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Advanced Energy Business Management Training

ZIW e.V.
Center for Innovation
and Further Education

Trier University
of Applied Sciences
HOCHSCHULE TRIER

Bender-IS

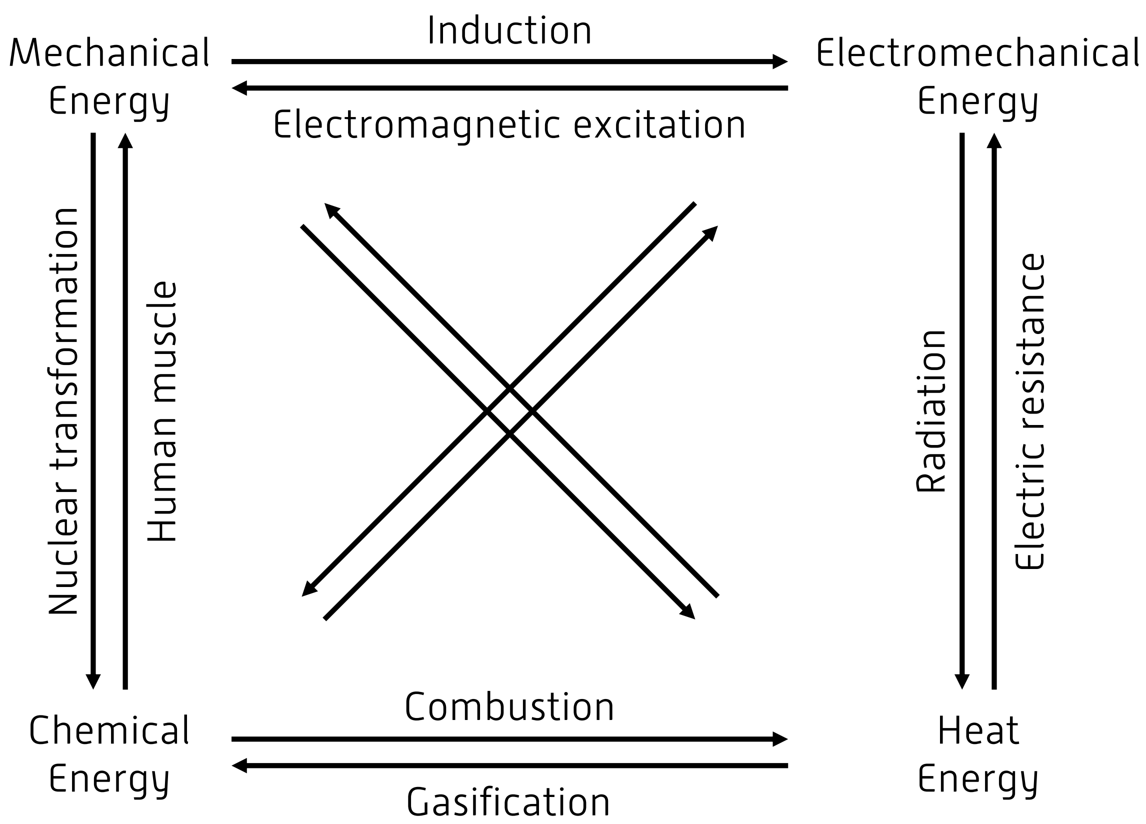
Overview on Renewable and Energy Conversion Technologies

Prof. Dr. Henrik te Heesen

Trier, 17th May 2022

https://www.umwelt-campus.de/en/hteheesen/tebm

Types and Transformation of Energy



Energy Sources

Primary Energy

Fossil Energy
- Hard Coal
- Lignite
- Oil
- Natural Gas

Nuclear Energy

Renewable Energy
- Hydropower
- Wind
- Photovoltaic
- Bioenergy
- Geothermal Energy

Losses
by transformation
and transportation

Secondary Energy

Fuel
Heating Oil
Gas
Coal
Fuelwood
Electricity

Losses
by transformation
and transportation

Useful Energy

Electricity
Heat
Transportation

Energy Units and Conversion Factors

Metric Prefixes

Kilo (k) = 10^3

Mega (M)= 10^6

Giga (G) = 10^9

Tera (T) = 10^{12}

Peta (P) = 10^{15}

Exa (E) = 10^{18}

Volume

1 m^3 = 1,000 litres (l)

1 US gallon = 3.78 l

1 Imperial gallon = 4.55 l

multiply by	GJ	Toe	MBtu	MWh
GJ	1	0.024	0.948	0.278
Toe	41.868	1	39.683	11.630
MBtu	1.055	0.025	1	0.293
MWh	3.600	0.086	3.412	1

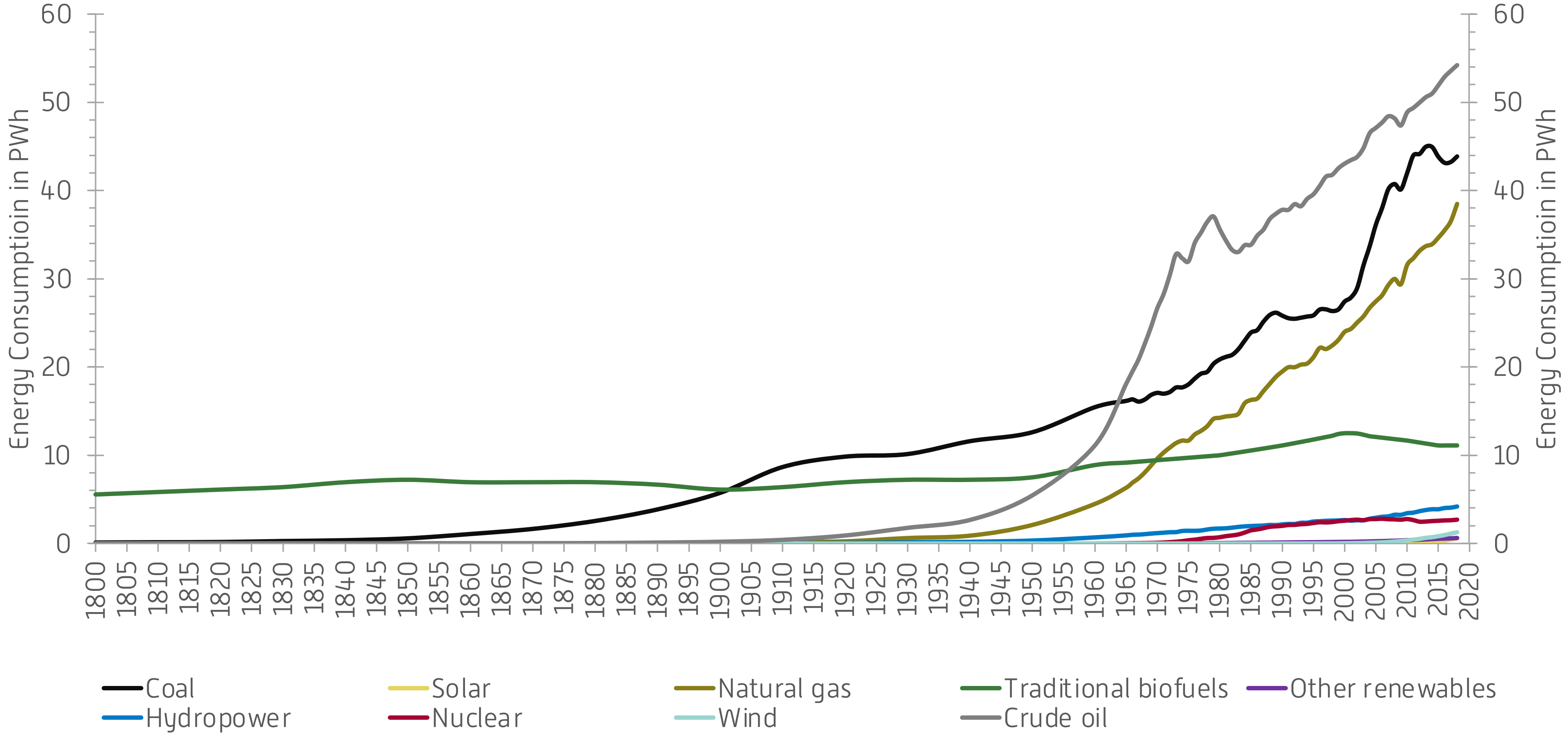
GJ: Giga Joule

Toe: Tonne of Oil Equivalent

MBtu: Mega British Thermal Unit

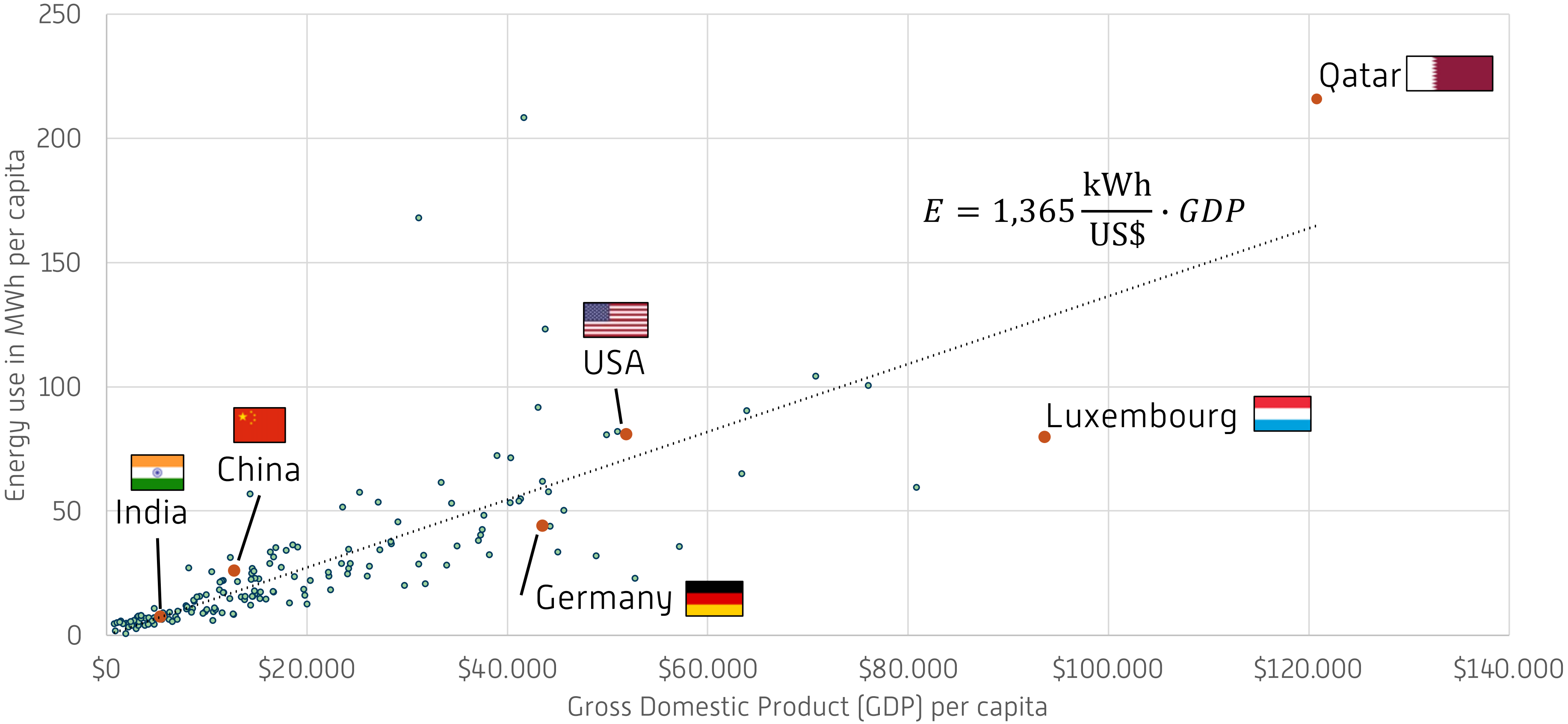
MWh: Mega Watts Hours

Global primary energy consumption by source



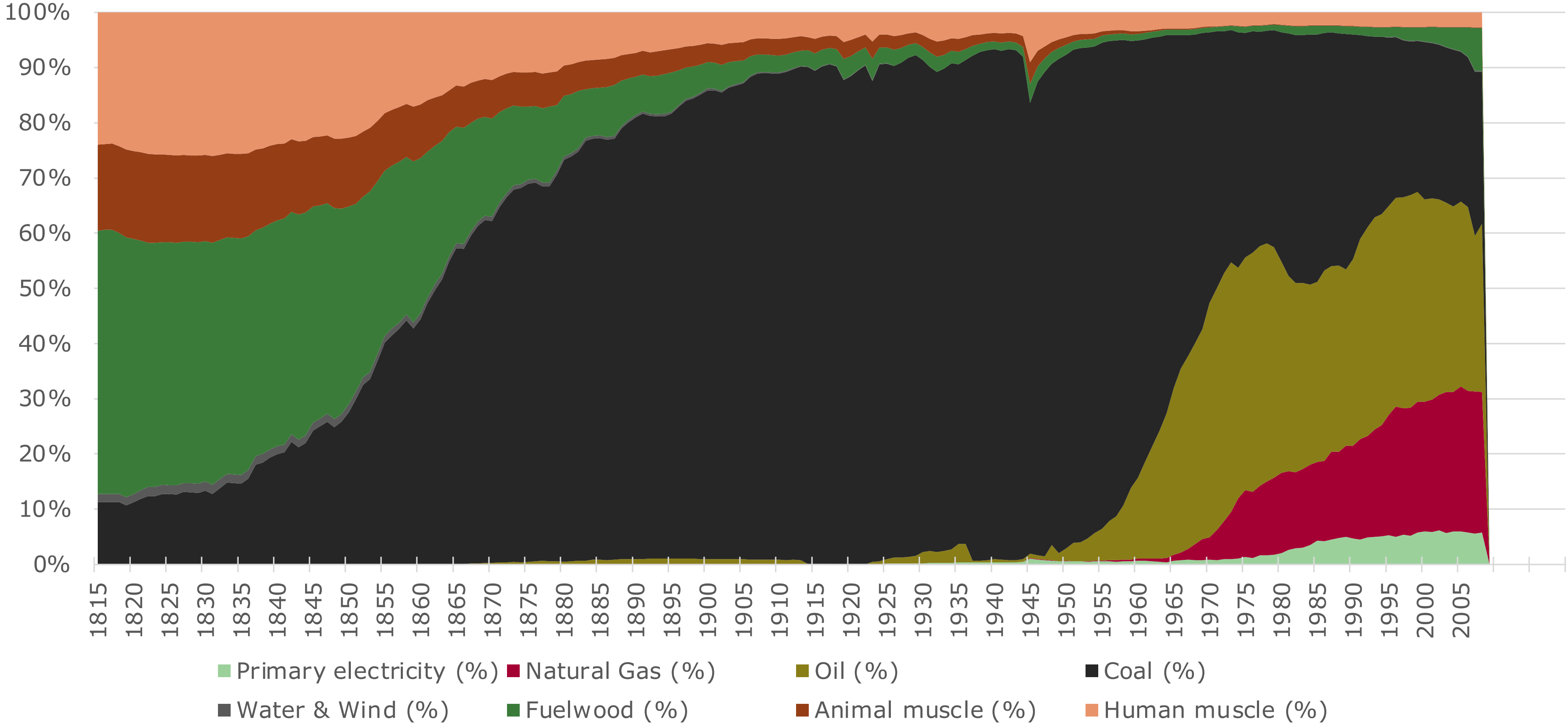
Data source: Our World in Data. https://ourworldindata.org/energy

Energy use vs. GDP per capita 2014



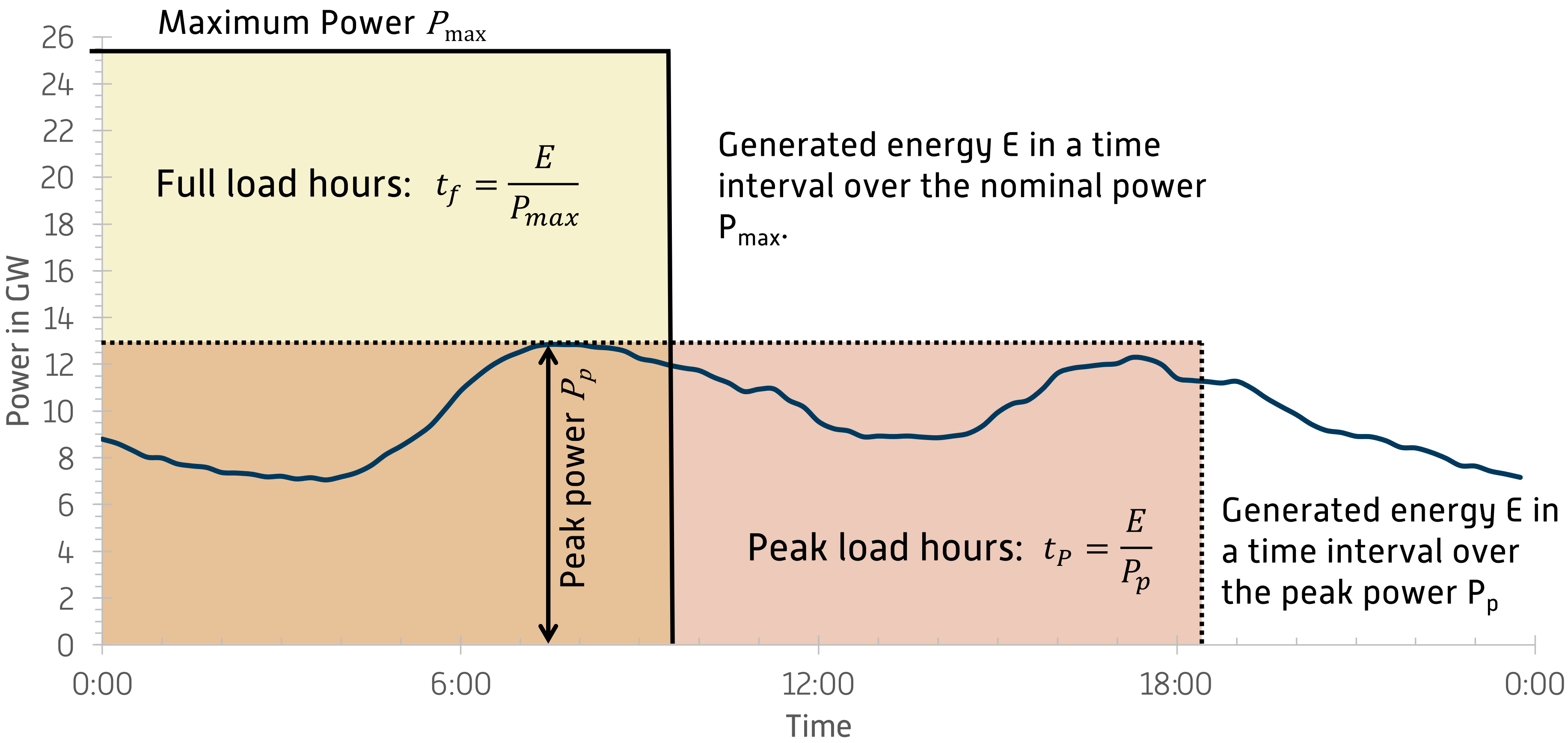
Data source: Our World in Data. https://ourworldindata.org/energy

A long-term view of the energy transition in Germany from 1815 to 2019 shows that only 13% of the energy supply is renewable.



