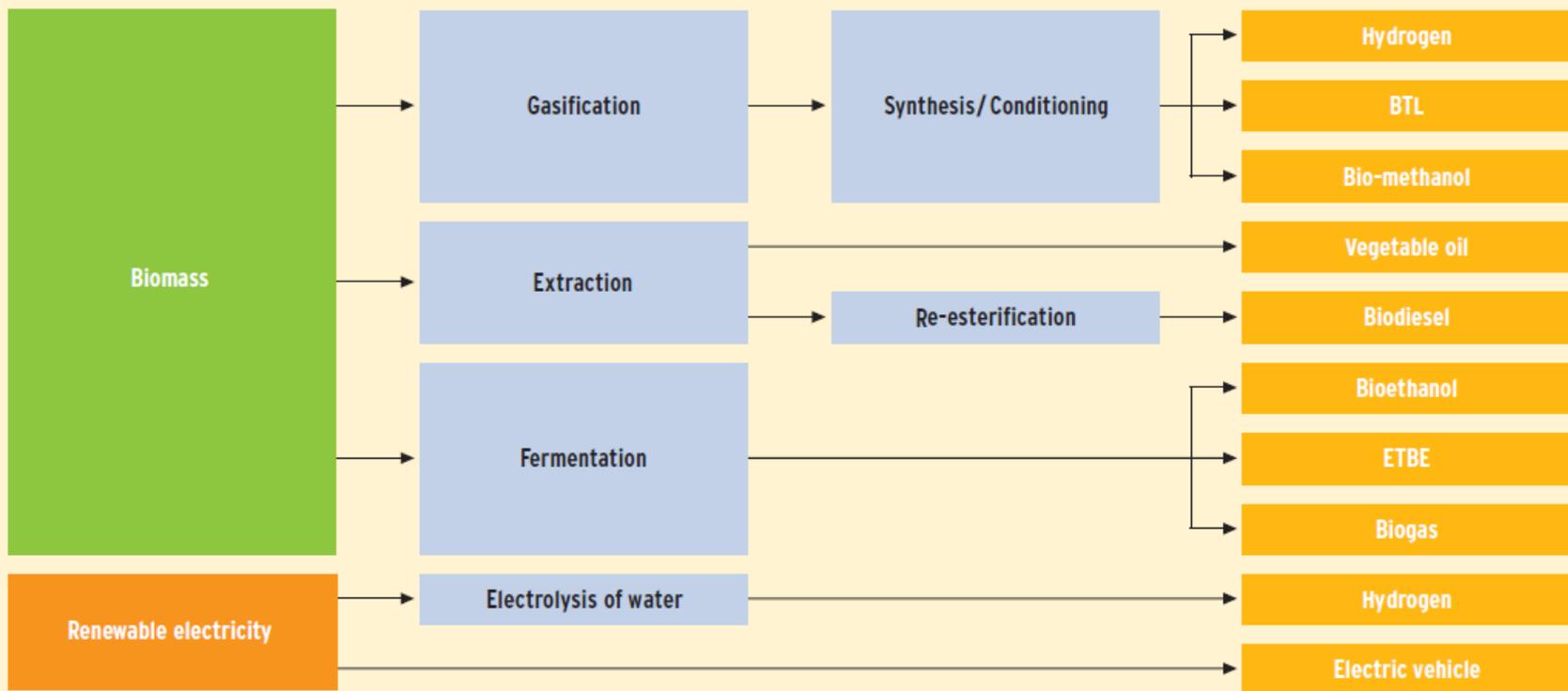


Source: IFEU





→ Fuel production paths



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

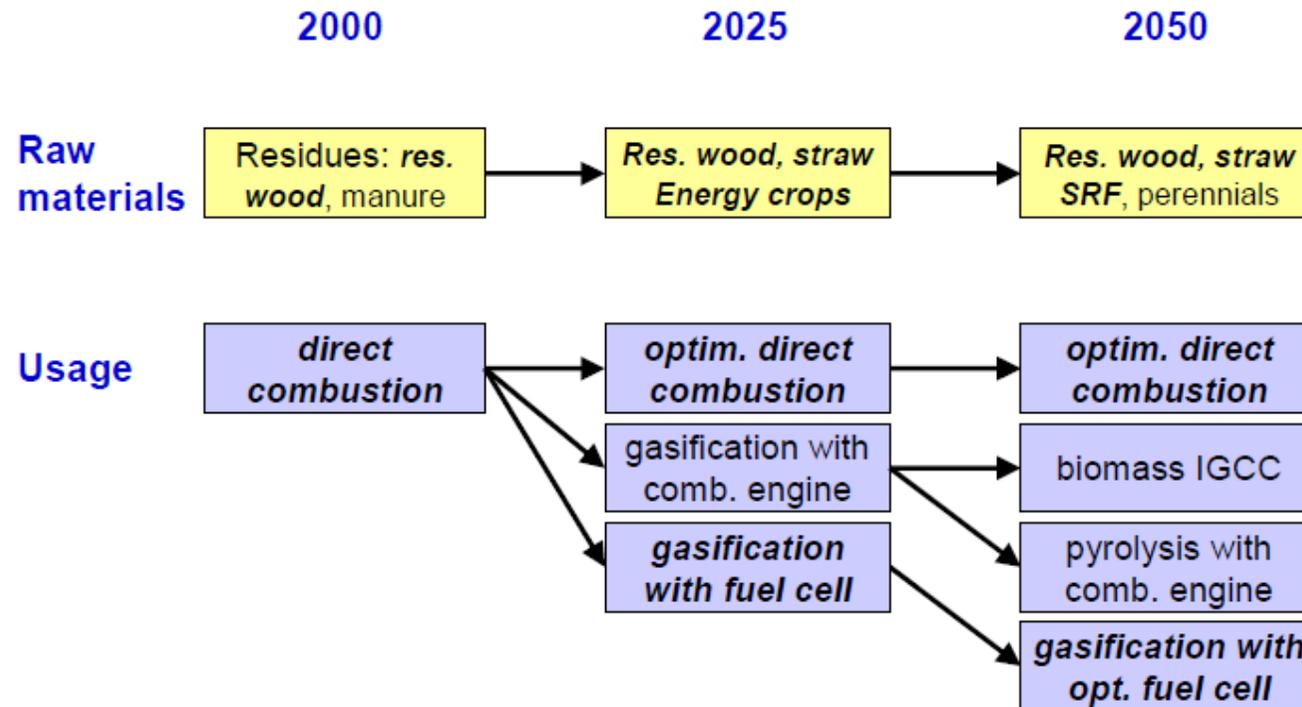


Energy Yield from One Hectare (ha) of Energy Crops

| | Biomass yield in tons | Yield of final energy in GJ |
|--|-----------------------|-----------------------------|
| Solid biofuels | | |
| Short rotation poplar | 20 | 180 |
| Triticale (whole plant) | 14 | 170 |
| <i>Miscanthus × giganteus</i> | 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



