Thermal Turbo Machines I
1. Basics

Winter Semester 2021/2021

Institut für Thermische Strömungsmaschinen
Prof. Dr.-Ing. Hans-Jörg Bauer

1.1 Turbo Machines: Definition & Historical Retrospection

- Characteristics of a thermal turbo machine
  - Conversion of thermal energy (enthalpy) to mechanical energy ("Power Engine") or vice-versa ("Working Engine")
  - Energy conversion conducted in a rotor
  - Stator casing equipped with guide vanes
- Turbine:
  - "Power Engine": drives e.g. generator or compressor
  - Energy taken from fluid – transferred to rotor
  - Pressure, temperature, density decrease – compressibility
- Compressor:
  - "Working Engine": driven by an engine (electric motor, turbine etc.)
  - Task: to increase fluid pressure
  - Temperature increase is side effect (via compressibility & losses) rather than main intent
- Difference to a „hydraulic" turbo machine
  - Compressible fluid <u>and</u> high pressure ratio (ρ, $T \neq$ const.)

Comparison Steam Turbine vs Gas Turbine

	Steam Turbine	Gas Turbine
Max. pressure of working fluid	280 bar	24 / 32 / 50 bar
Max. Temp. of working fluid	850 / 870 K	1.600 K (stationary) 1.900 K (jet engines)
Pressure after expansion	~ 0,03 bar	1 bar
Temperature after expansion	~ 300 K	~ 800 K (953 K)
Maximum power	~ 1.600 MW (nuclear) ~ 950 MW (fossil)	567 MW (50 Hz) 388 MW (60 Hz)
Enthalpy head (turbine)	~ 1.500 – 2.500 kJ/kg	~ 800 – 1.100 kJ/kg
Number of turbine stages	20 - 40	4 – 6
Thermal efficiency (power plant)	> 47 % (max)	42,6 % (max)
Thermal efficiency (CC)	> 63% (? max)	
Ratio of specific volumes	~ 4.000	~ 6 - 12

Historical Retrospection

Year	Event / Introduction
Ca. 120 v. Chr.	Heron‘s Ball: First idea of a „thermal turbo machine“ technical toy / cultic object

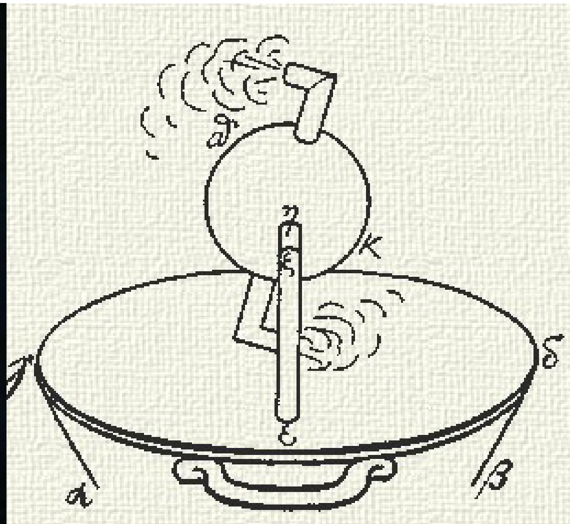


Fig. 56 a.