Datenquelle: Hannah Ritchie and Max Roser (2020) - "Energy". Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy

Full Load Hours and Peak Load Hours



Data Source: Federal Network Agency. smard.de

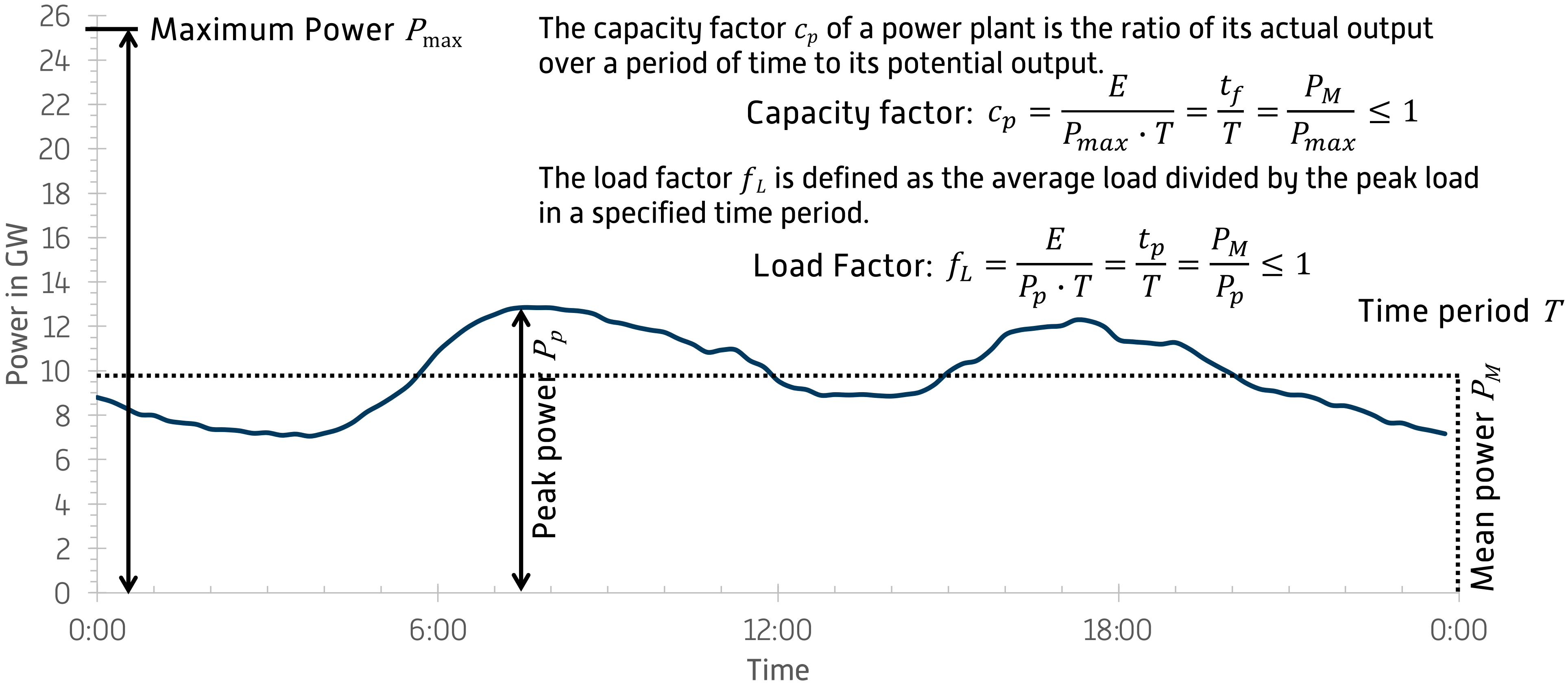
Capacity Factor and Load Factor

The capacity factor c_p of a power plant is the ratio of its actual output over a period of time to its potential output.

$$\text{Capacity factor: } c_p = \frac{E}{P_{max} \cdot T} = \frac{t_f}{T} = \frac{P_M}{P_{max}} \leq 1$$

The load factor f_L is defined as the average load divided by the peak load in a specified time period.

$$\text{Load Factor: } f_L = \frac{E}{P_p \cdot T} = \frac{t_p}{T} = \frac{P_M}{P_p} \leq 1$$



Data Source: Federal Network Agency. smard.de

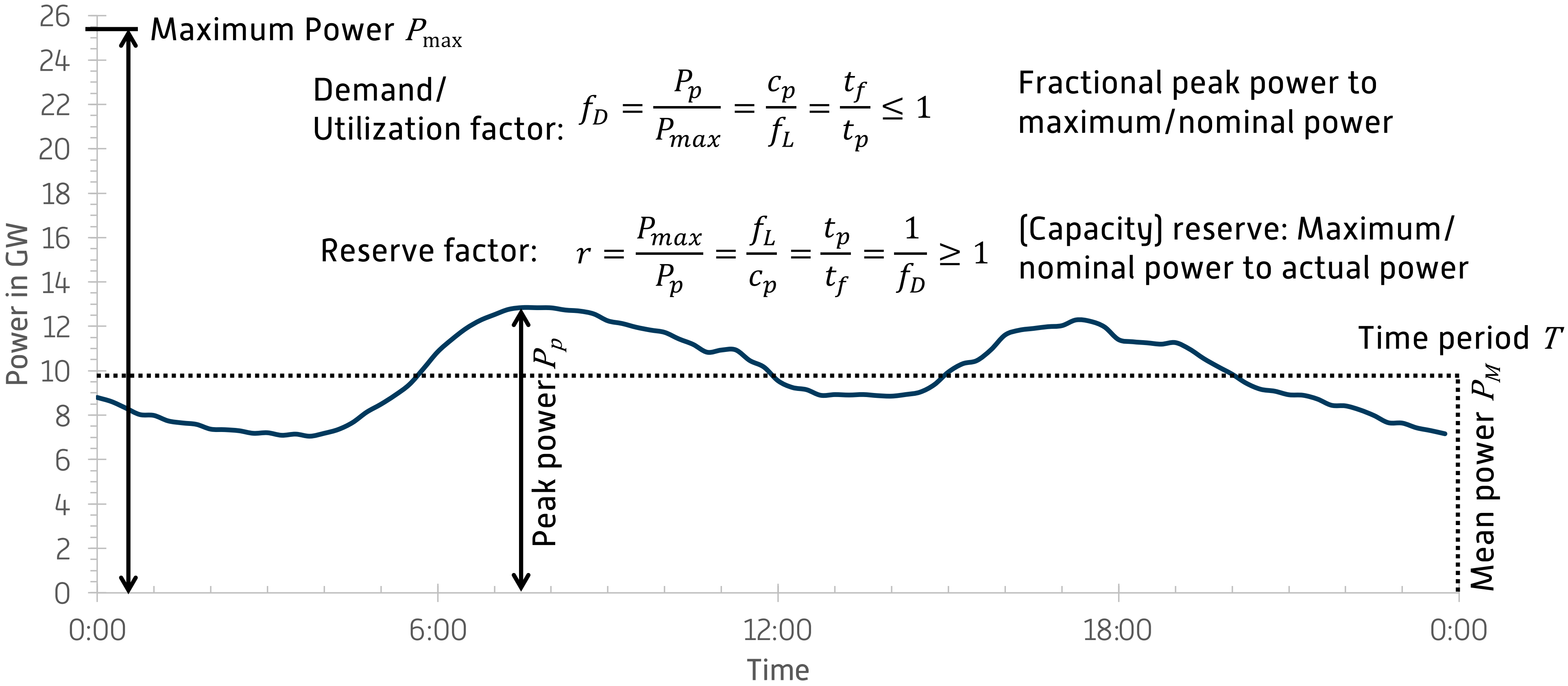
Demand/Utilization Factor and Reserve Factor

Demand/ Utilization factor: $f_D = \frac{P_p}{P_{max}} = \frac{c_p}{f_L} = \frac{t_f}{t_p} \leq 1$

Fractional peak power to maximum/nominal power

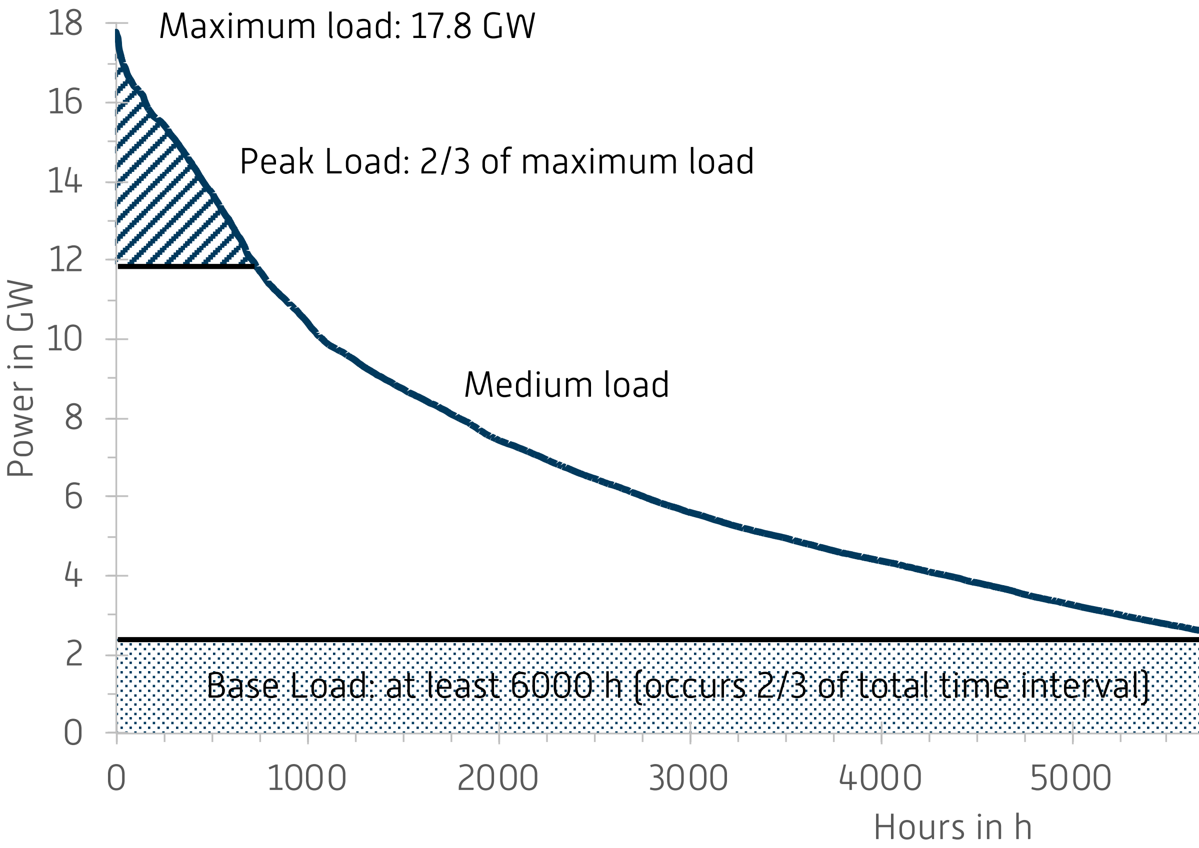
Reserve factor: $r = \frac{P_{max}}{P_p} = \frac{f_L}{c_p} = \frac{t_p}{t_f} = \frac{1}{f_D} \geq 1$

(Capacity) reserve: Maximum/ nominal power to actual power



Data Source: Federal Network Agency. smard.de

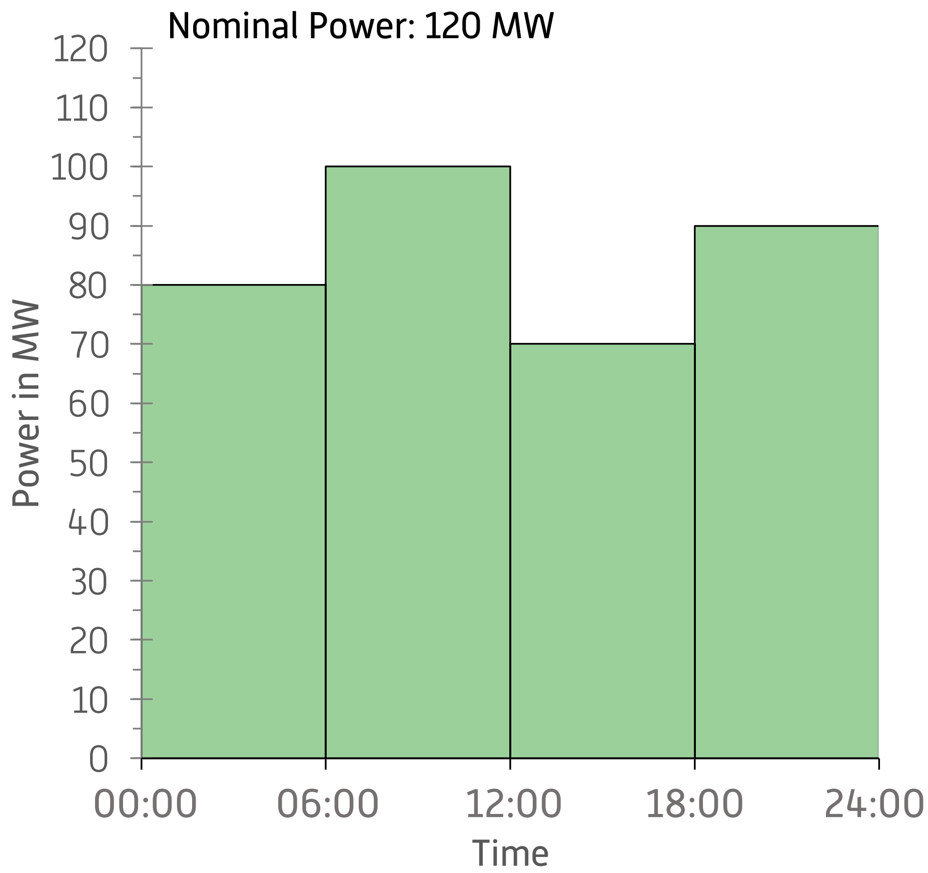
Load Duration Curve



Power generation of hard coal power plants in Germany 2019

Data Source: Federal Network Agency. smard.de

Example: Calculation of Energy Indicators



Please calculate

Generated Energy:

Mean power:

Peak load hours:

Full load hours:

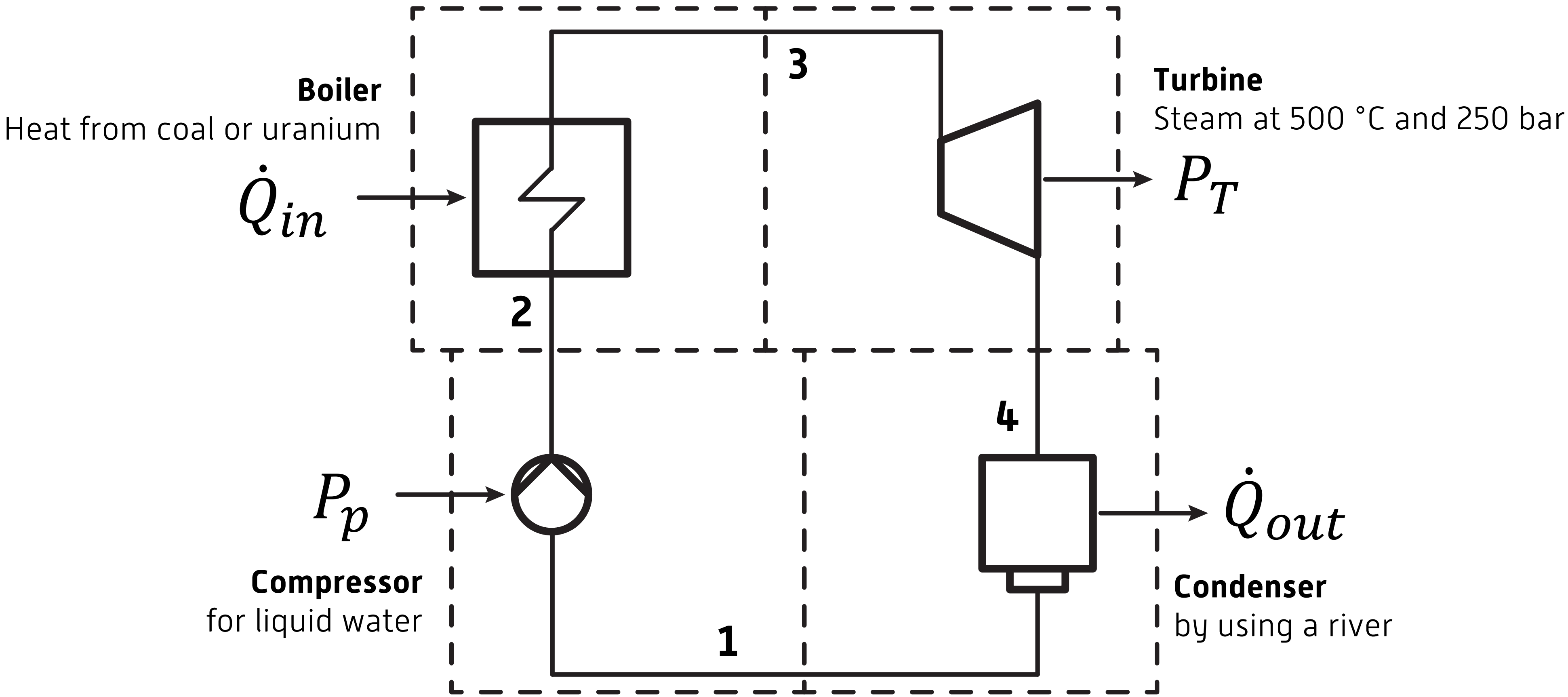
Capacity factor:

Load factor:

Demand factor:

Reserve factor:

Simplified cycle process of a steam power plant



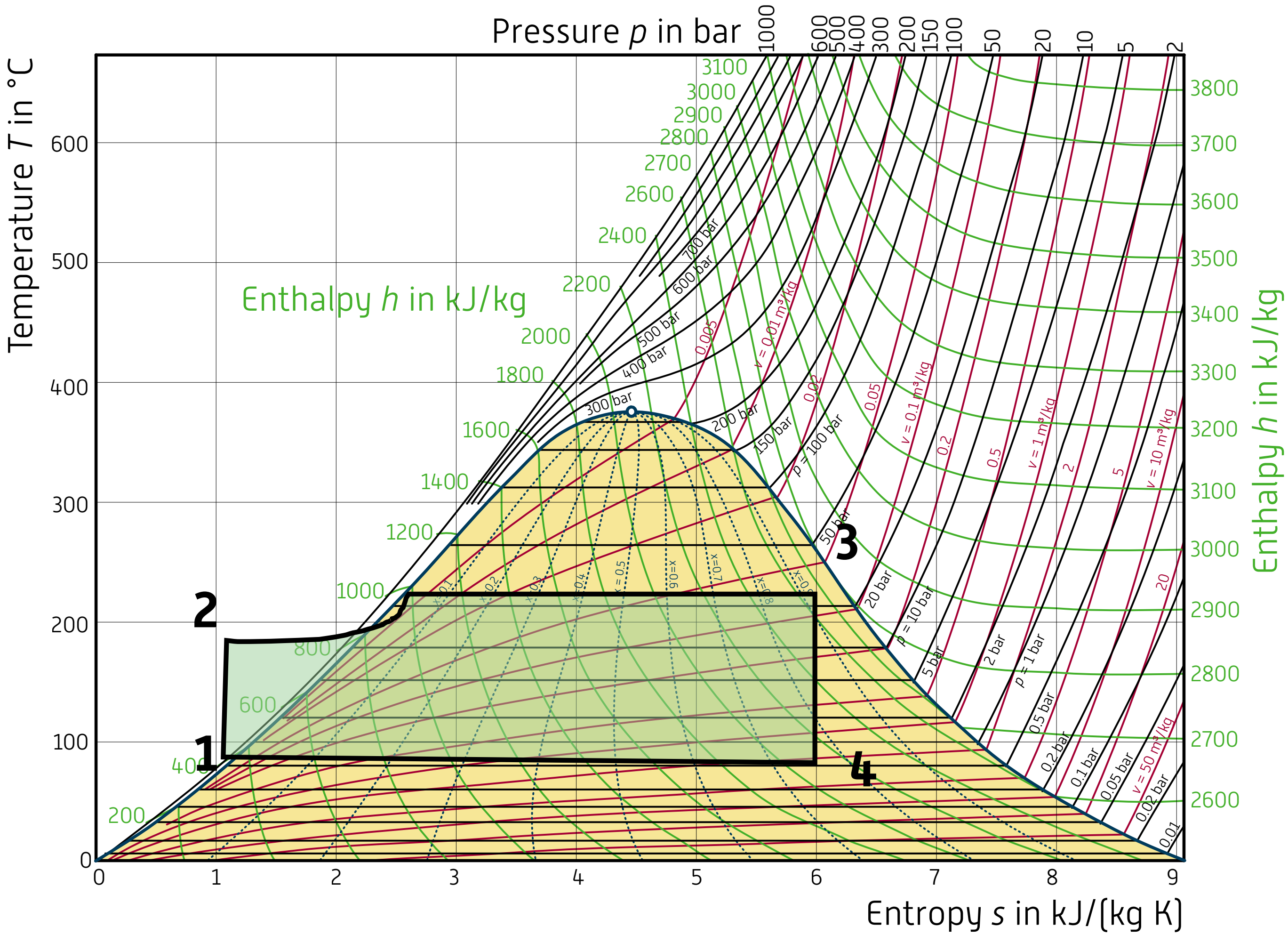
Rankine Circle

1↦2
Isentropic compression of the liquid water

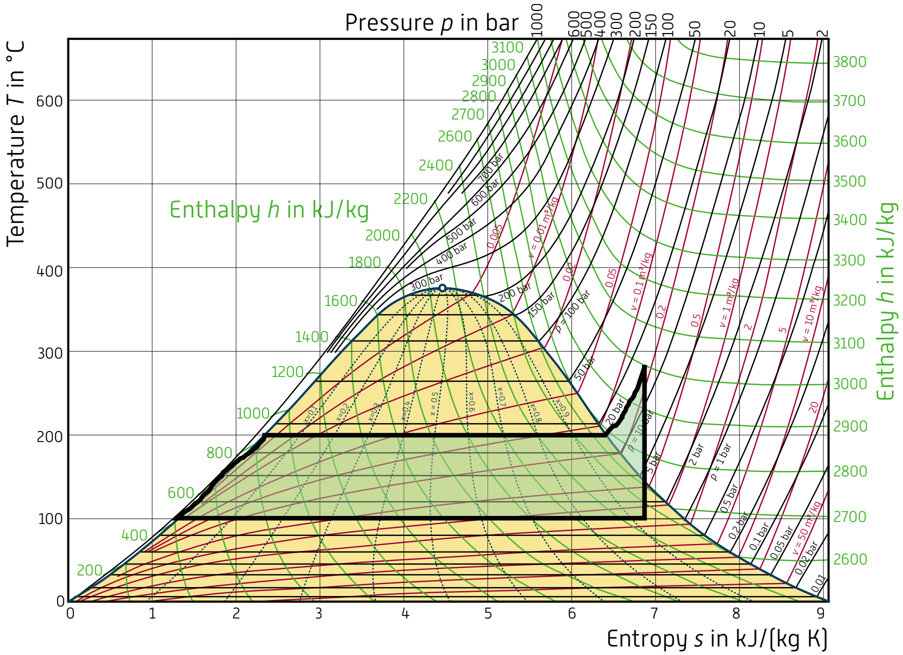
2↦3
Isobaric heat supply in the boiler

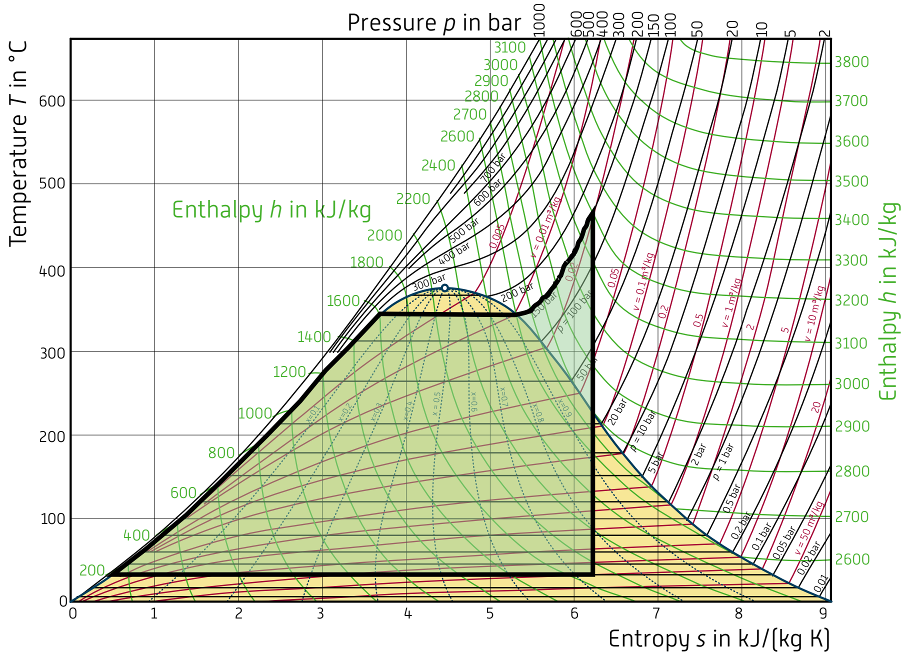
3↦4
Isentropic expansion in the turbine

4↦1
Isobaric heat dissipation and condensation



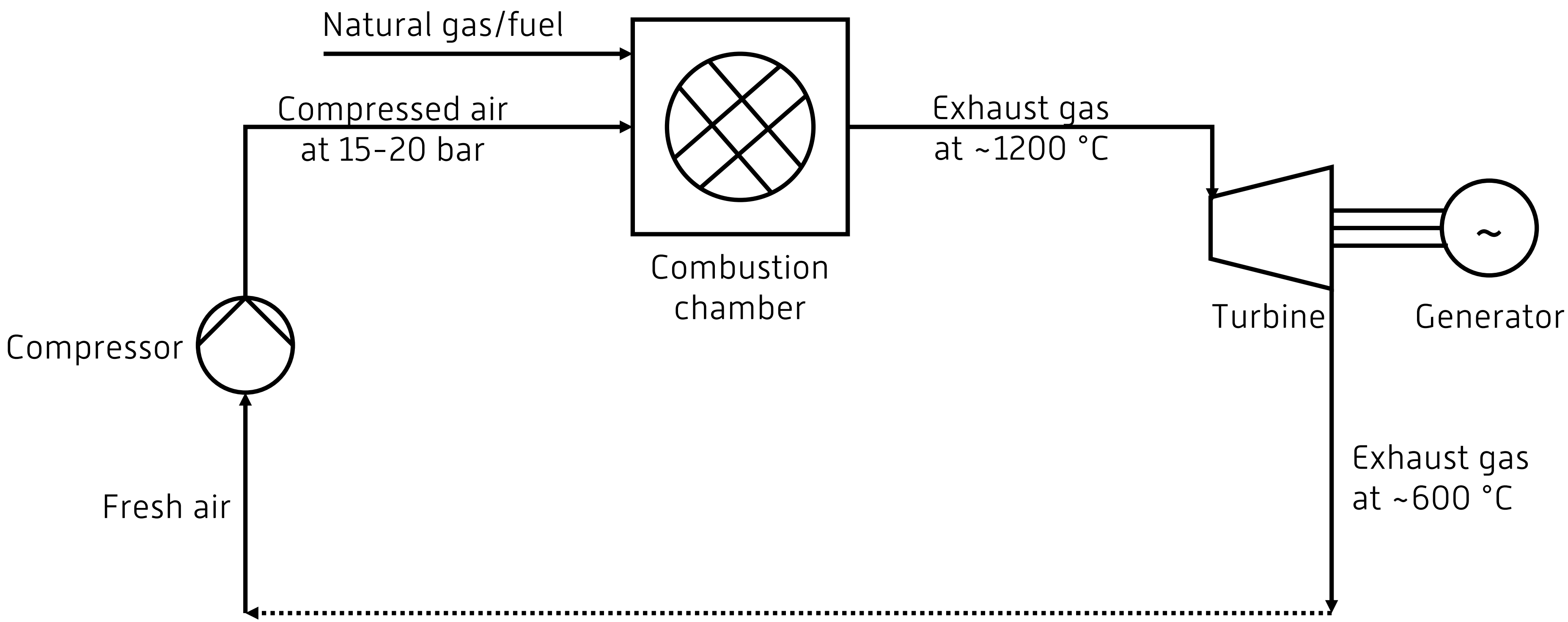
Increase of efficiency: High pressure near critical point and low pressure in condenser (0.04 bar)



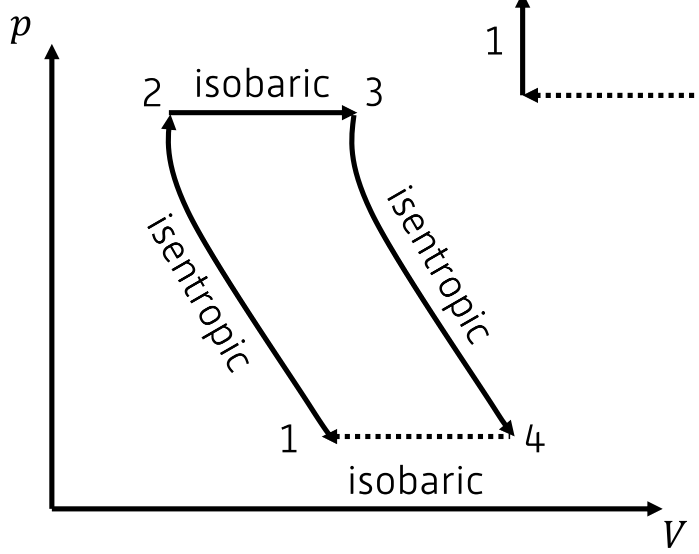


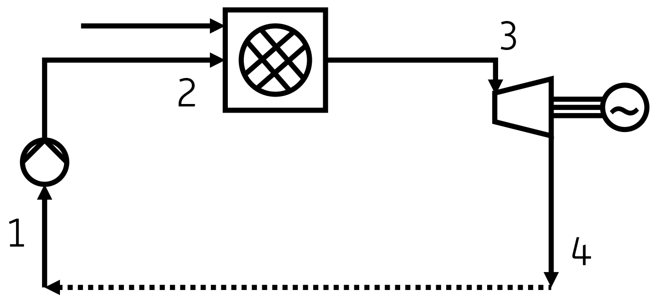
Higher temperature (450 °C) and higher pressure (up to 250 bar)

Basic design of a gas turbine power plant



Brayton or Joule Circle





1↦2
Isentropic compression of fresh air

2↦3
Isobaric heat addition by burning the gas/fuel in the combustion chamber

3↦4
Isentropic expansion in the turbine

4↦1
Isobaric heat rejection to the atmosphere

Definition of power plant types

Baseload power plants

- Nuclear, lignite and run-of-river power plants
- Utilization time from 6000 to 7000 hours per year
- 50 % of the maximum annual load and 70 % of energy consumption

Medium-load power plants

- Hard coal-fired power plants and individual oil/gas-fired power plants
- Utilization time 3000 to 5000 hours per year
- Technical suitability for frequent load changes

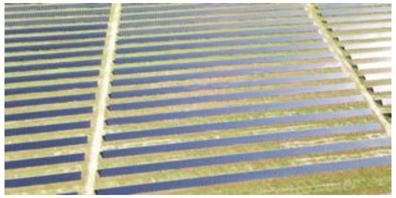
Peak-load power plants

- Gas turbine, storage and pumped storage power plants
- Utilization time about 1000 hours per year
- Start-up and shutdown several times a day with short start-up times and high-power changes

Volatile energy systems

- Wind energy, photovoltaics
- Strongly limited controllability (only switch-off)



Steam Power Plants

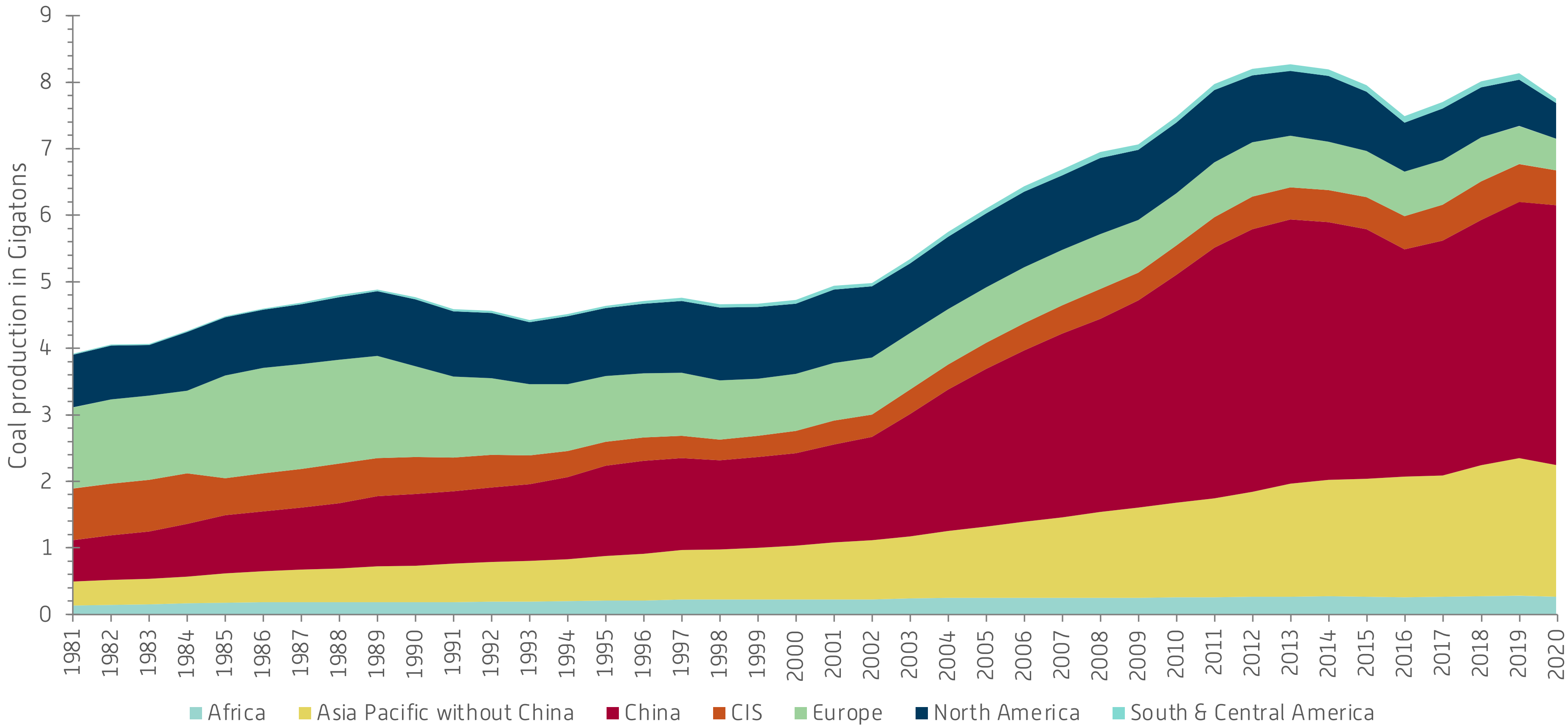
Coal burned in the boiler heats water to produce steam. The steam spins the turbine, which drives the generator.


K·F

Demolished Village Borschemich in Western Germany

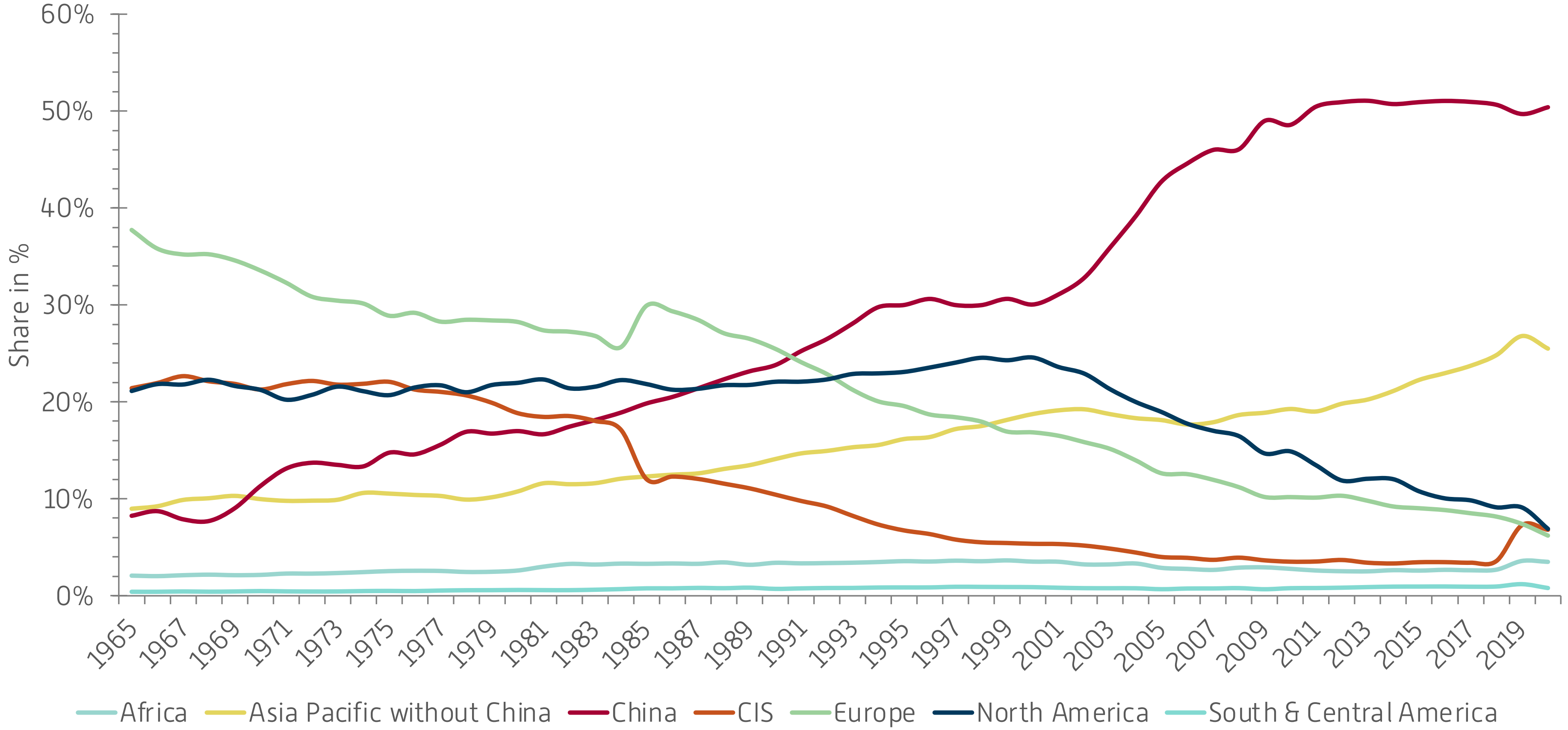

Neuotzenrath
Jüchen
Wanlo
Holz
Tagebau Garzweiler
Kuckum
Keyenberg
Borschemich
Garzweiler
Spenrath
Google Earth