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

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

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

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

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

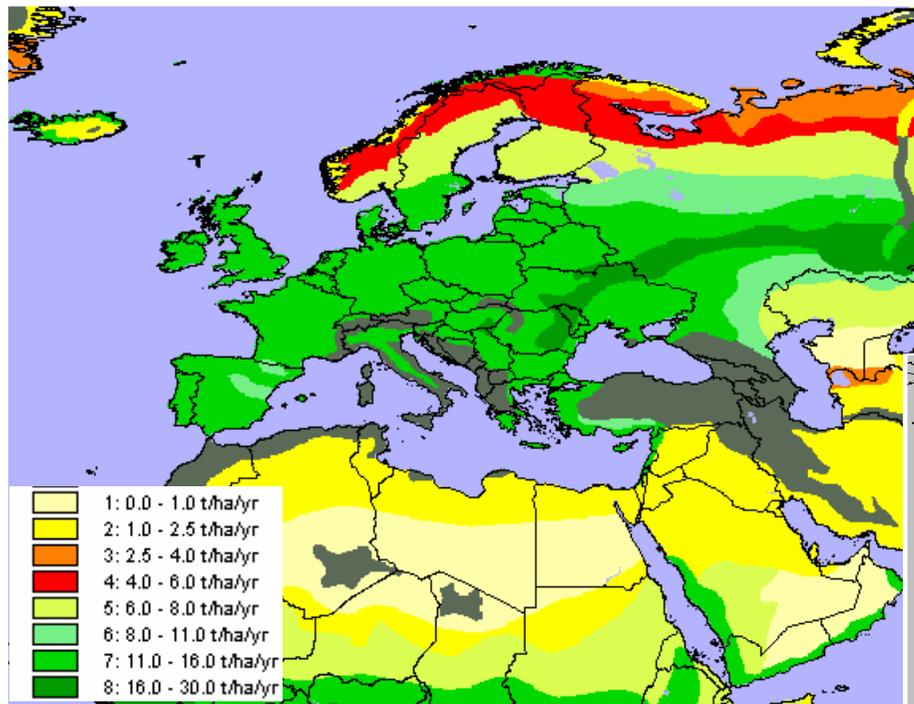
ρ_{wood} Solid biomass productivity from wood [tons/ha/year] from mapping