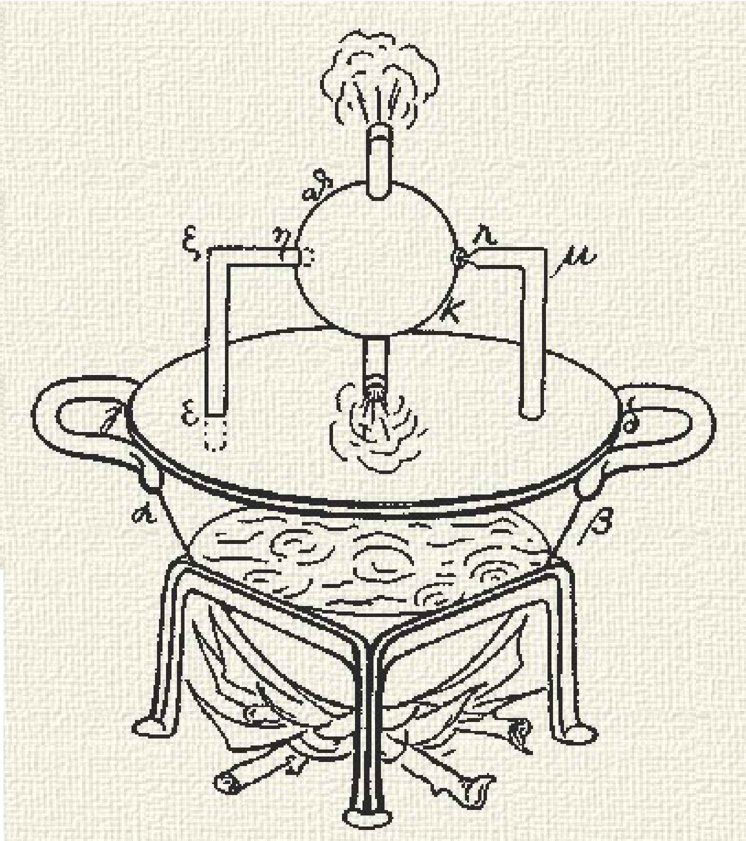
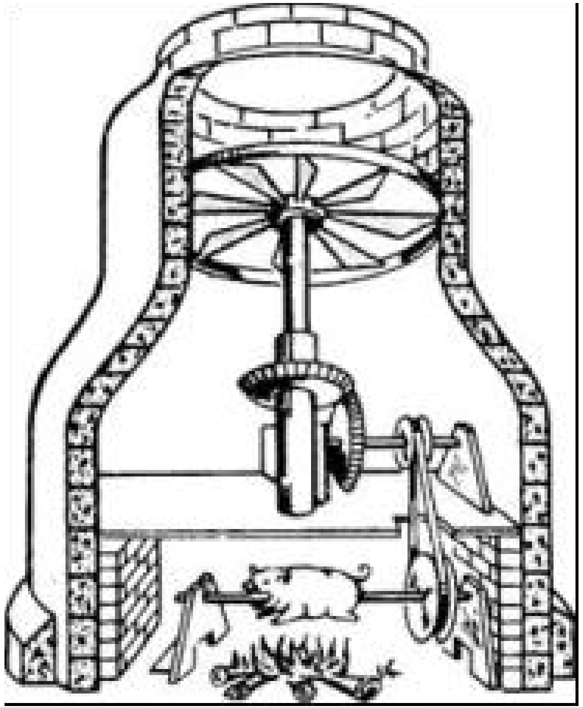


Fig. 55.