Coal Production from 1981 to 2020



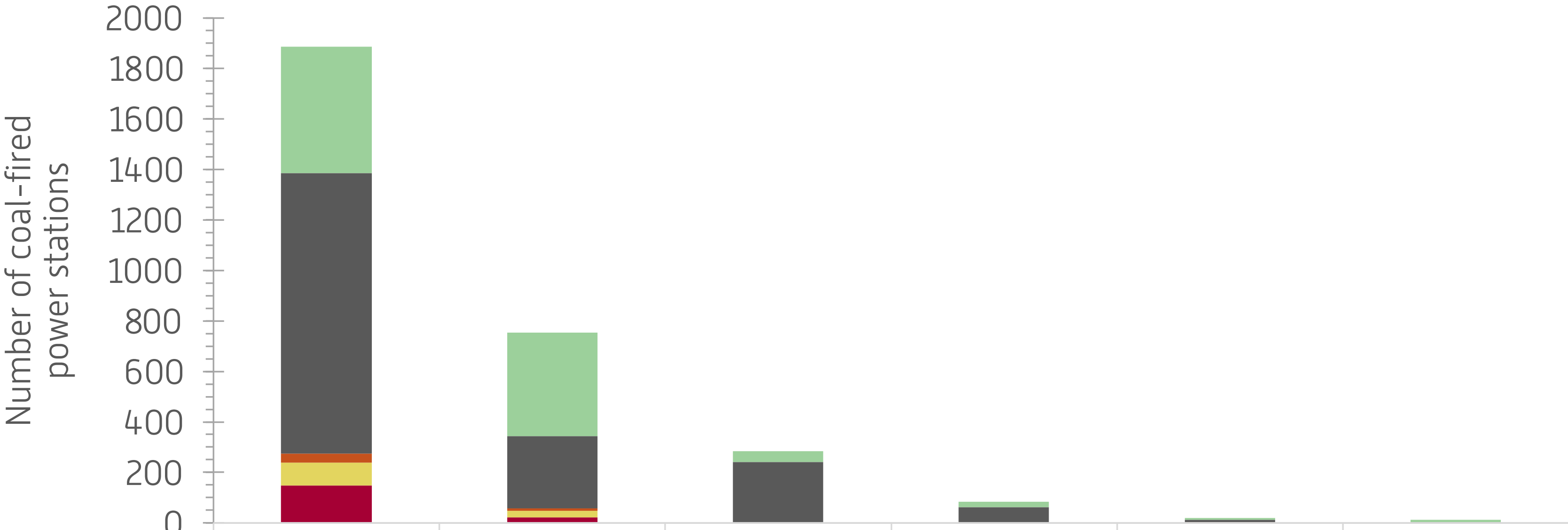
Source: BP. Statistical Review of World Energy. March 2022.

Share of Key Regions in Global Coal Demand



Source: BP. Statistical Review of World Energy. June 2019.

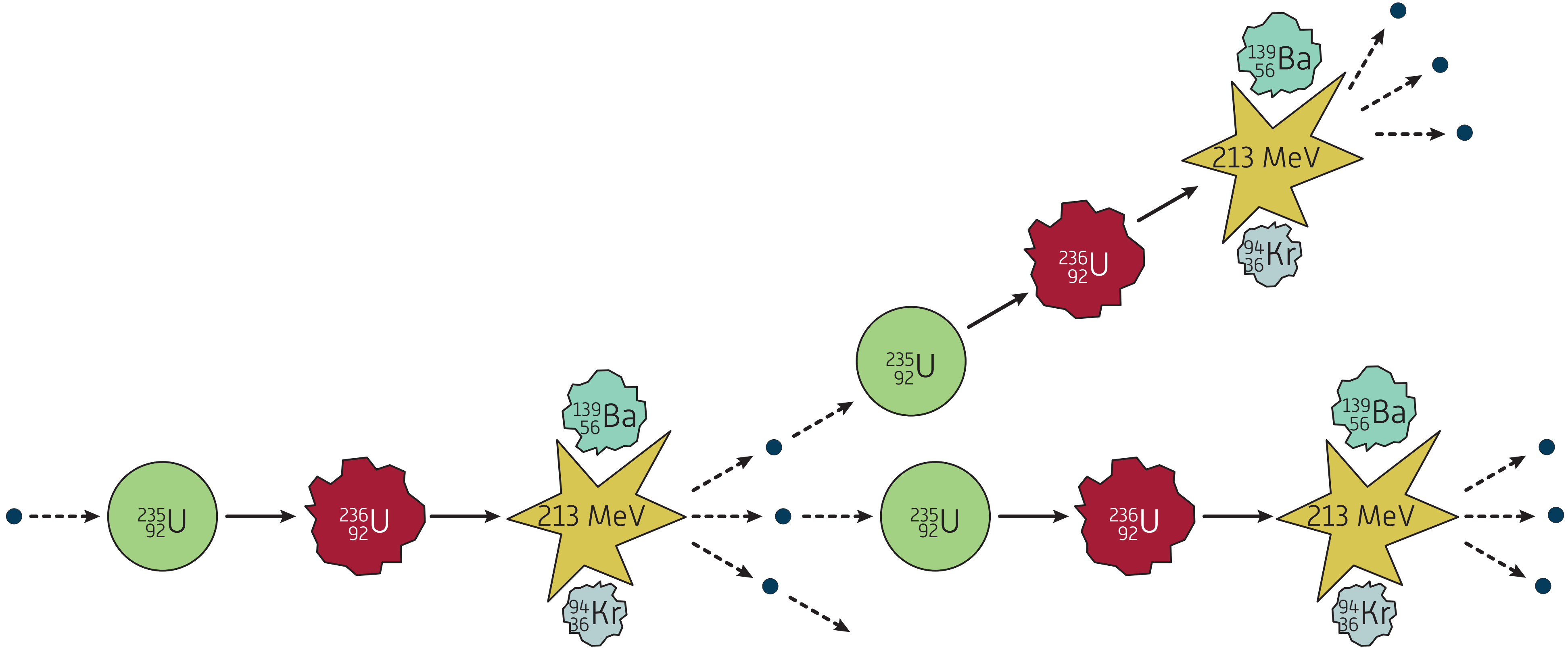
Number of coal-fired power stations by country



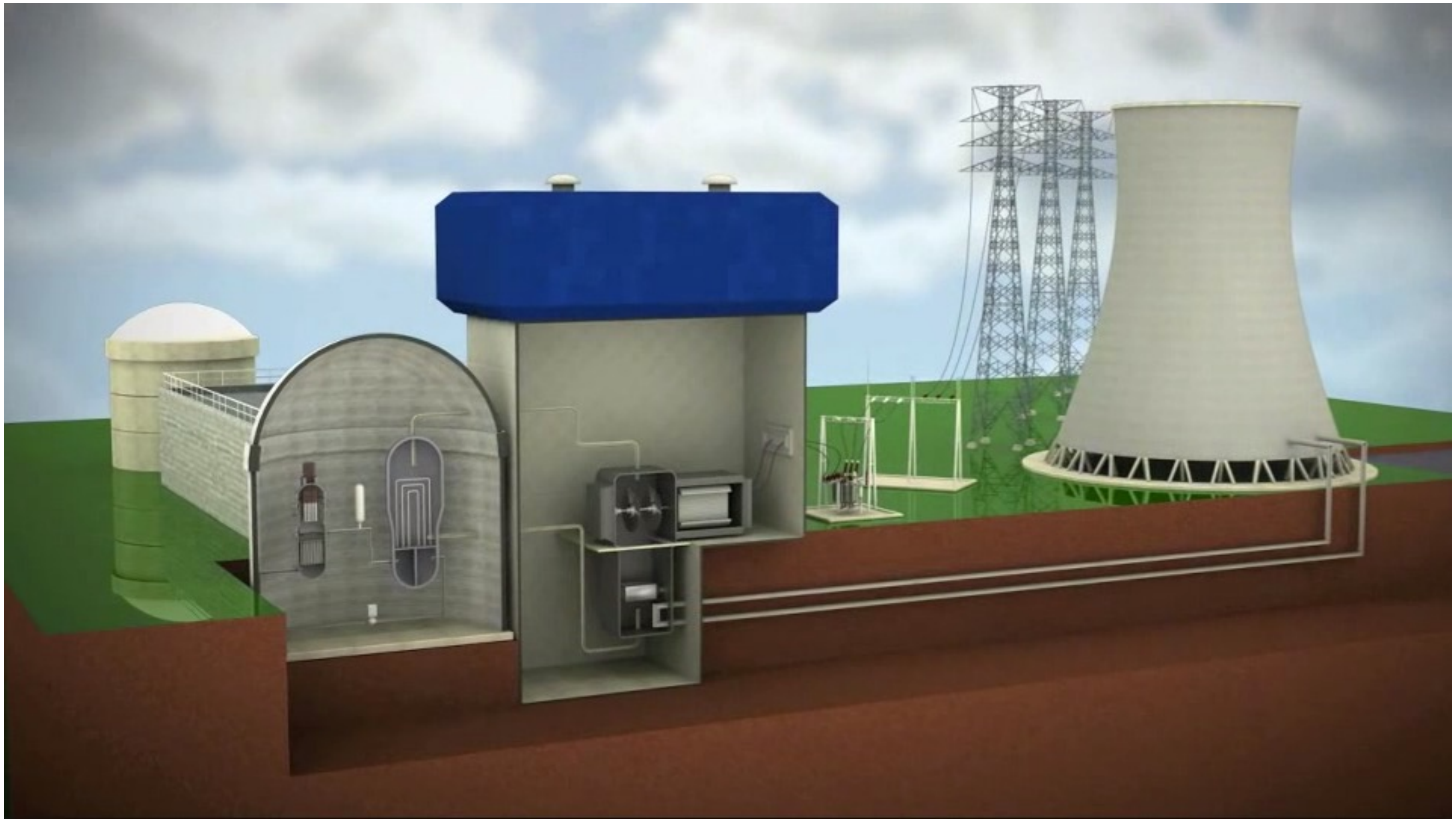
	China	India	USA	Germany	Thailand	UK
Cancelled 2010-2019	502	410	44	22	7	9
Operating	1110	285	240	63	10	4
Shelved	35	11	0	0	1	0
Construction	92	26	0	0	0	0
Preconstruction	148	22	1	0	1	0

Source: endcoal.org. March 2022

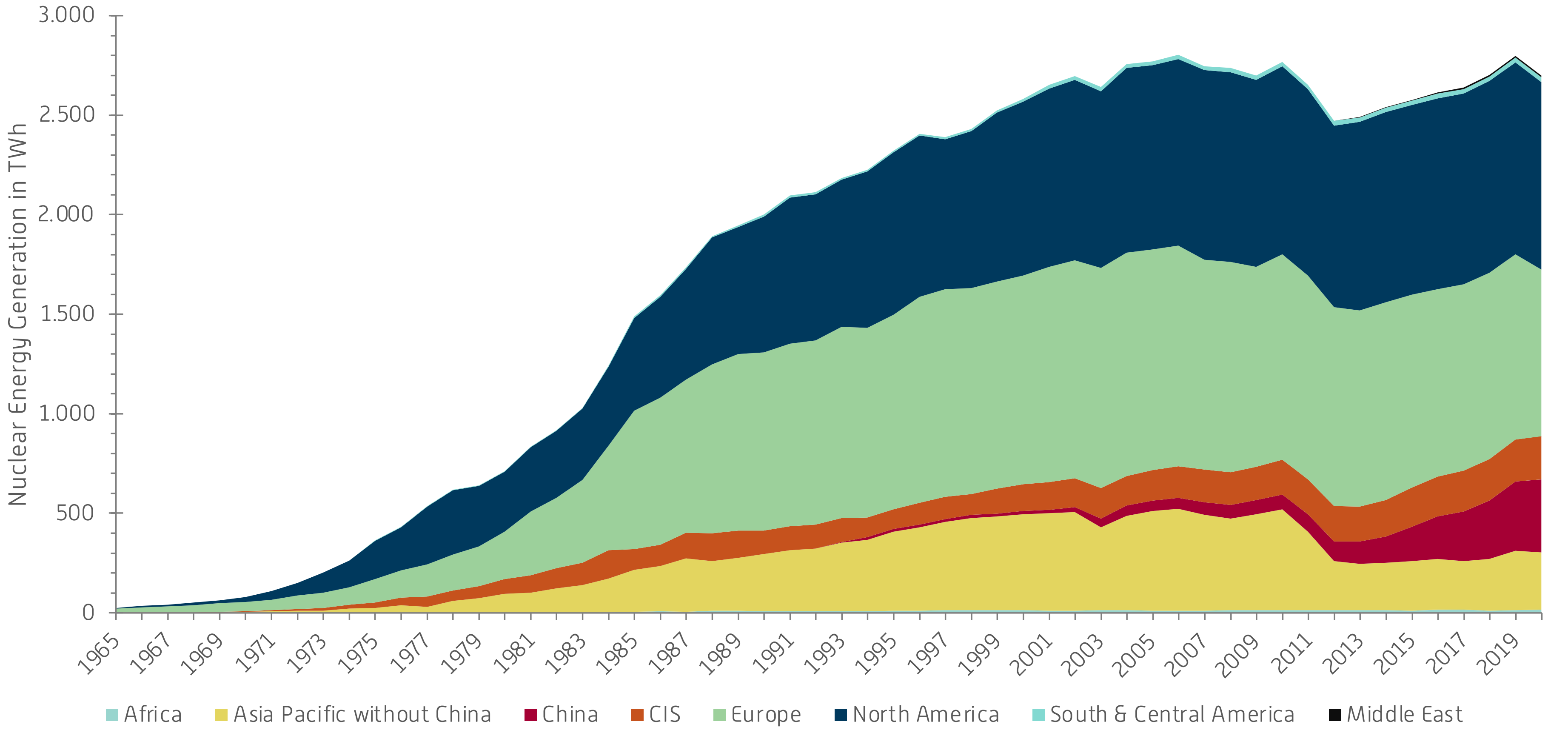
Fission of ^{235}U



Nuclear Power Plant

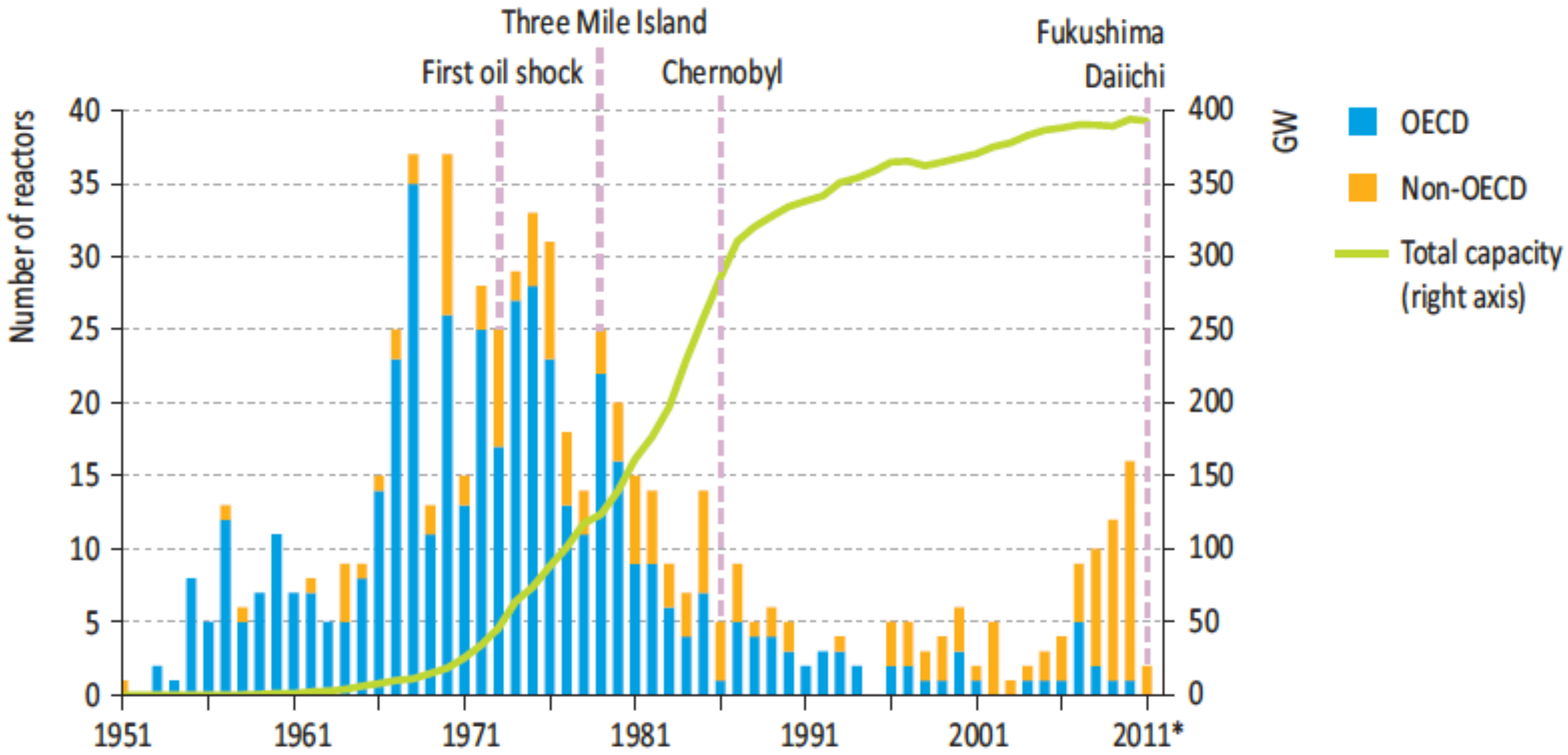


Global Energy Production by Nuclear Power



Source: BP. Statistical Review of World Energy. March 2022.

New construction of nuclear power plants



Source: IEA. World Energy Outlook 2011. P. 450

IAEA

Power Reactor
Information
System

PRIS

Costs of natural disasters caused by nuclear reactor accidents

- Harrisfield (1979): EUR 1,5 billion
- Chernobyl (1986): EUR 140 billion
- Fukushima (2011): EUR 235 billion
- Asse: EUR 6 billion

Probability of nuclear power plant failure: approx. 10,000 years
Number of nuclear piles: 437
=> Design basis event (DBE): every 25 years

Photo: Ingmar Runge

Namie, Prefecture Fukushima, Japan

https://goo.gl/maps/xXNFruTWvMJ4iiyw9

Source: Google. March 2013

Differences between gas and steam power plants

No steam is generated in a gas turbine power plant.