A_{forest} Forest area of a country [ha] from mapping

N Urban population [persons] from statistics

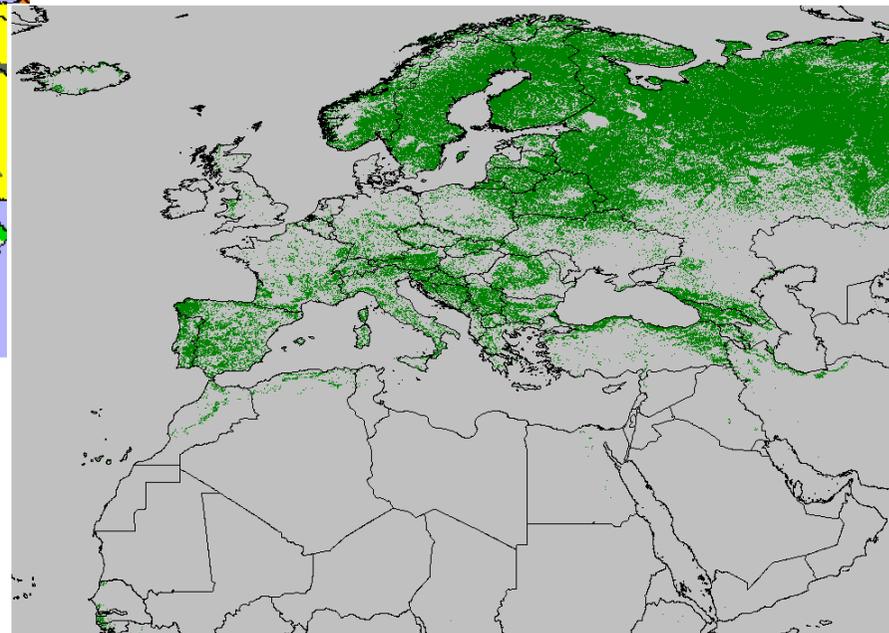


Biomass Resources



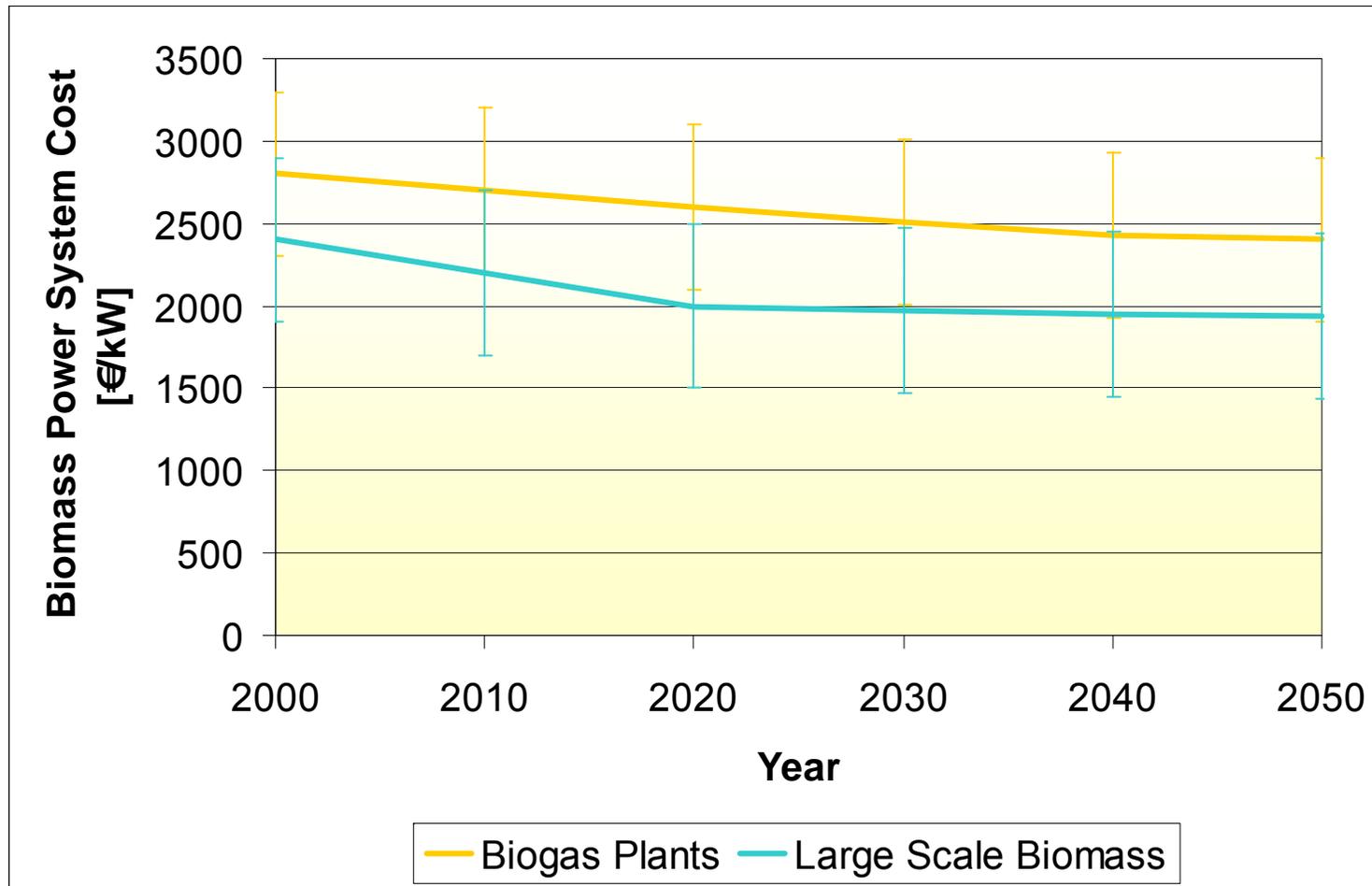
Map of biomass productivity /Bazilevich 1994/