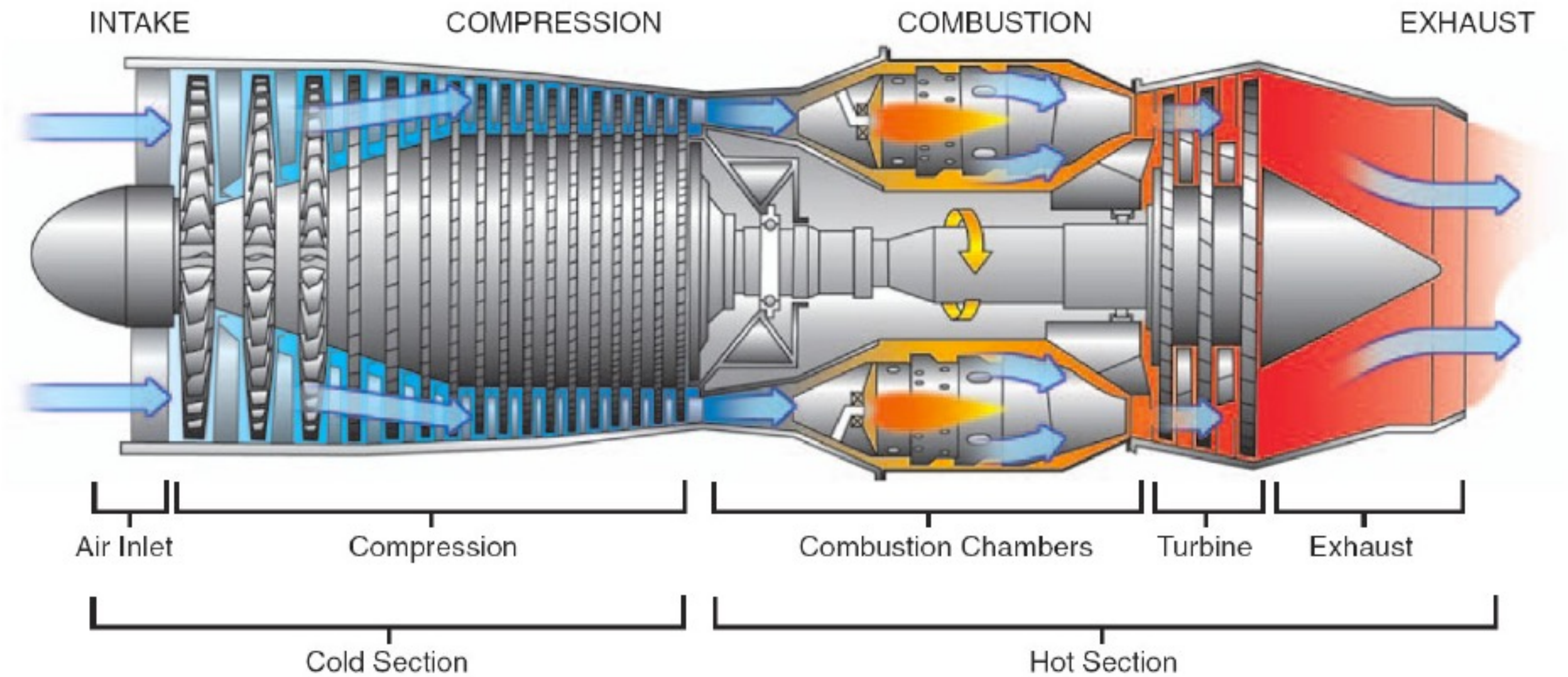
The exhaust gases generated by the combustion process are fed directly to the turbine blades.

Gas turbines can produce full power within a few seconds, so gas turbine power plants are suitable as a minute reserve.

Gas turbine power plants are composed of

- gas turbine
- compressor
- auxiliary facilities

Section through a turbine



Gas-fired power plant

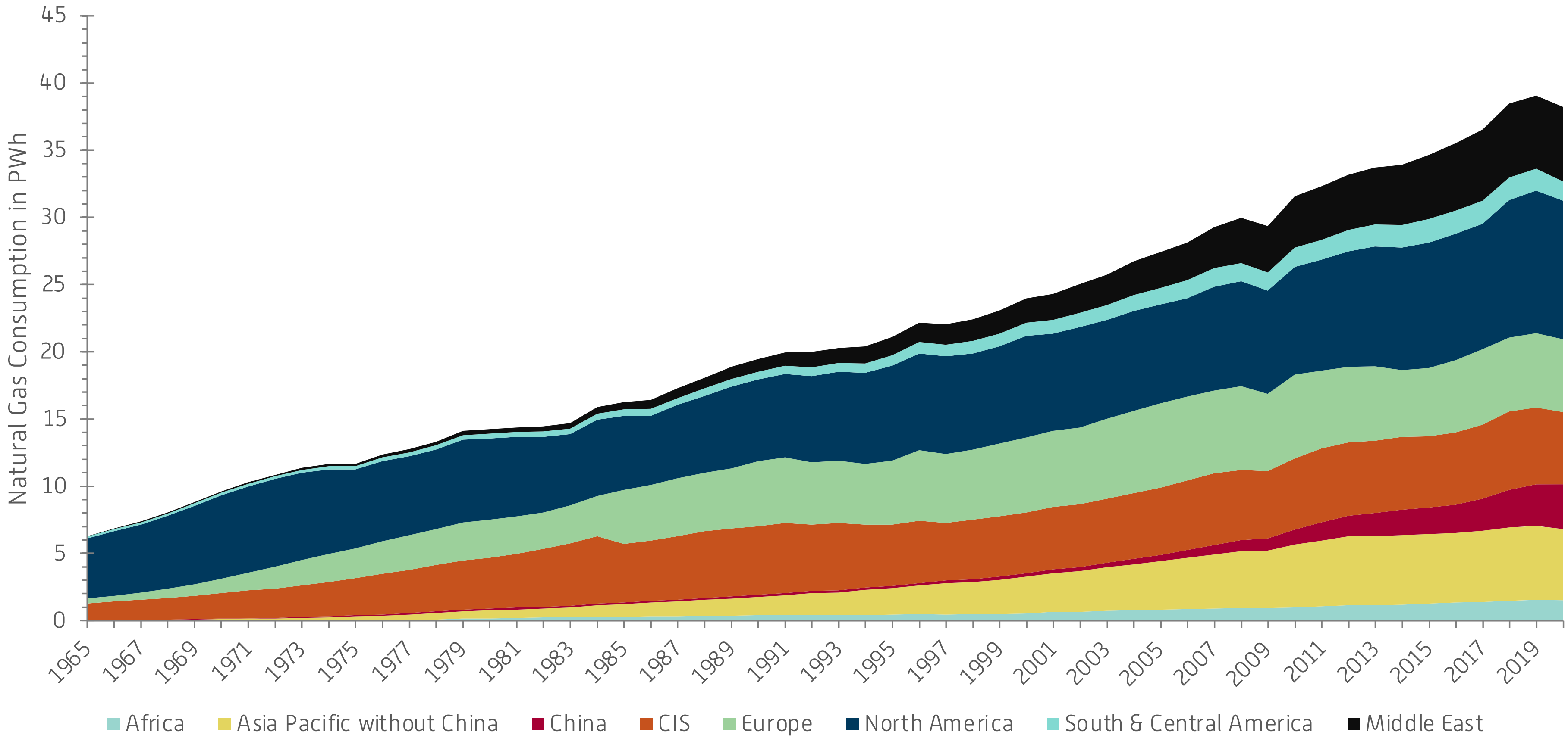
- The gas turbine produces extremely high combustion temperatures of 900 to 1,250 °C at a pressure of 15 to 20 bar. For this reason, extremely high-quality materials must be used to withstand these process conditions.

- The rotational energy of the turbine drives the generator and the compressor.

- The compressor sucks in the combustion air, compresses the combustion air consumes about 2/3 of the energy of the gas burned in the gas turbine.

- Advantage of gas-fired power plants: No cooling equipment and no exhaust gas cleaning necessary.

Global Natural Gas Consumption 1965-2020



Source: BP. Statistical Review of World Energy. March 2022

Wind Energy

Kinetic energy E of the wind

$$E = \tfrac{1}{2} \cdot m \cdot v^2$$

Power P of the wind

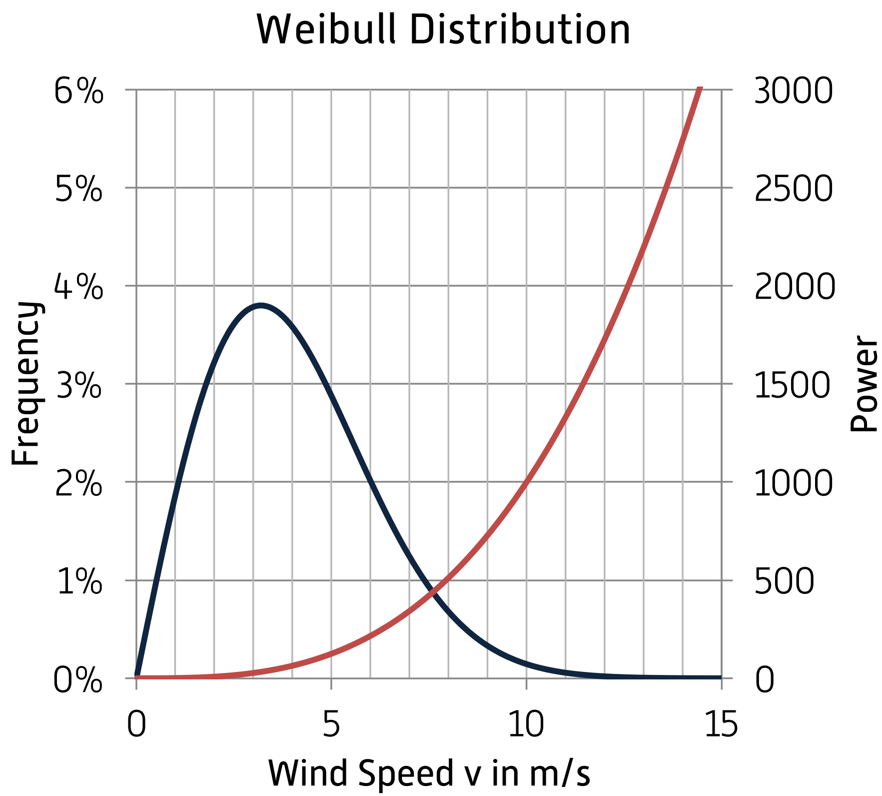
$$P = \dot{E} = \tfrac{1}{2} \cdot \dot{m} \cdot v^2$$

Air-mass flow of the wind

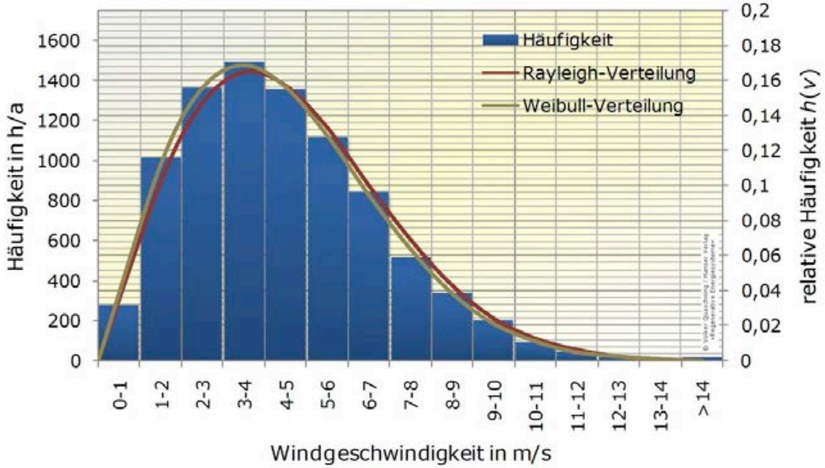
$$m = \rho \cdot V \Rightarrow \dot{m} = \rho \cdot \dot{V} = \rho \cdot A \cdot \dot{s} = \rho \cdot A \cdot v$$

Power P of the wind as a function of the the wind speed v

$$\Rightarrow P = \tfrac{1}{2} \cdot \rho \cdot A \cdot v^3$$



Weibull Wind Speed Distribution



Location	k	a	v in m/s
Berlin	1,85	4,4	3,9
Hamburg	1,87	4,6	4,1
München	1,32	3,2	2,9
Saarbrücken	1,76	3,7	3,3

$$f(v) = \frac{k}{a} \cdot \left(\frac{v}{a}\right)^{k-1} \cdot \exp\left\{-\left(\frac{v}{a}\right)^{k}\right\}$$

a: Scale parameter
k: Shape parameter

Mean wind speed;

$$\overline{v} = a \cdot \left(0,568 + \frac{0,434}{k}\right)^{\frac{1}{k}}$$

$$a_{k=2} = \frac{\overline{v}}{0,886} \approx \frac{2}{\sqrt{\pi}}\overline{v}$$

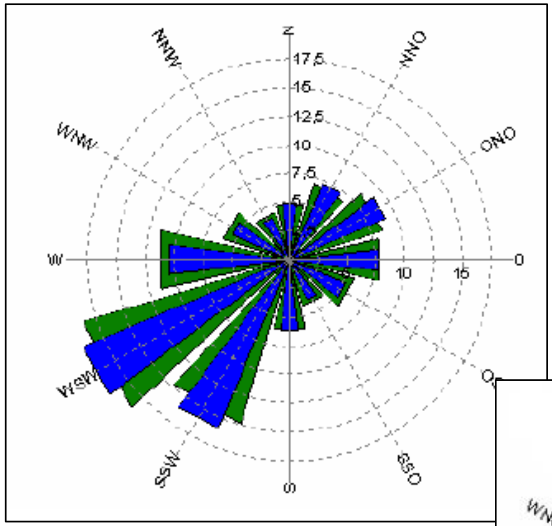
Rayleigh distribution

$$f(v) = \frac{\pi}{2} \cdot \frac{v}{\overline{v}^2} \cdot \exp\left\{-\frac{\pi}{4}\left(\frac{v}{\overline{v}}\right)^{2}\right\}$$

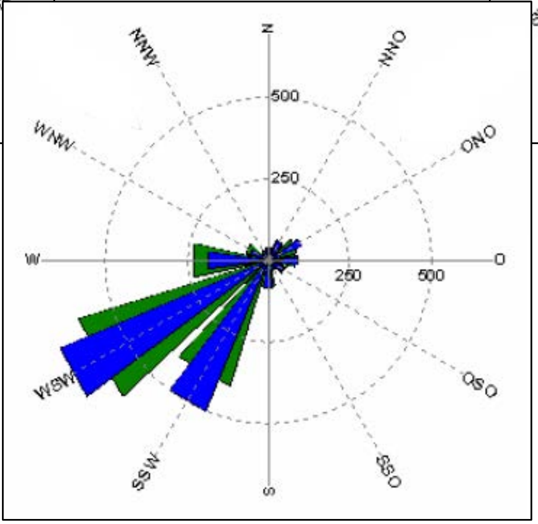
Source: Quaschning. Regenerative Energiesysteme. P 243

Yield Calculation of a Wind Turbine

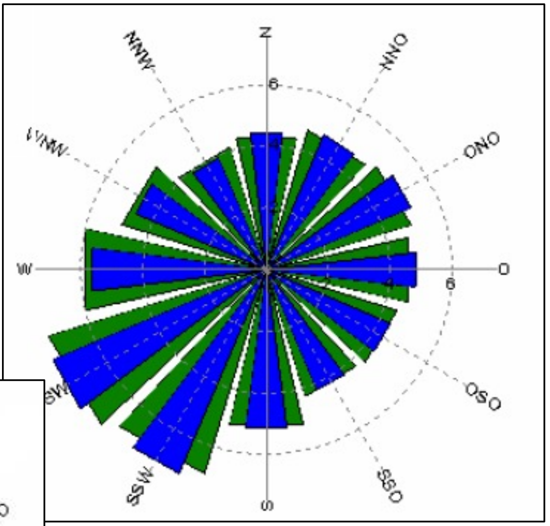
Frequency distribution



Yield distribution



Wind speed distribution



$$P = \frac{1}{2} \cdot \rho \cdot \pi \cdot r^2 \cdot v^3$$

Betz' Power Coefficient

The mass flow through the turbine is

$$\dot{m} = \rho \cdot \dot{V} = \rho \cdot A_1 \cdot v_1 = \rho \cdot A \cdot v = \rho \cdot A_2 \cdot v_2 = const.$$

The wind power in front of the turbine is

$$P_0 = \tfrac{1}{2} \cdot \rho \cdot A \cdot v_1^3$$

und the power taken from the turbine

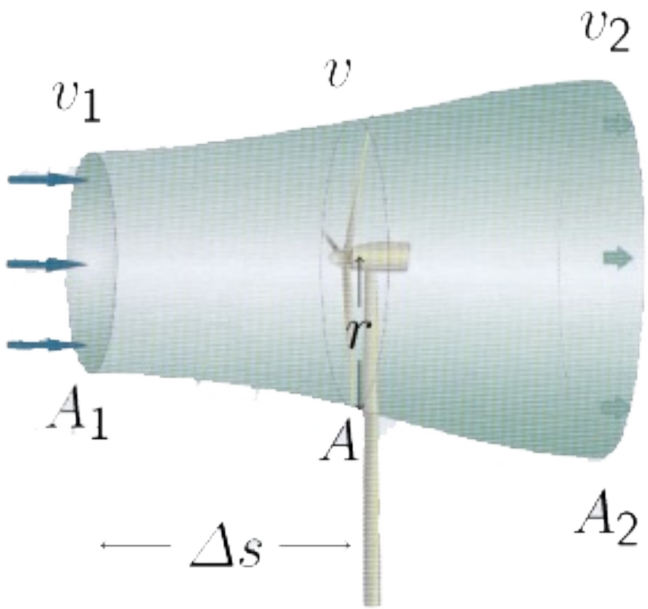
$$P_N = \tfrac{1}{2} \cdot \dot{m} \cdot (v_1^2 - v_2^2) \text{ mit } \dot{m} = \tfrac{1}{2} \cdot \rho \cdot A \cdot (v_1 + v_2)$$

$$\Rightarrow P_N = \tfrac{1}{4} \cdot \rho \cdot A \cdot (v_1 + v_2) \cdot (v_1^2 - v_2^2)$$

The ratio is the Betz' Power Coefficient c_p

The maximum power coefficient c_p=0.593
is called the Betz' Power Coefficient.

$$c_p := \frac{P_N}{P_0} = \frac{(v_1 + v_2) \cdot ({v_1}^2 - {v_2}^2)}{2 \cdot {v_1}^3}$$



Flow profile of a free-flowing turbine

Betz' Power Coefficient

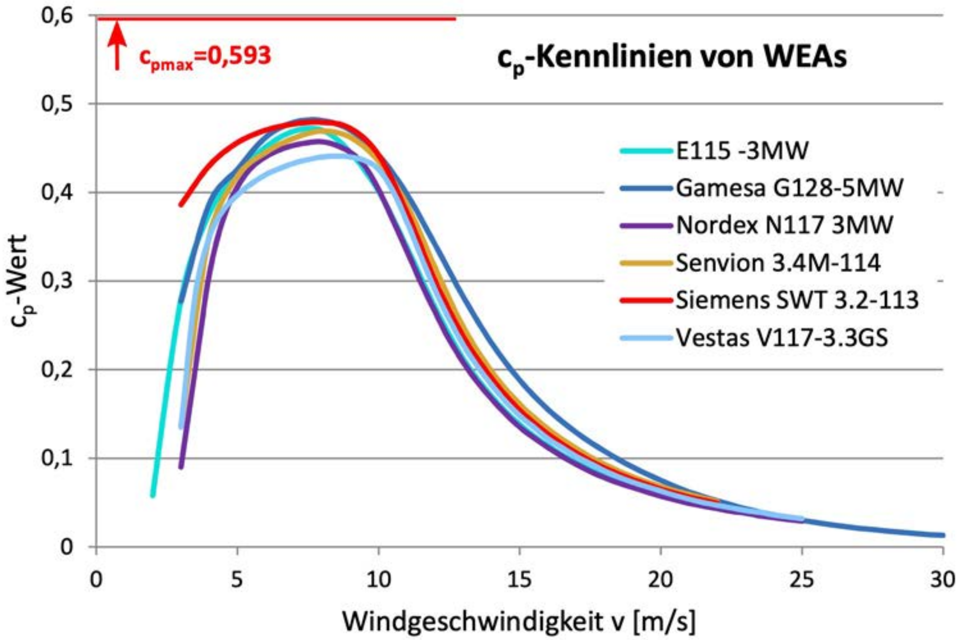
Power Curve

Power Curve of a Wind Turbine

$$P_T = \frac{1}{2} \cdot c_P\,(v) \cdot A \cdot \rho \cdot v^3$$

Coefficient of power c_P:
The amount of energy a turbine converts from the free-flowing fluid vs. the total potential energy in the fluid flow.