Map of forest areas /USGS 2002





Biomass Investment Cost Perspectives



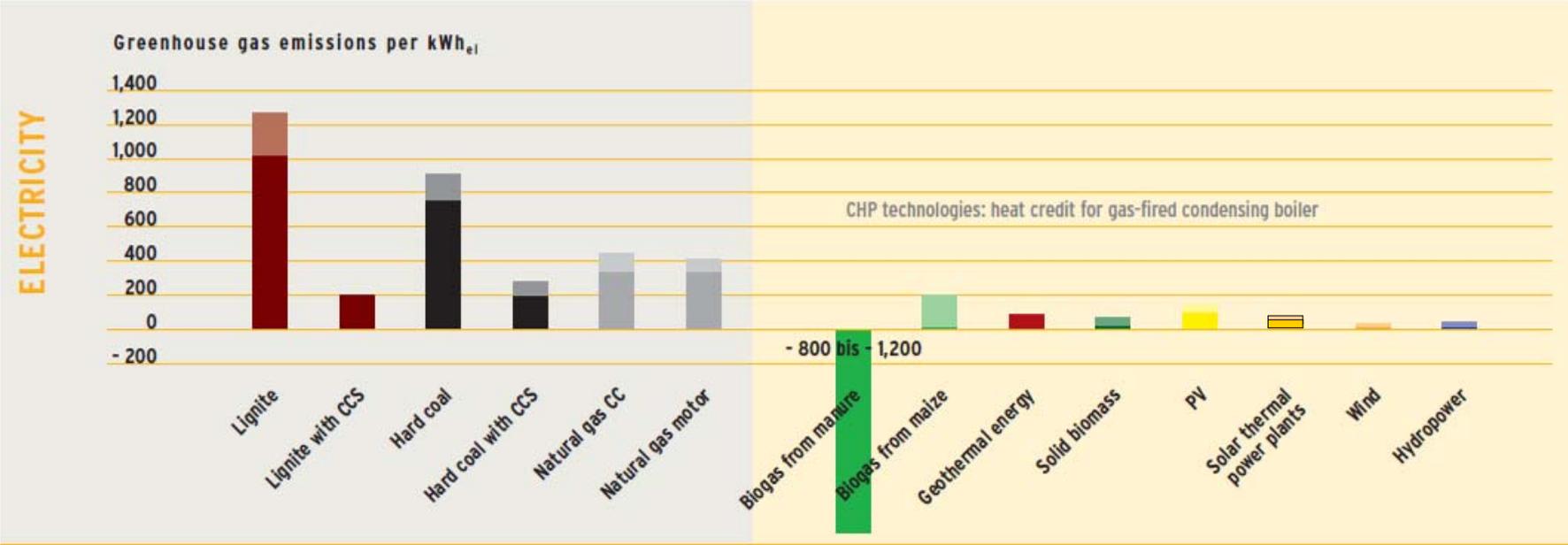


Environmental Impacts of Biomass Electricity

- 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



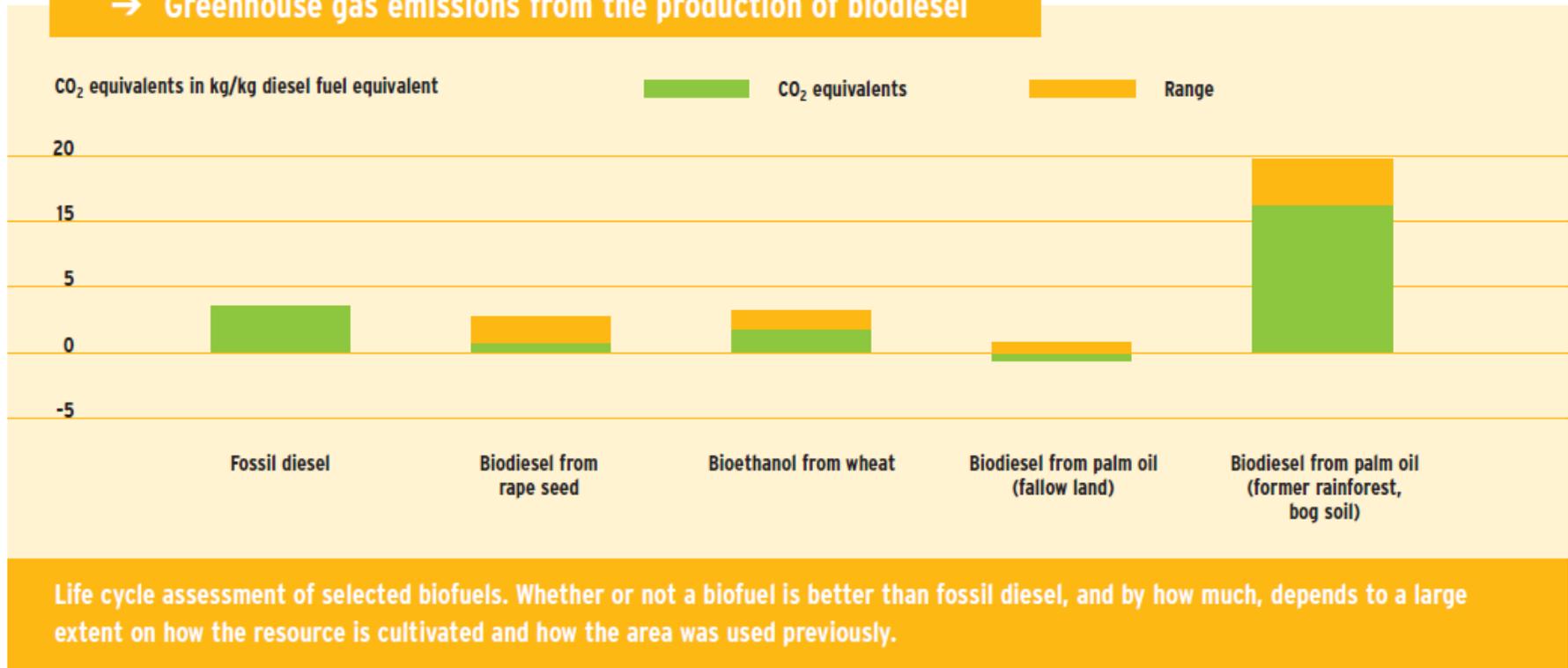
GHG Emissions: 0 - 200 g/kWh
 Energy Payback Time: 3 - 7 months



Biodiesel Life Cycle Carbon Emissions

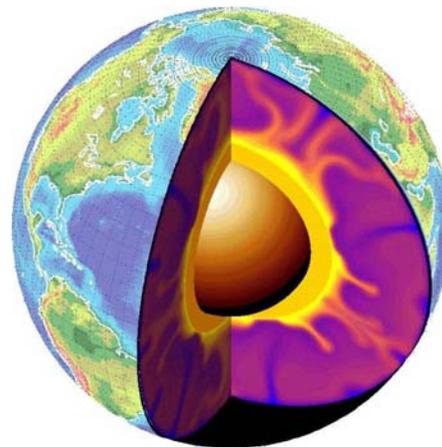
→ Greenhouse gas emissions from the production of biodiesel