Mean value for c_P: 0.48



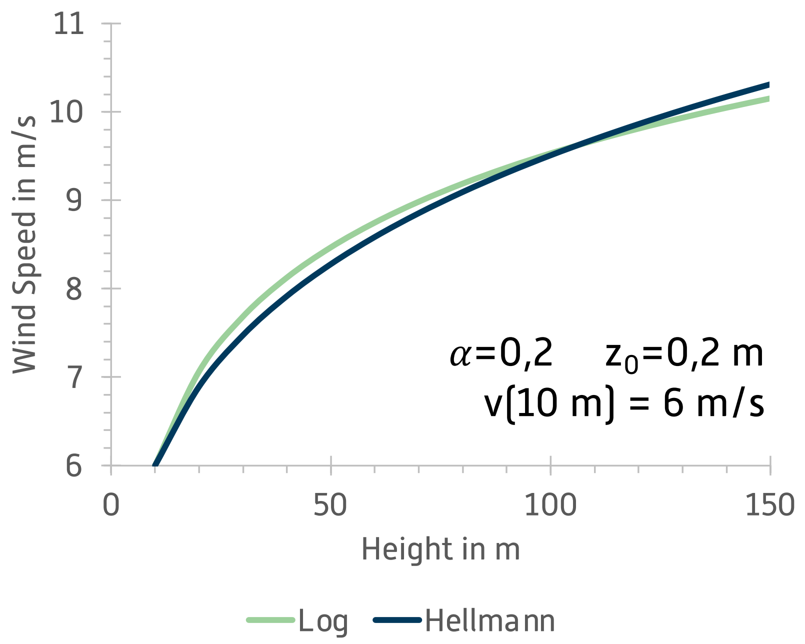
Hellmann Equation and Logarithmic Wind Profile

$$v(h_2) = v(h_1) \cdot \left(\frac{h_2}{h_1}\right)^{\alpha}$$

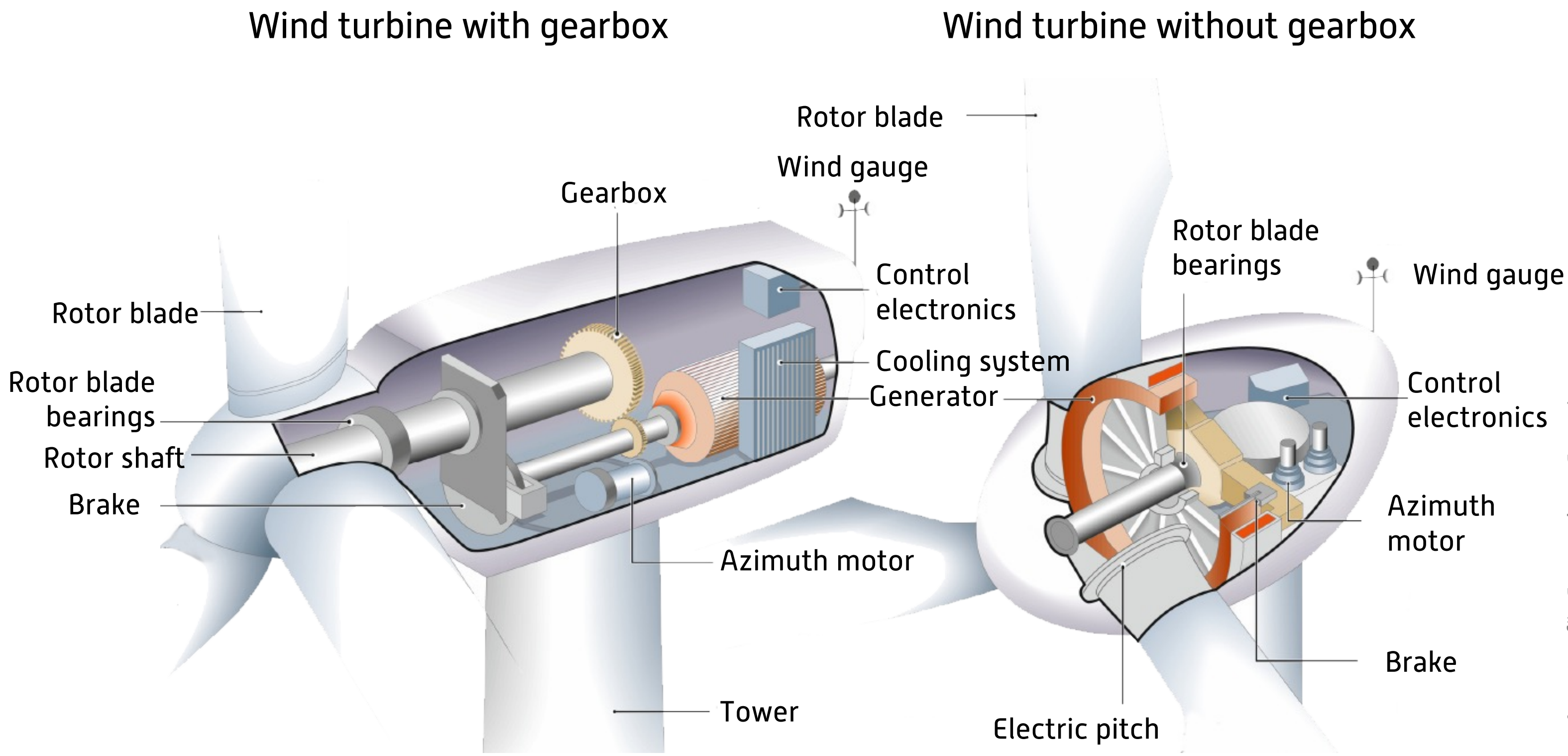
α: Hellmann exponent

$$v(h_2) = v(h_1) \cdot \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)}$$

Location	α
Unstable air above the open water surface:	0.06
Neutral air above the open water surface:	0.10
Unstable air over shallow open coast:	0.11
Neutral air over shallow open coast	0.16
Stable air above open water surface:	0.27
Unstable air over areas inhabited by humans:	0.27
Neutral air over inhabited areas:	0.34
Neutral air over open coast:	0.40
Stable air over areas inhabited by humans:	0.60



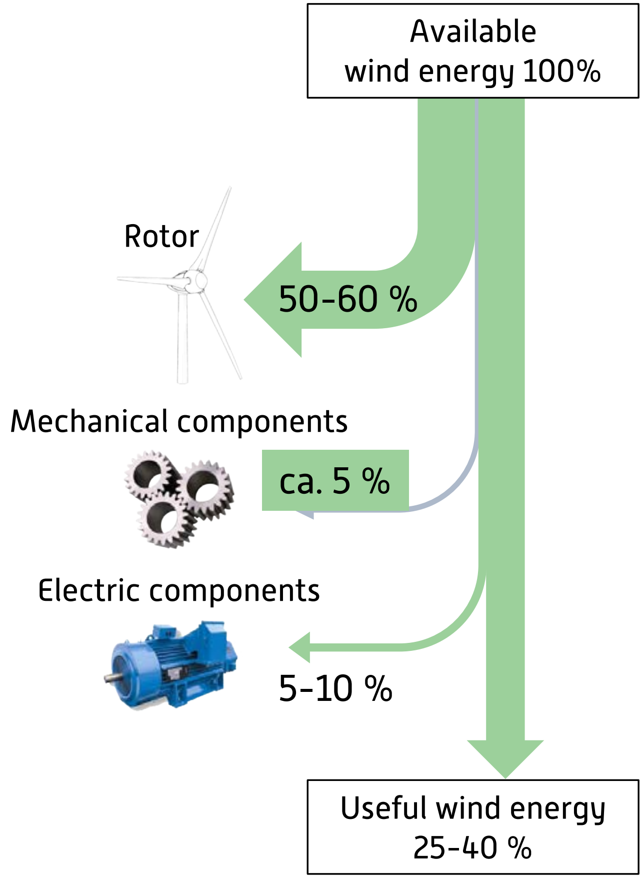
Construction of Wind Turbines



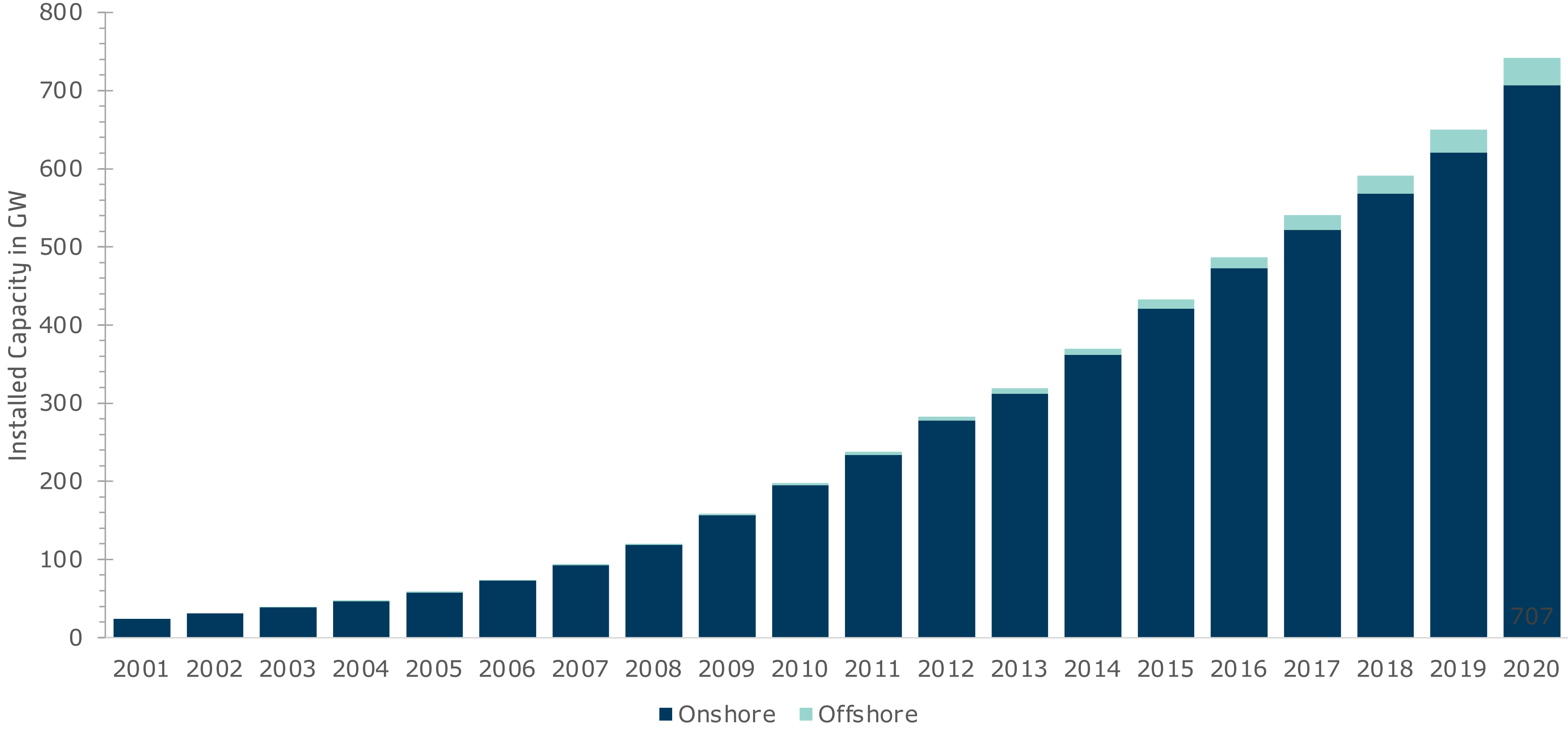
Source: Agentur für Erneuerbare Energien

Performance of a Wind Turbine

- The theoretically usable maximum wind energy of 59.3% (Bertz' power coefficient) is not achieved by real rotors.
- Three-blade rotors achieve an efficiency of up to 50%.
- Losses caused by mechanical components (gearing, tracking) are approximately 5%.
- The conversion of mechanical to electrical energy causes further losses of 5-10%.

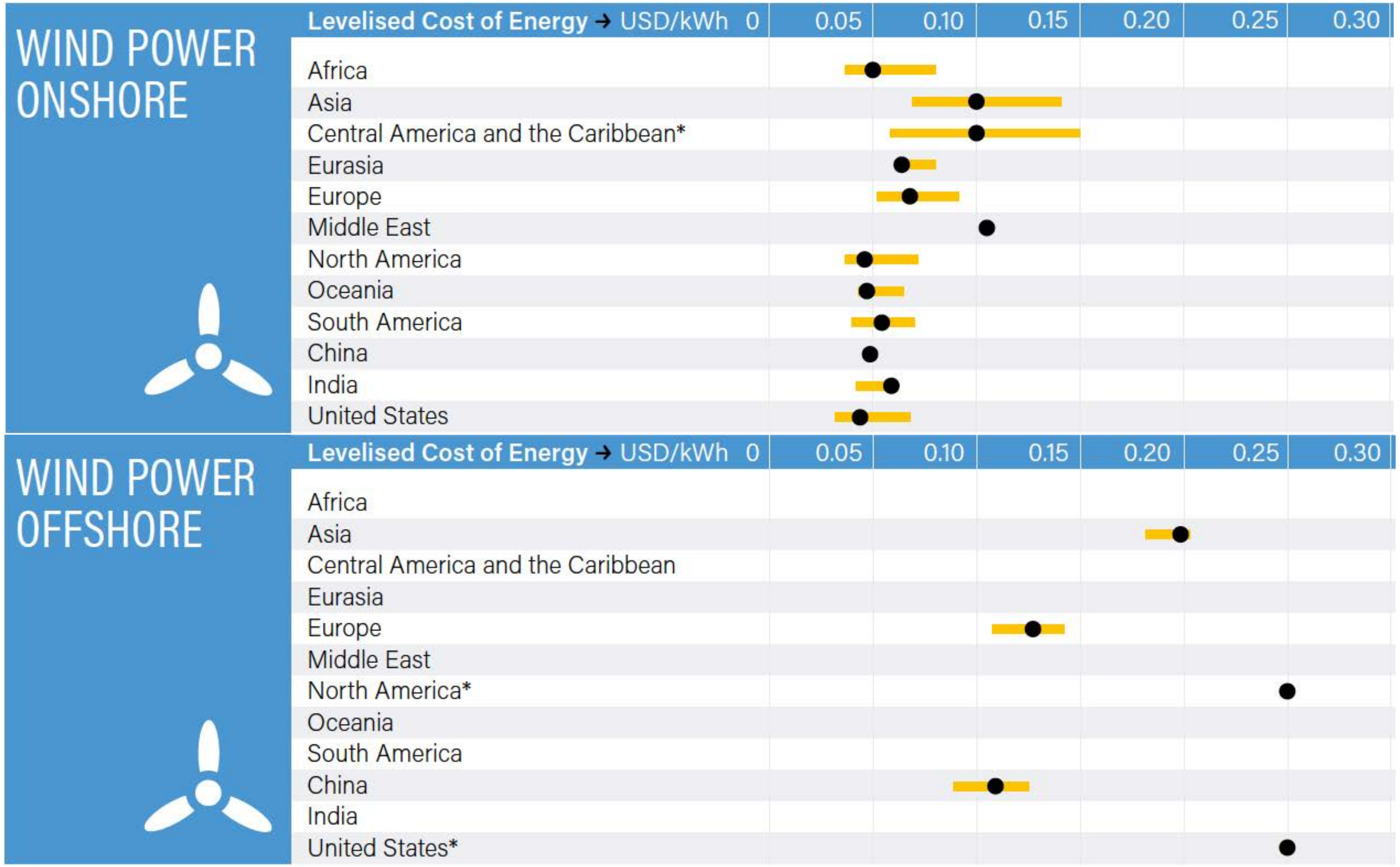


Global Wind Energy Capacity



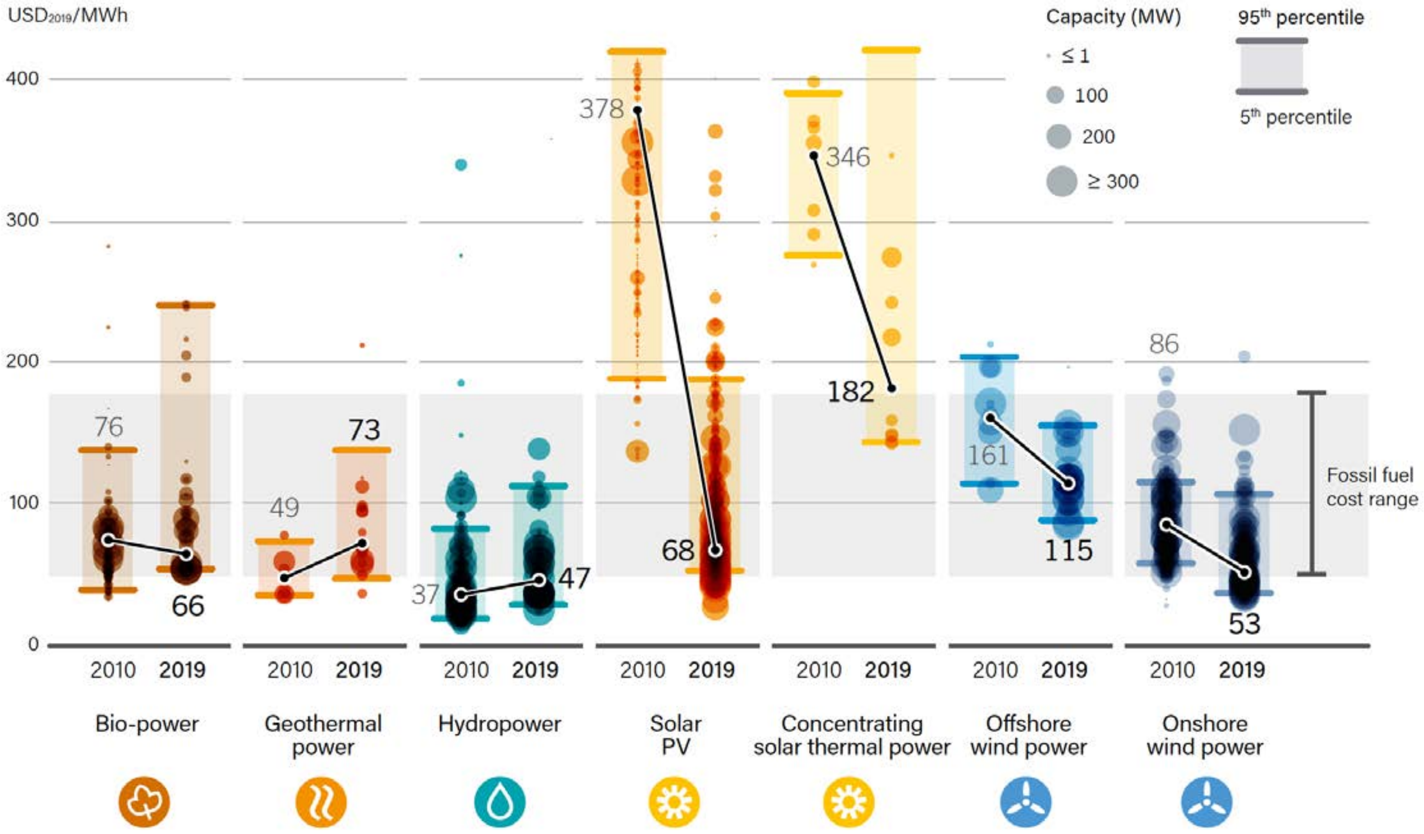
Source: Global Wind Report 2021. GWEC. P. 52