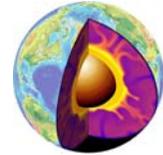
Source: IFEU 2007



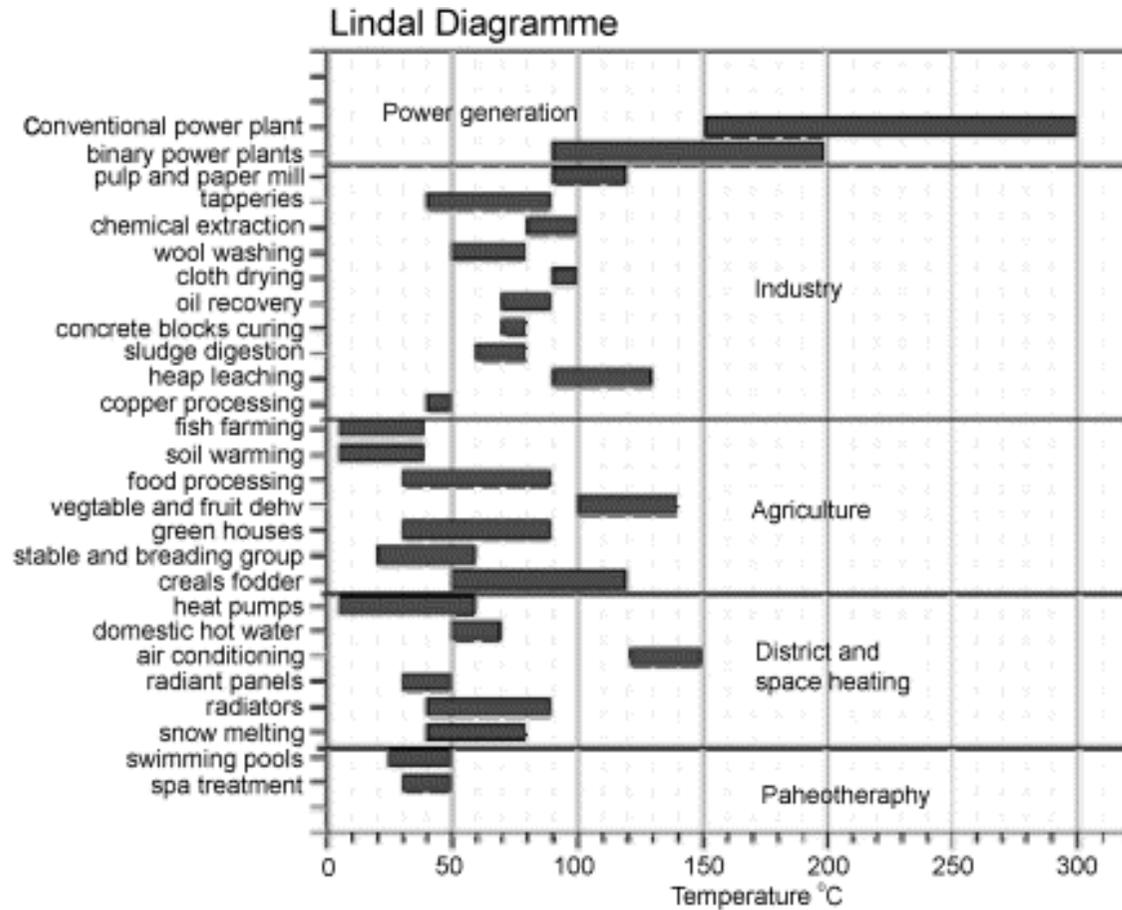


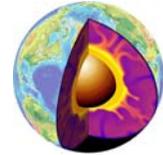
Geothermal Power





Geothermal Heat Applications





Geothermal Power Options

Hydrothermal Power Plant

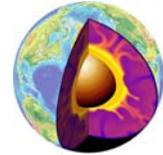


Blue Lagoon, Reikjavik, Island

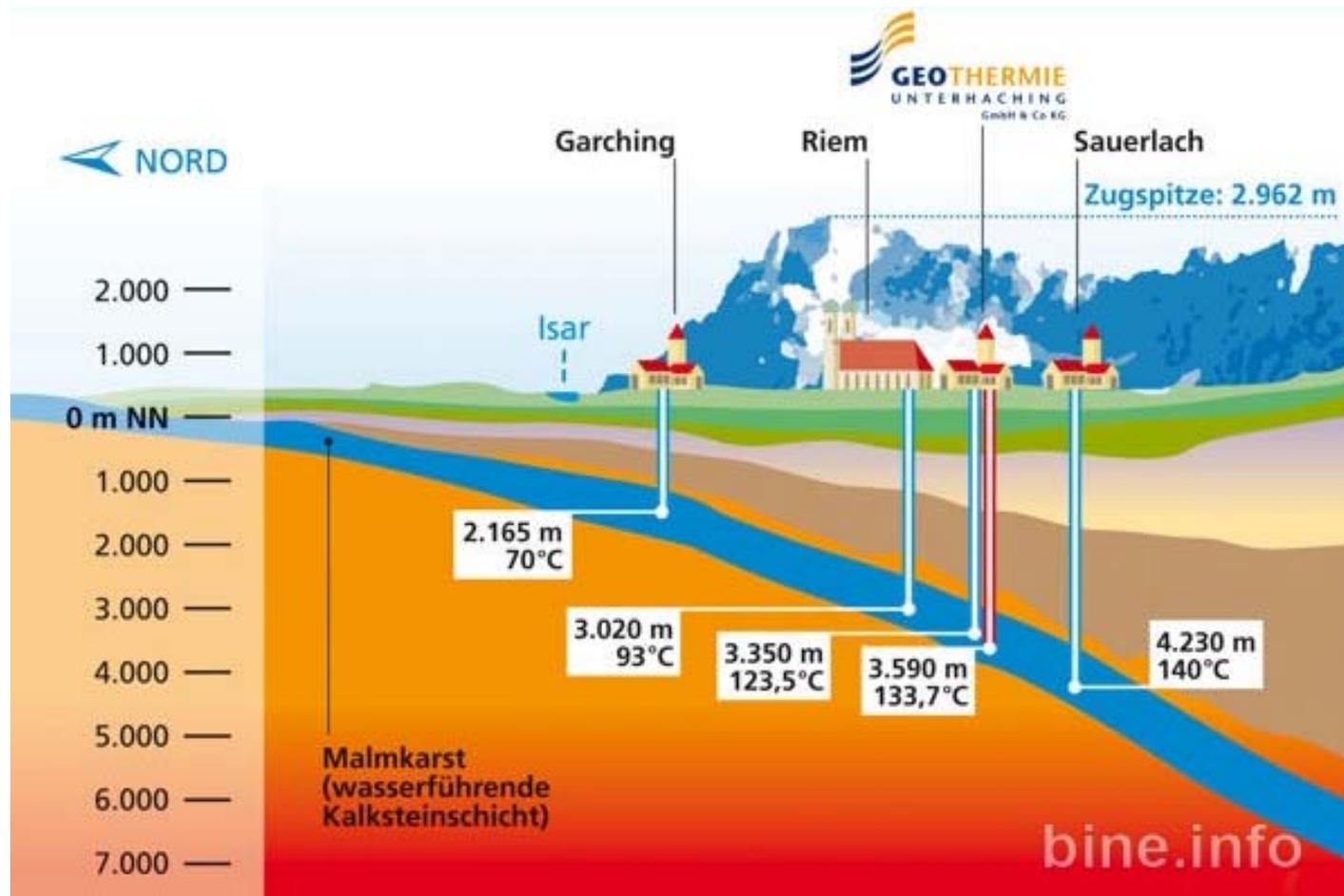
Power from Deep Hot Dry Rock



HDR Drilling in Basel, Switzerland

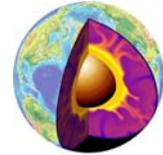


Hydrothermal Systems



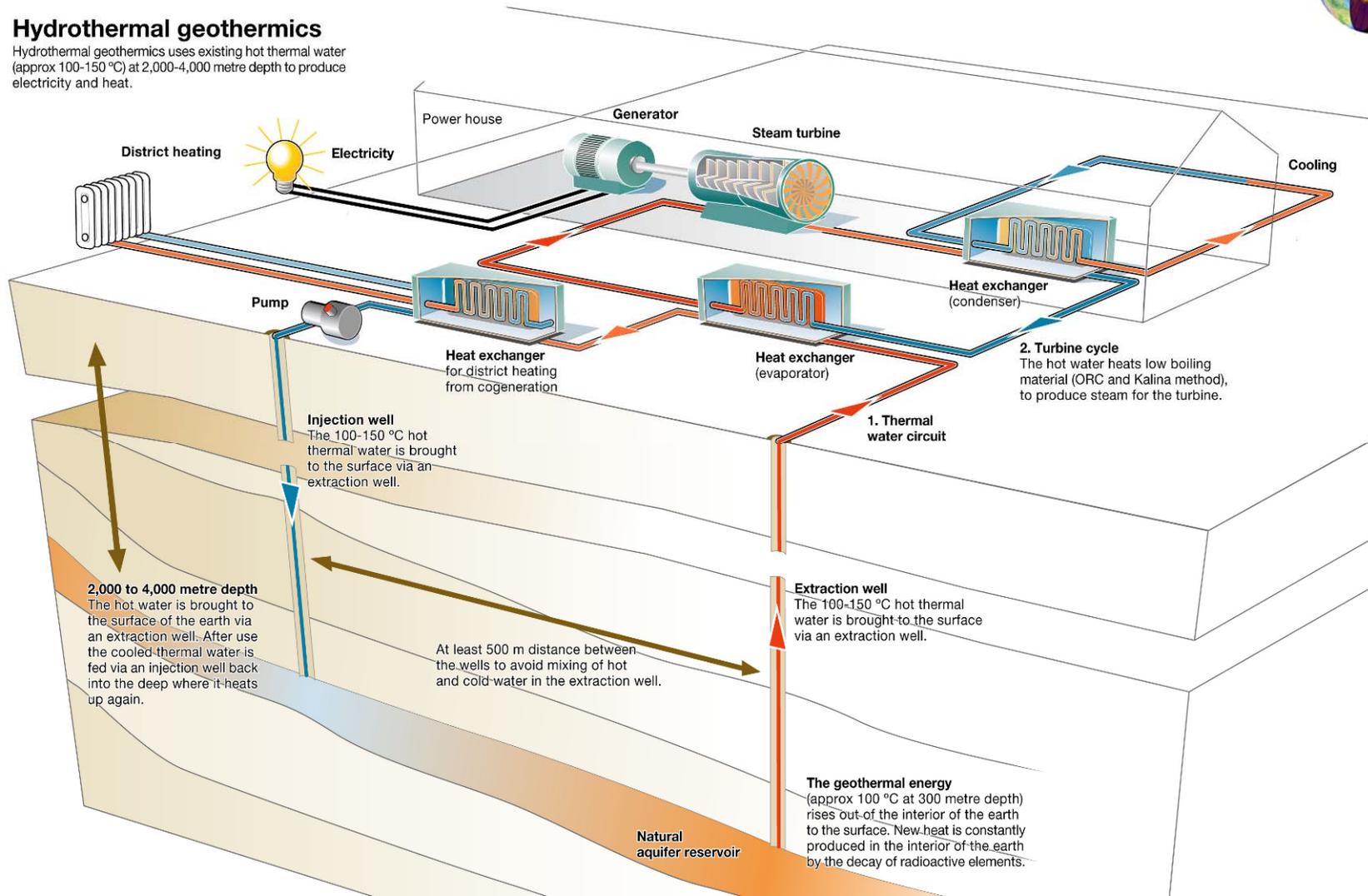