Levelized Cost of Wind Energy



Source: REN21. Renewables 2019. Global Status Report. S. 130

Global Levelized Costs of Electricity from Newly Commissioned, Utility-Scale Renewable Power Generation Technologies 2010 and 2019



Source: REN21. Renewables 2020. Global Status Report. S. 145

Types of hydro power plants

Installed capacity

- Small hydropower plants (< 1 MW)
- medium-sized hydropower plants (1-100 MW)
- Large hydropower plants (> 100 MW)

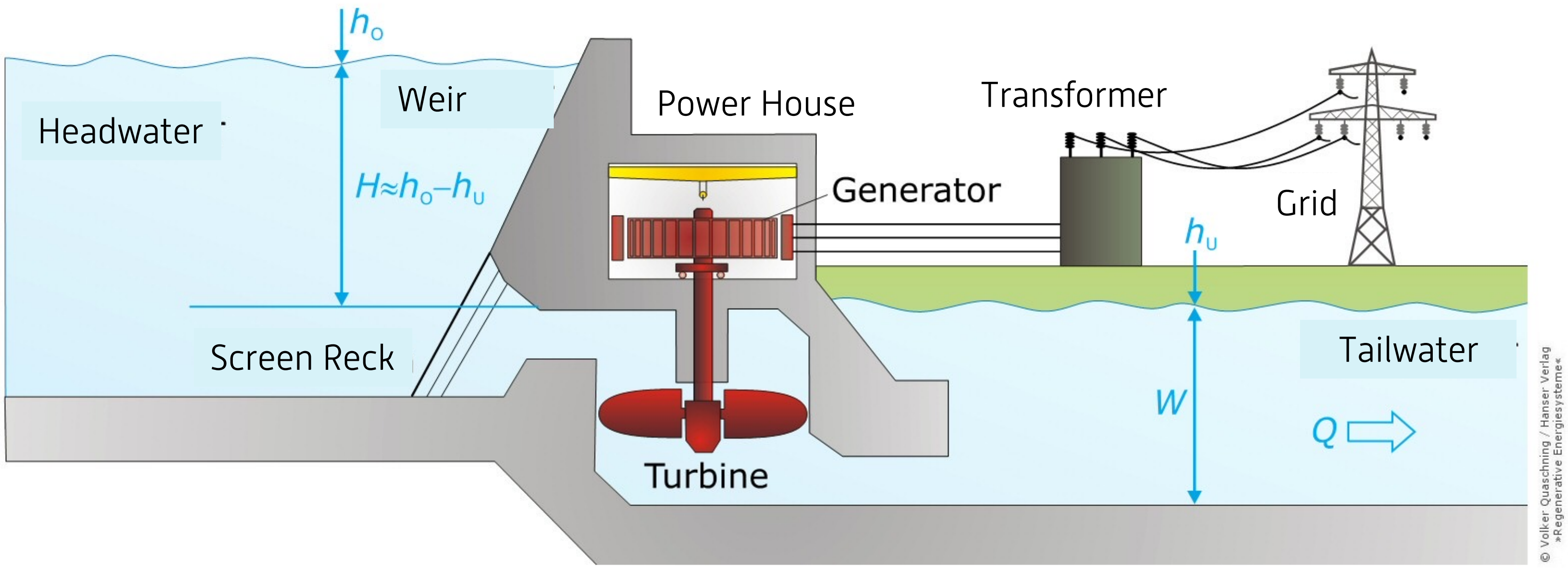
Topography

- Underflow (river power station)
- Mittellauf (running water and storage power station)
- Upper course (storage power station)

Effective head

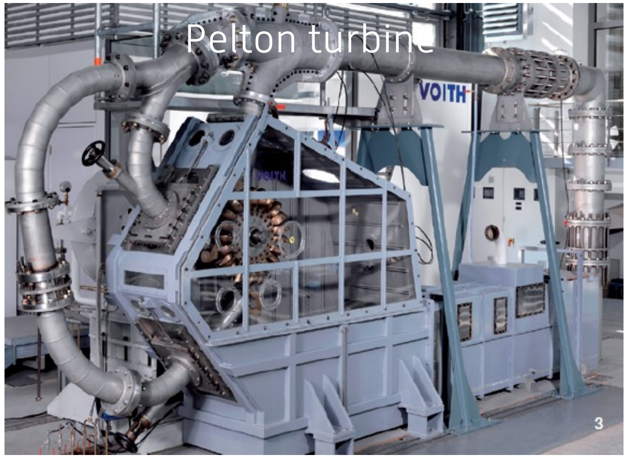
- Low pressure system (drop height < 15 m)
- Medium pressure system (drop height 15-50 m)
- High pressure system (drop height > 50 m)

River Power Plant



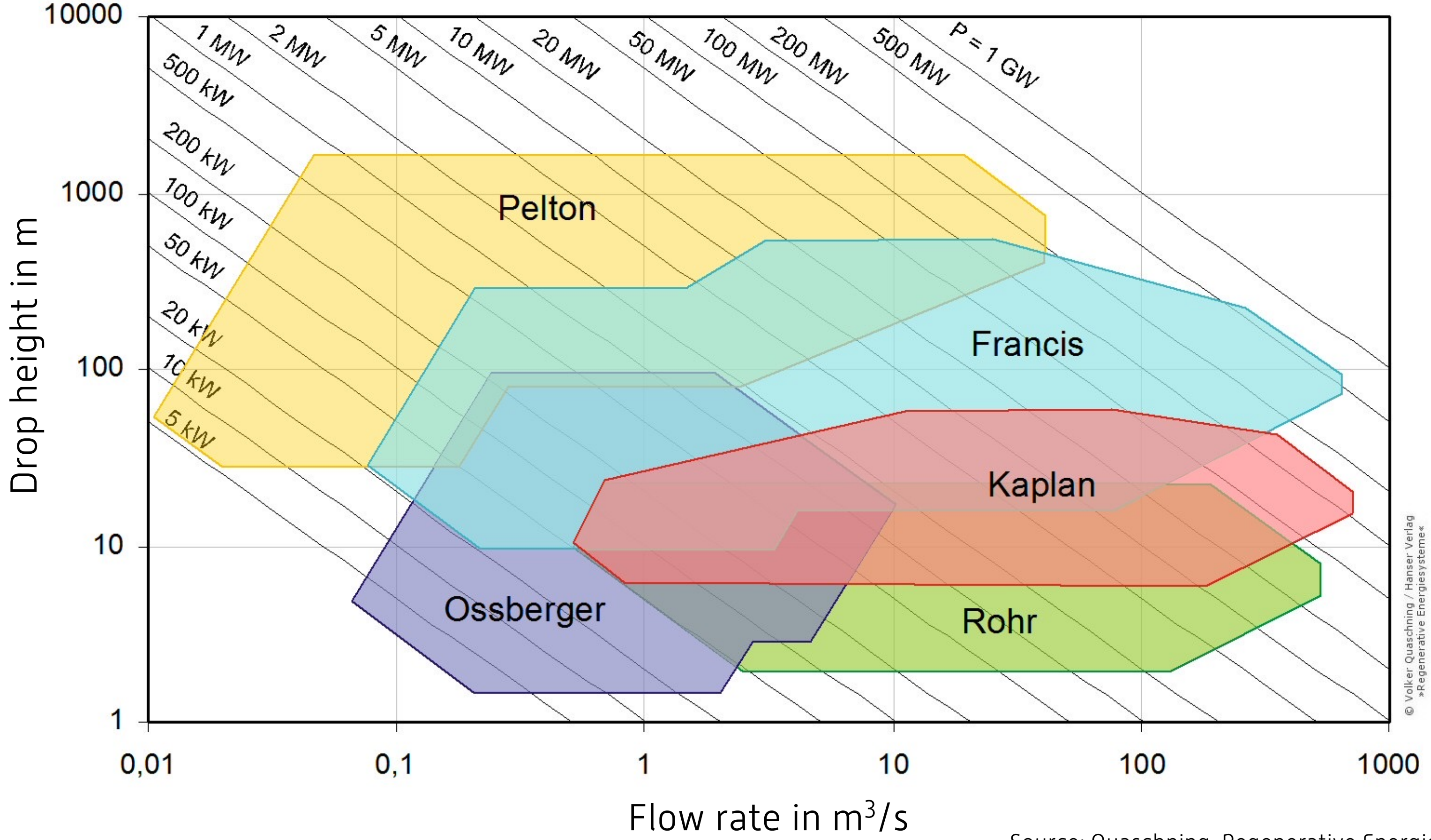
Source: Quaschning. Regenerative Energiesysteme. S. 299

Types of turbines



Source : Voith Siemens Hydro Power Generation, K. Hermann

Efficiency of different turbine types



Source: Quaschning. Regenerative Energiesysteme. S. 305

Power of a run-of-river power plant

Potential Energy $$E_{pot} = m \cdot g \cdot h$$

Density $$\rho = \frac{m}{V} \Rightarrow m = \rho \cdot V$$

$$\Rightarrow E_{pot} = \rho \cdot V \cdot g \cdot h$$

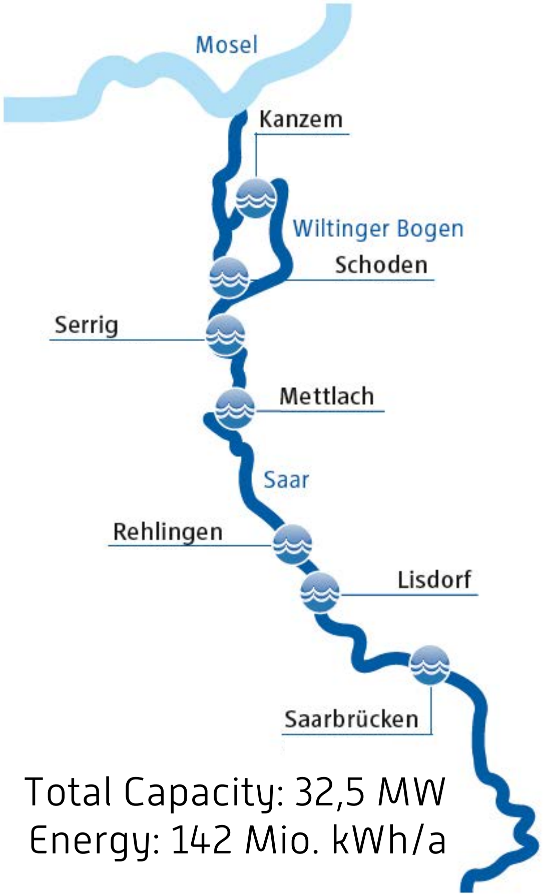
Flow rate $$Q = \frac{\Delta V}{\Delta t}$$

Power $$P = \frac{\Delta E}{\Delta t}$$

$$\Rightarrow P = \rho \cdot g \cdot h \cdot \frac{\Delta V}{\Delta t} = \rho \cdot g \cdot h \cdot Q$$

Total Power $$\Rightarrow P_{ges} = \eta \cdot \rho \cdot g \cdot h \cdot Q$$

Calculation of hydro power capacity at the river Saar



Total Capacity: 32,5 MW
Energy: 142 Mio. kWh/a

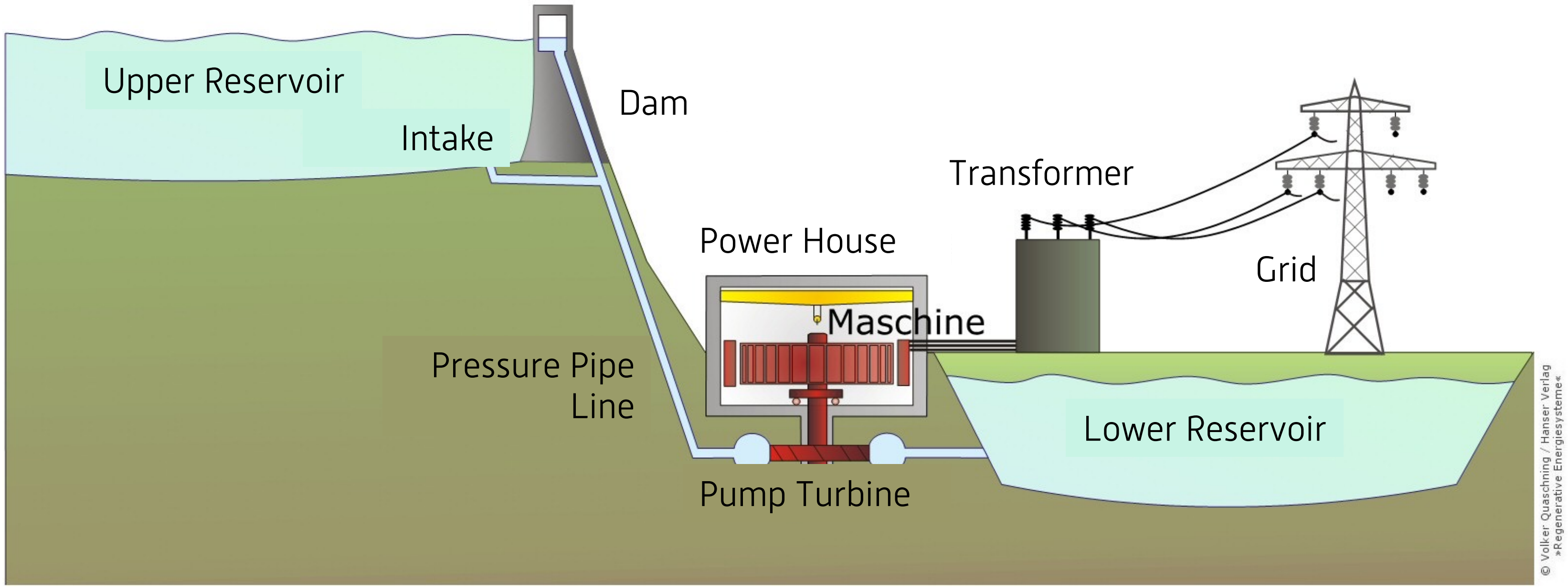
System	Height in m	Maximum flow rate in m^3/s
Kanzem	12 m	21
Schoden	6 m	65
Serrig	14.5 m	93
Mettlach	11 m	65
Rehlingen	8 m	62.5
Lisdorf	4 m	39
Saarbrücken	6 m	41

$$P_{ges} = \eta \cdot \rho \cdot g \cdot h \cdot Q$$

$\eta = 0.9$ $\rho = 1$ kg/l $g = 10$ m/s^2

Mean flow rate = 50 % of maximum flow rate

Pumped-storage hydro power station



Source: Quaschning. Regenerative Energiesysteme. S. 302

Tidal power plants

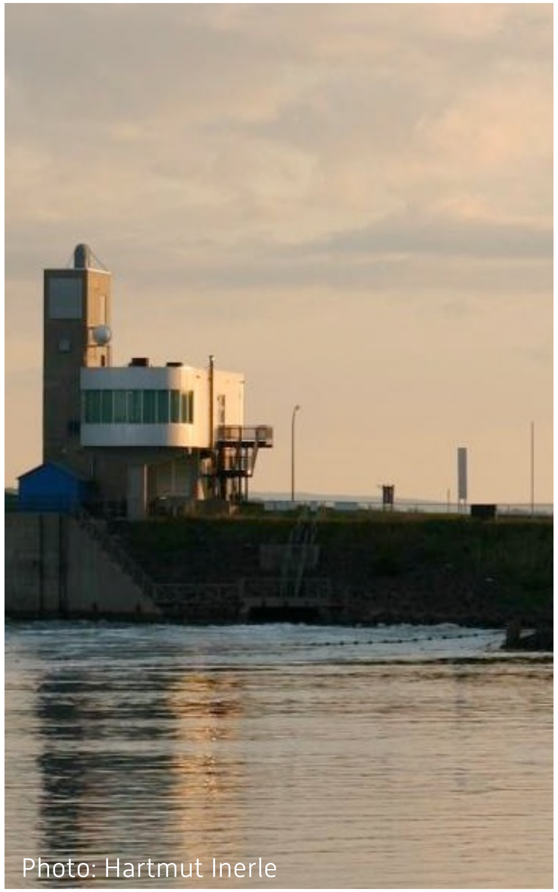


Photo: Hartmut Inerle

- Use of wave energy and conversion into electrical energy
- Separation of a bay in the coastal area with large tidal difference by a dam
- inflow of water into the bay at high tide, outflow at low tide
- Turbine drive
- High investment costs for tidal power plants with comparatively moderate energy yield

Wave power systems

Float systems: Conversion of the wave movement via a float into energy

Chamber systems: Propulsion of a turbine by the air flow in a closed cabin

Theoretical potential worldwide: 0.67 EJ = 186 TWh

Implementation difficult due to technical problems:

- Adaptation to local conditions
- Consideration of storm waves

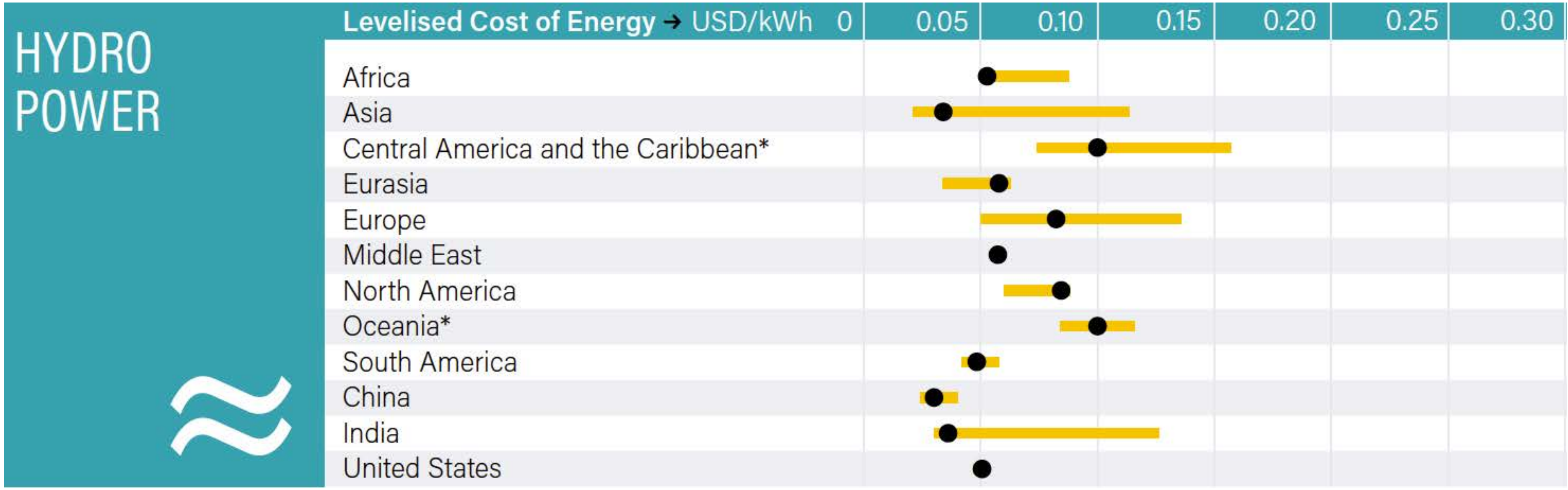
Photo: Lindoe Offshore Renewables Center