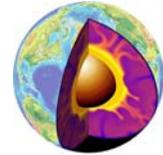
Hydrothermal System for Heat & Power



Hydrothermal geothermics

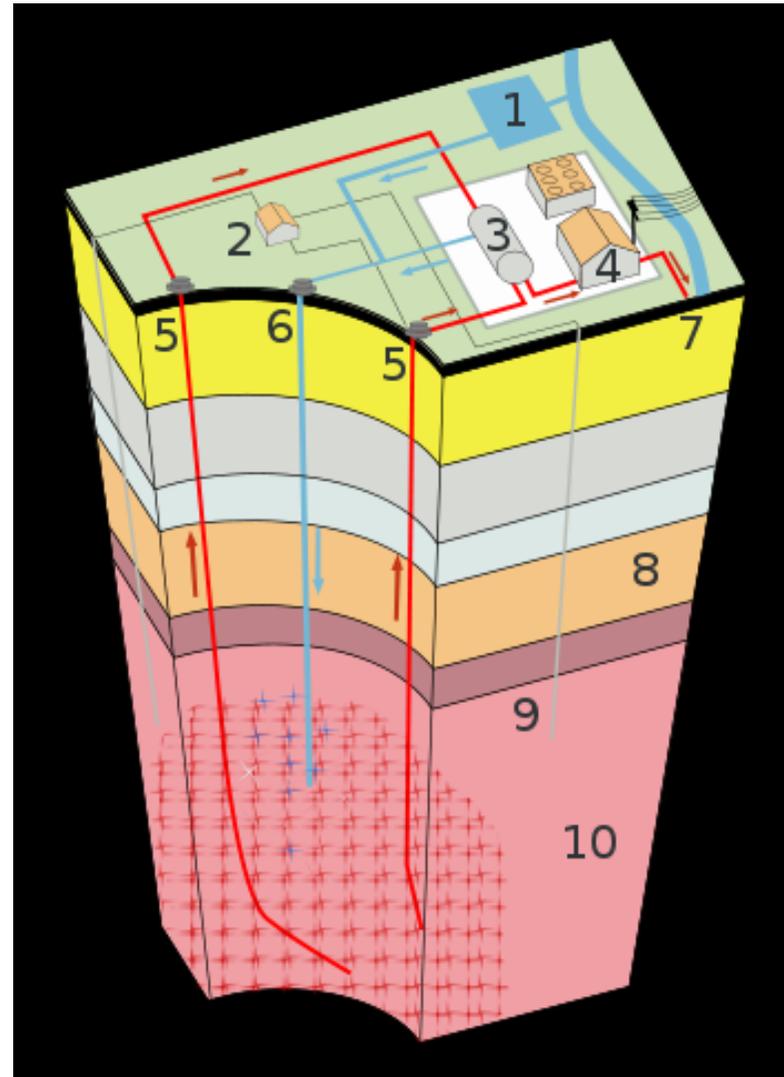
Hydrothermal geothermics uses existing hot thermal water (approx 100-150 °C) at 2,000-4,000 metre depth to produce electricity and heat.

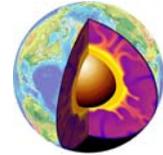




Hot Dry Rock System for Heat & Power

- 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

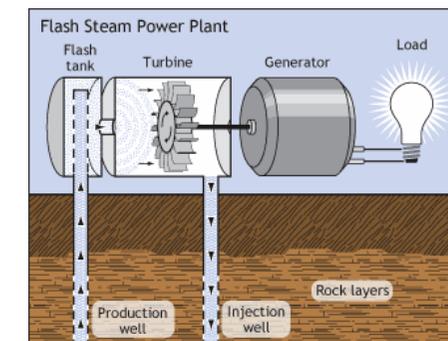
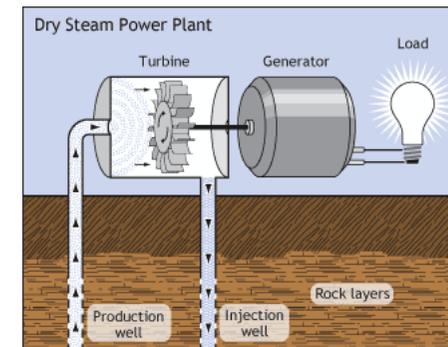
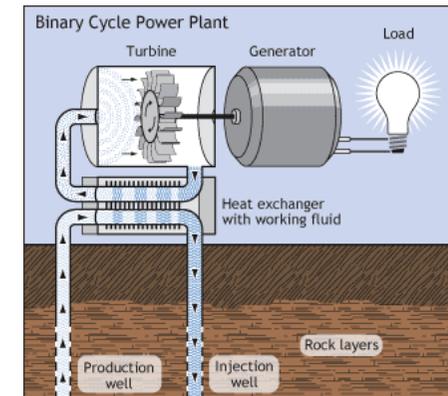