Tidal stream power plants

- Functionality comparable with wind power plant
- Conversion of ocean current into rotational energy of a rotor for power generation
- Nowadays an economic operation is possible.
- Application with large tidal range near the coast

Photo: Fundy

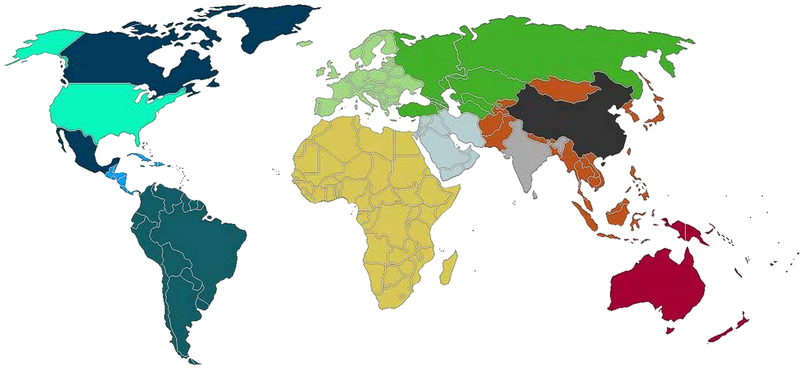
Levelized costs of hydropower



Source: REN21. Global Status Report 2019. P. 130

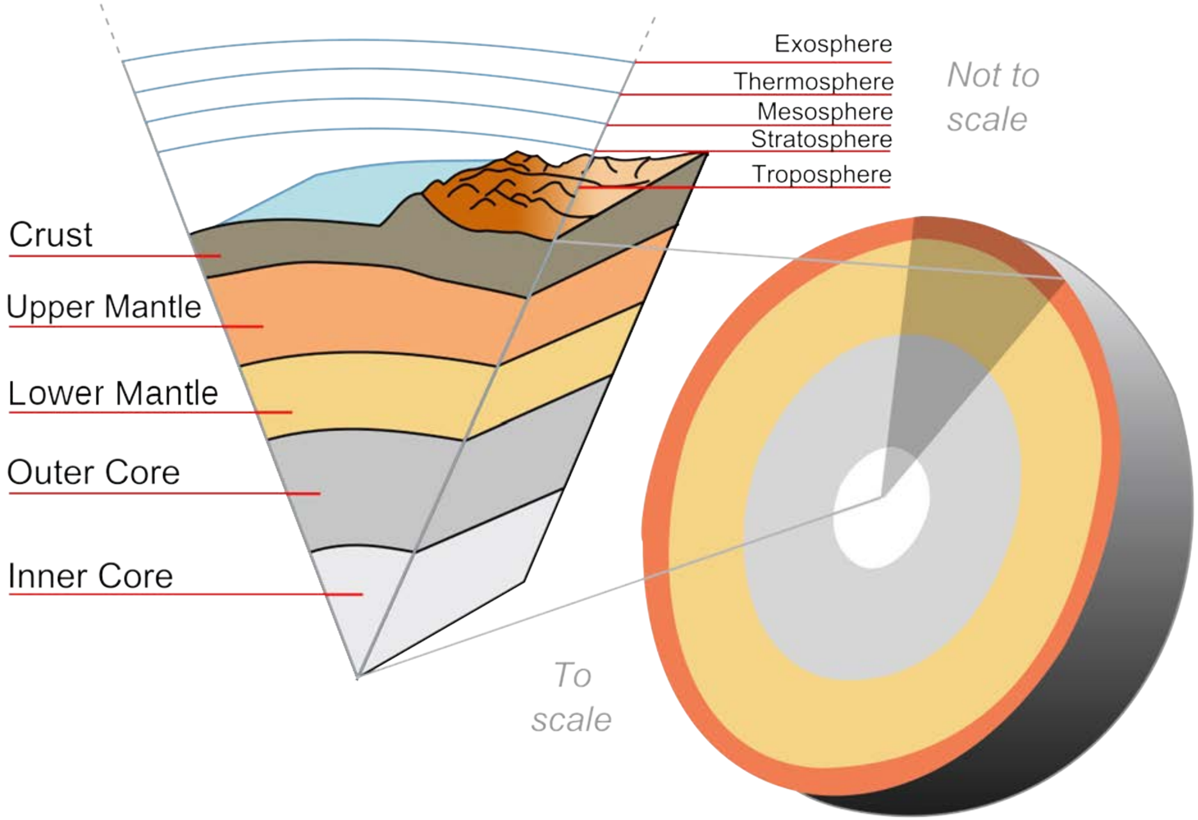
Hydropower: Total investment costs and capacity factor

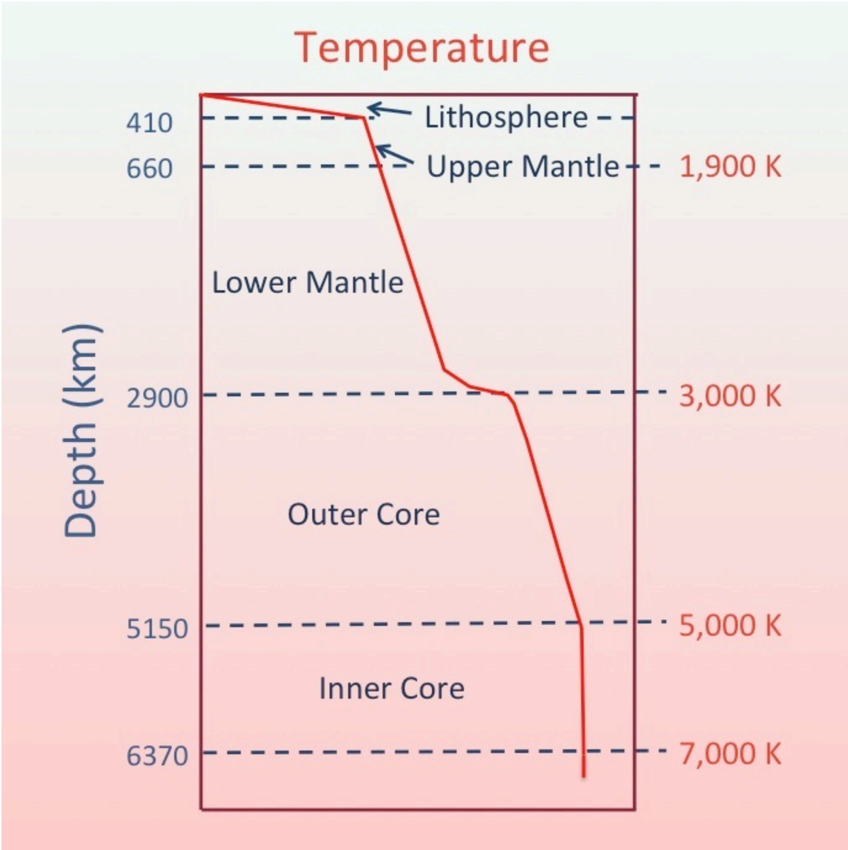
Total Investment Cost → USD/kW	min	max	wa	Capacity Factor →	min	max	wa
Africa	1,937	3,405	2,265		0.47	0.81	0.56
Asia	657	4,540	1,350		0.33	0.64	0.46
Central America and the Caribbean	1,720	4,665	3,549		0.32	0.55	0.53
Eurasia	1,864	2,606	2,462		0.52	0.61	0.53
Europe	877	4,820	1,488		0.16	0.44	0.24
Middle East	1,255	1,255	1,255		0.27	0.27	0.27
North America	3,366	5,843	5,665		0.42	0.73	0.71
Oceania	3,886	3,888	3,888		0.31	0.50	0.45
South America	1,519	2,248	2,029		0.50	0.59	0.53
China	975	1,286	1,184		0.40	0.51	0.49
India	1,105	2,446	1,489		0.28	0.57	0.49
United States	2,232	3,028	2,490		0.54	0.64	0.57



Source: REN21. Global Status Report 2019. P. 131

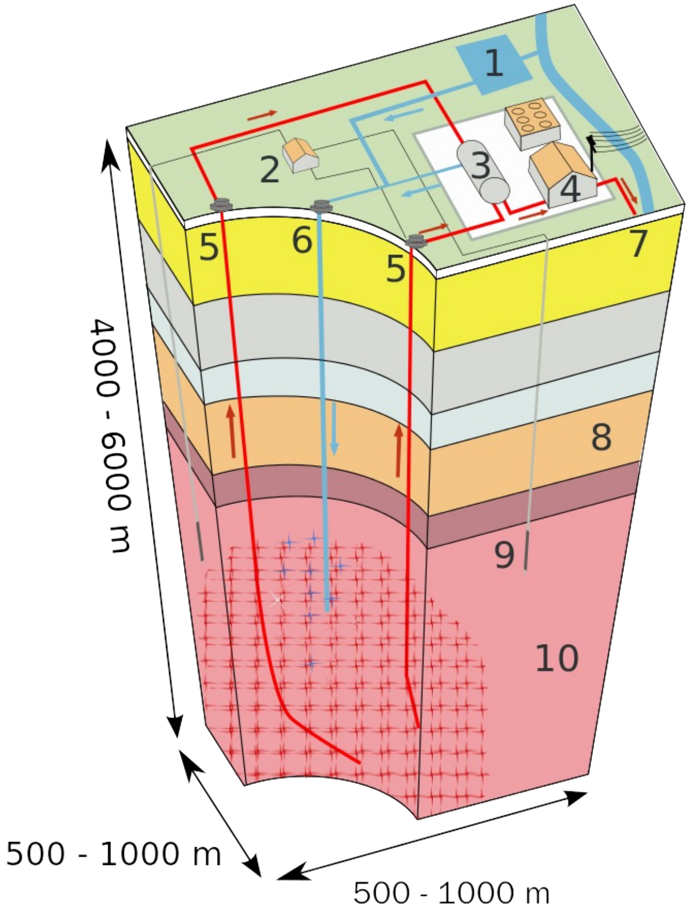
Earth cutaway from core to exosphere





Source: Surachit. Bkilli1. Licence. CC BY-SA 3.0

Geothermal energy plant



1: Reservoir

2: Pump house

3: Heat exchanger

4: Turbine hall

5: Production well

6: Injection well

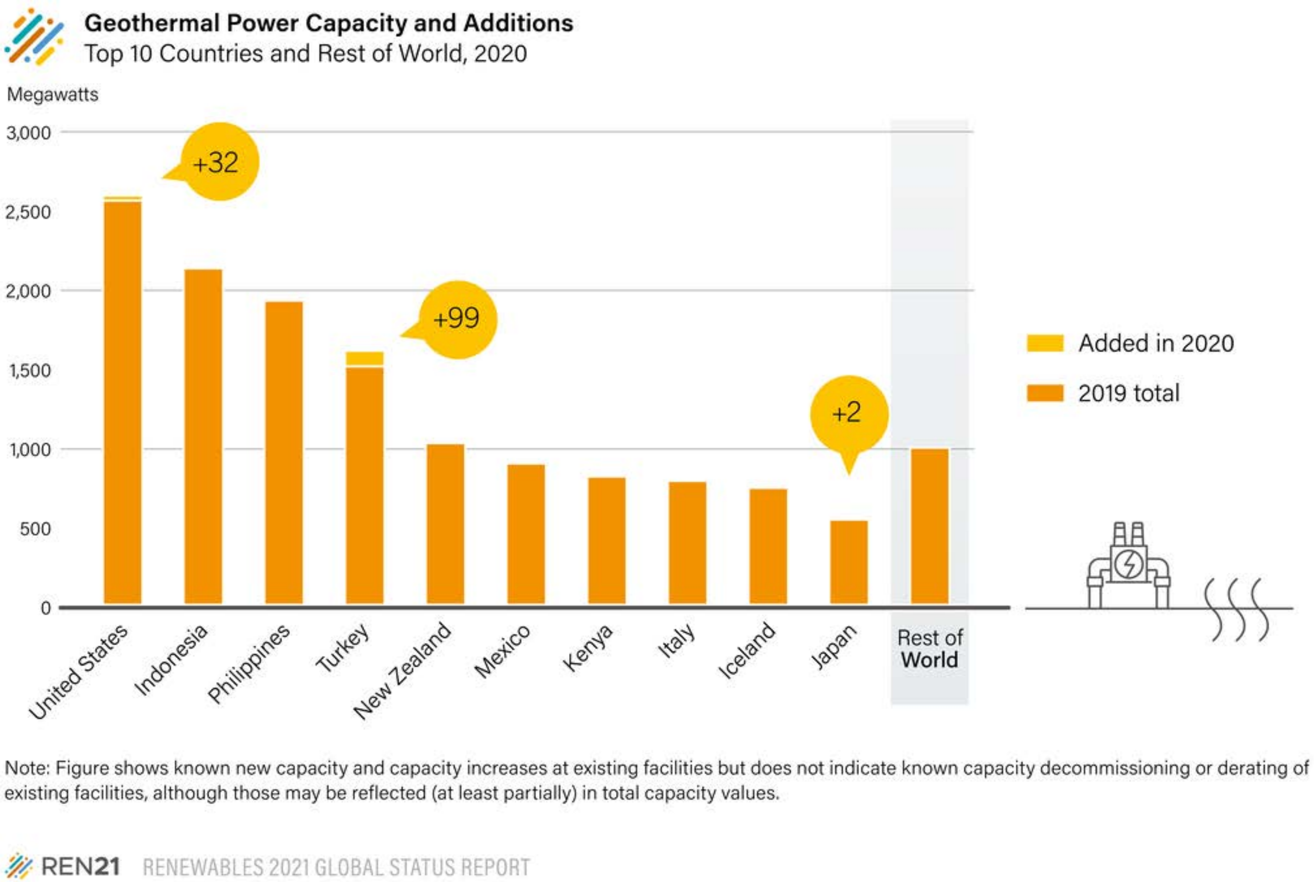
7: Hot water to district heating

8: Porous sediments

9: Observation well

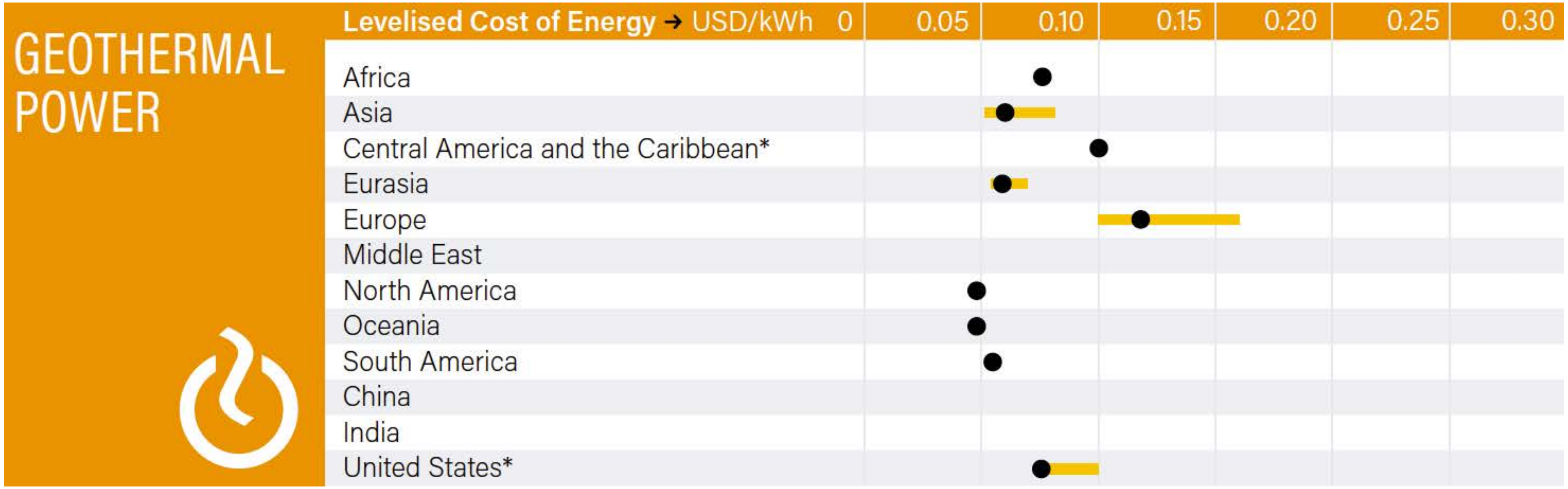
10: Crystalline bedrock

Geothermal power capacity and additions



Source: REN21. Global Status Report 2021

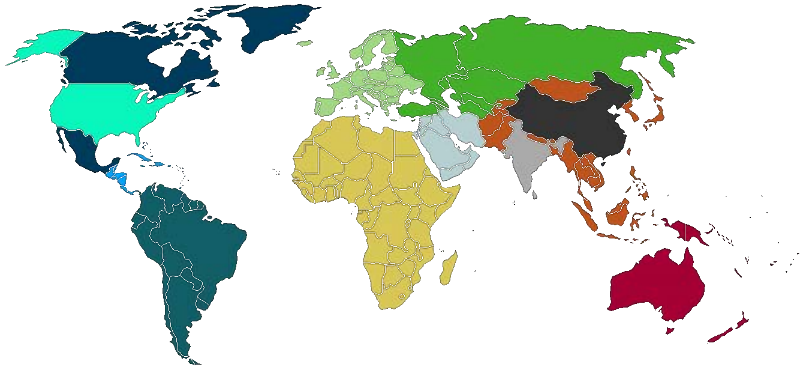
Levelized costs of geothermal power



Source: REN21. Global Status Report 2019. P. 130

Geothermal power: Total investment costs and capacity factor

Total Investment Cost → USD/kW	min	max	wa	Capacity Factor →	min	max	wa
Africa	4,612	4,612	4,612		0.80	0.80	0.80
Asia	3,045	5,150	3,612		0.64	0.89	0.83
Central America and the Caribbean	3,688	3,688	3,688		0.57	0.57	0.57
Eurasia	4,507	4,869	4,793		0.77	0.98	0.92
Europe	5,142	10,599	7,192		0.72	0.75	0.74
Middle East							
North America	3,833	3,833	3,833		0.91	0.91	0.91
Oceania	3,794	3,794	3,794		0.90	0.90	0.90
South America	3,140	3,140	3,140		0.80	0.80	0.80
China							
India							
United States	5,382	7,007	5,555		0.80	0.80	0.80



Source: REN21. Global Status Report 2019. P. 131

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ZIW e.V.
Center for Innovation
and Further Education

Trier University of Applied Sciences
HOCHSCHULE TRIER

Bender-IS

Contact Information:
Name: Prof. Dr. Henrik te Heesen
Mail: h.teheesen@umwelt-campus.de
Web: www.umwelt-campus.de/hteheesen
Course: https://www.umwelt-campus.de/en/hteheesen/tebm