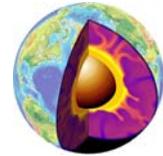


Geothermal Power Cycles

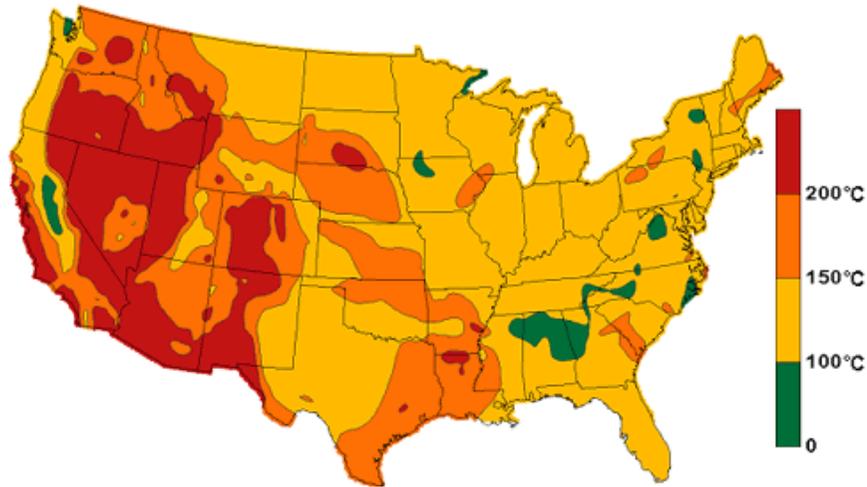
A binary cycle power plant is a type of geothermal power plant that allows cooler geothermal reservoirs to be used than with dry steam and flash steam plants. They are used when the temperature of the water is less than 175 °C. With binary cycle geothermal power plants, pumps are used to pump hot water 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%

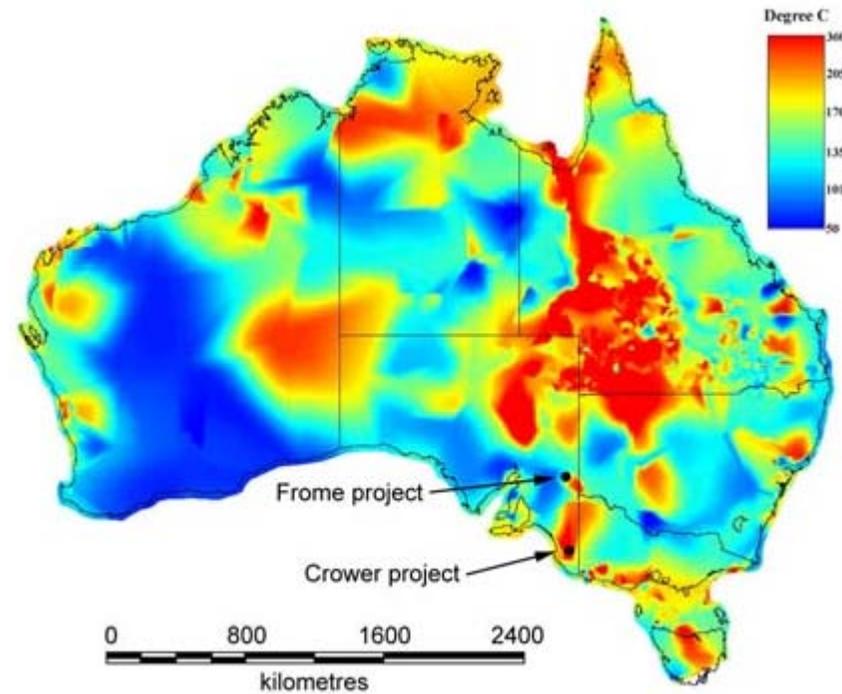


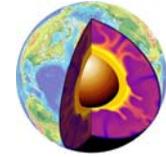


Geothermal Resources



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%

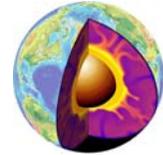
Capacity Factor = Average annual utilization of the system *

→ Base load, peak load or CHP possible, up to 90%

Storable Primary Energy:

Geothermal heat is stored energy → daytime and seasonal storage

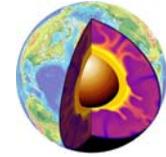
* can also be expressed as: equivalent full load hours / total hours per year



Geothermal Power Performance Example

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

$$\text{Overall Efficiency} = \eta \cdot R \cdot (1 - p) = 0.65\%$$



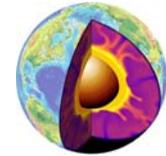
Geothermal Power Model

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

$$H_1 = R \cdot H_0$$

$$H_{el} = \eta \cdot H_1$$

- 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/m³]
 V : Rock volume [m³]
 T_R : Rock temperature [°C]
 T_0 : Temperature at the surface [°C], (mean annual temperature)
 R : Recovery factor [1]
 η : Efficiency [1]



Geothermal Power Model Parameters

| Temp.-class [°C] | Hot water aquifer | | | Faults, Crystalline rock | | | η |
|------------------|-------------------|-----|-------|--------------------------|-----|-------|------|
| | R | | | R | | | |
| | 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 |

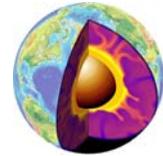
Recovery factors R [%] and efficiencies η [%]. CHP: Combined Heat and Power Production, CHP-W: Combined Heat and Power Production with heat pump

rock density $\rho_R = 2600 \text{ kg/m}^3$

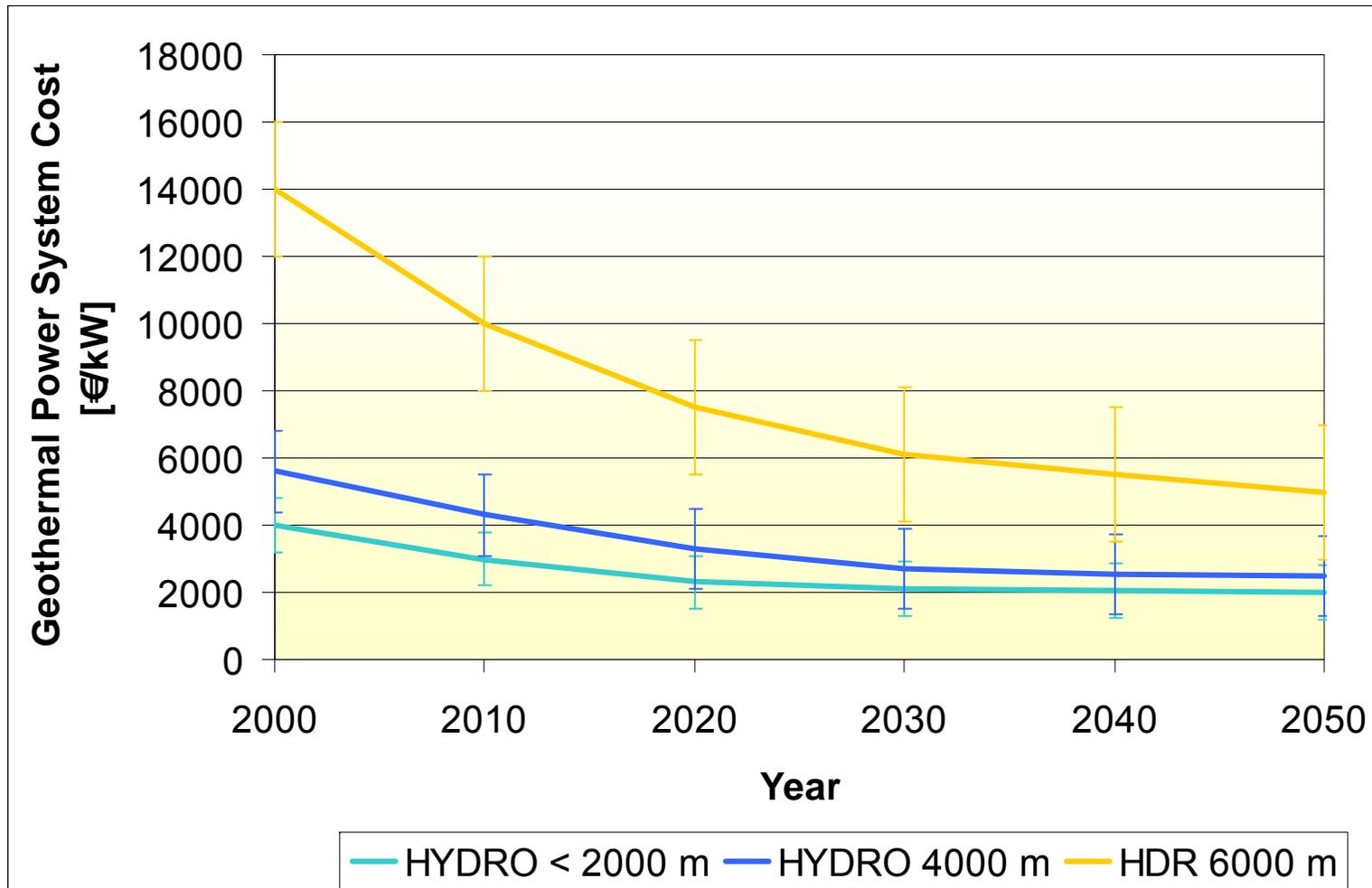
specific heat $c_R = 840 \text{ J/kg}$

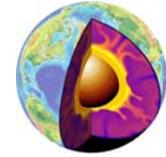
electricity $E_{\text{geo}} = H_{\text{el}} / (t_{\text{exploit}} \cdot 3.6 \cdot 10^{12}) \text{ [GWh/y]}$

Exploitation time $t_{\text{exploit}} = 100 \text{ years}$



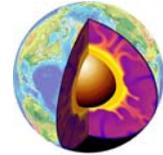
Geothermal Power Investment Cost Perspectives



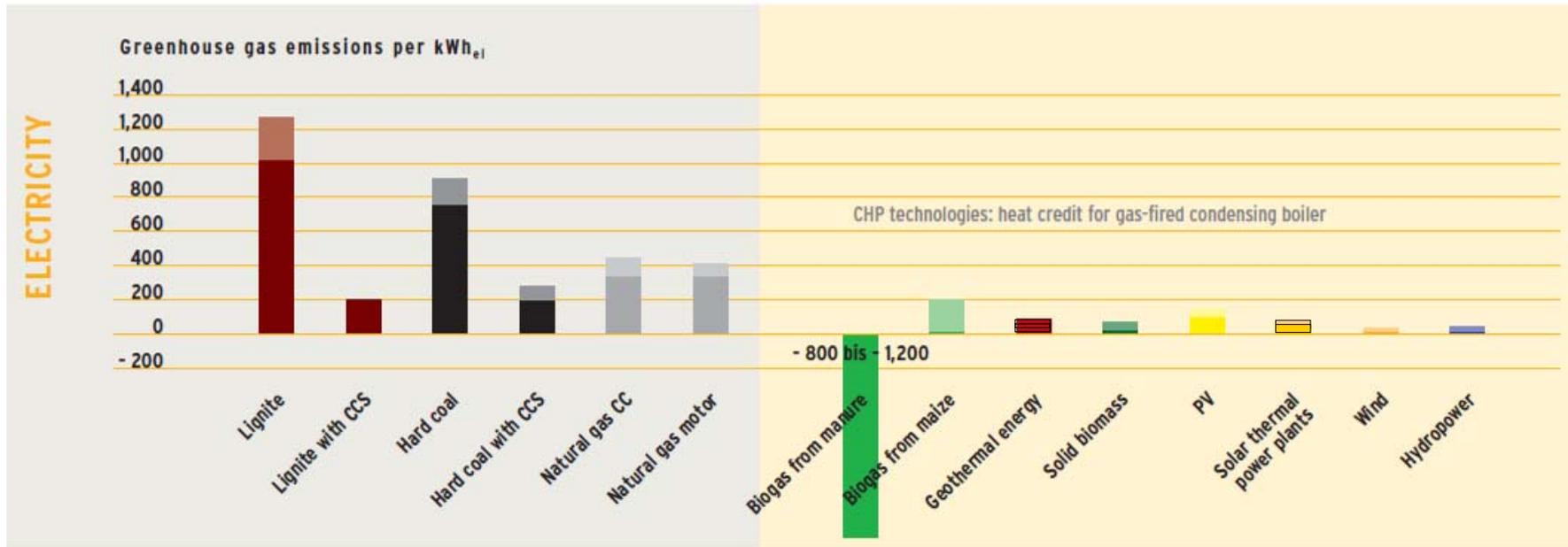


Environmental Impacts of Geothermal Electricity

- 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



Sources and Literature

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