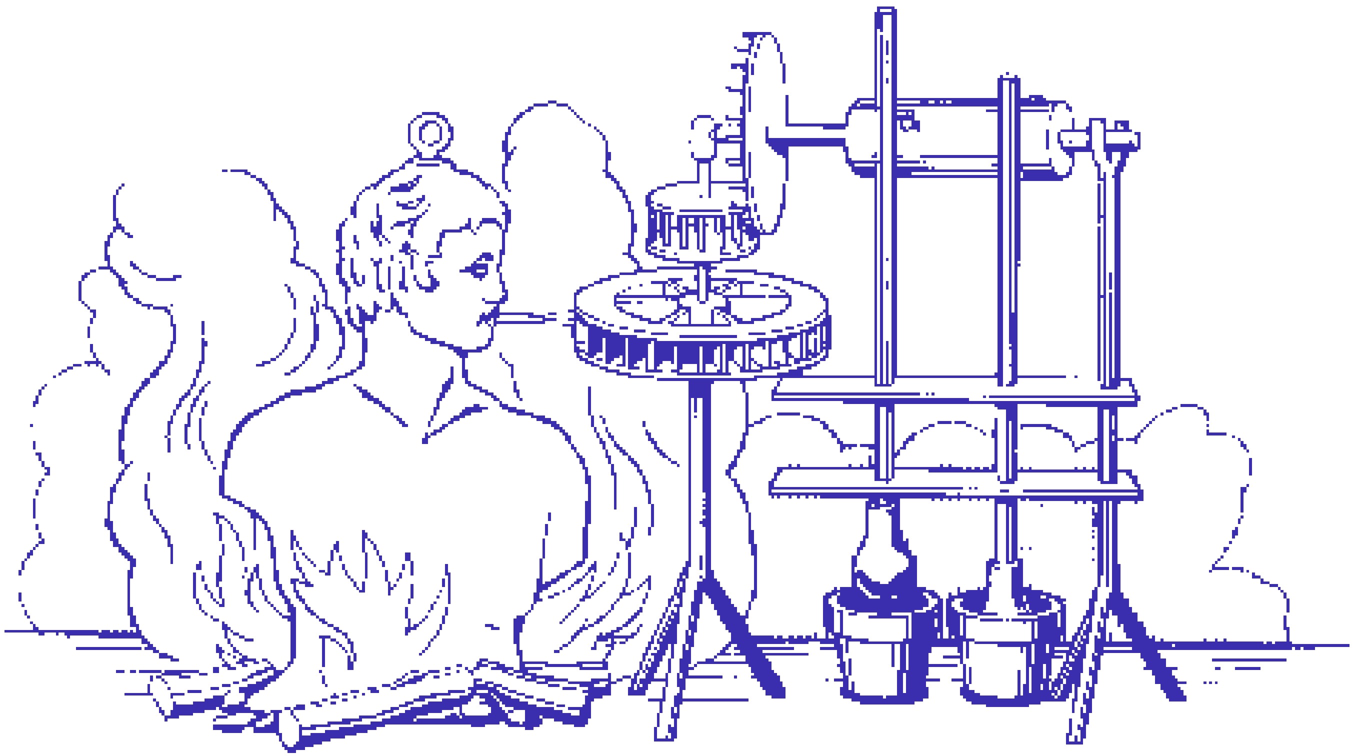
Historical Retrospection

Year	Event / Introduction
Ca. 700	Windmills with vertical axes in Persia
Ca. 1200	Windmills with horizontal axes, probably arabian origin
Ca. 1300	Firework rockets in China
Ca. 1500	Leonardo da Vinci: „Chimney Jack“ – Sketch of a turbine driven by hot ascending gases



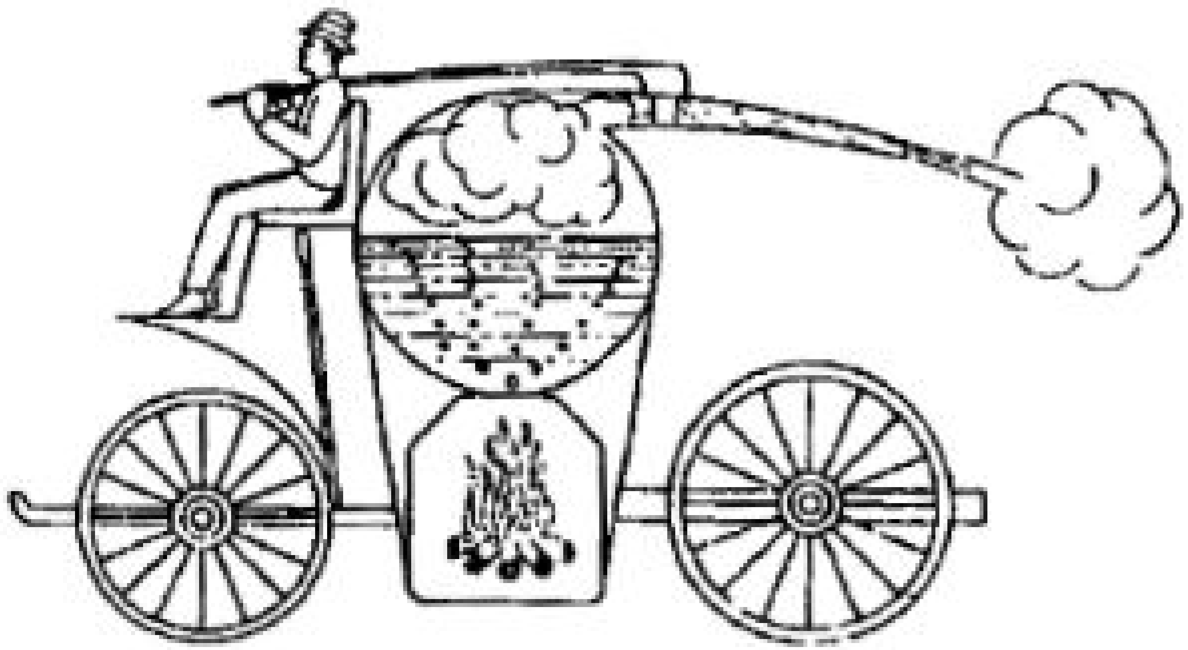
Historical Retrospection

Year	Event / Introduction
1629	Giovanni Branca: sketch of an impulse turbine

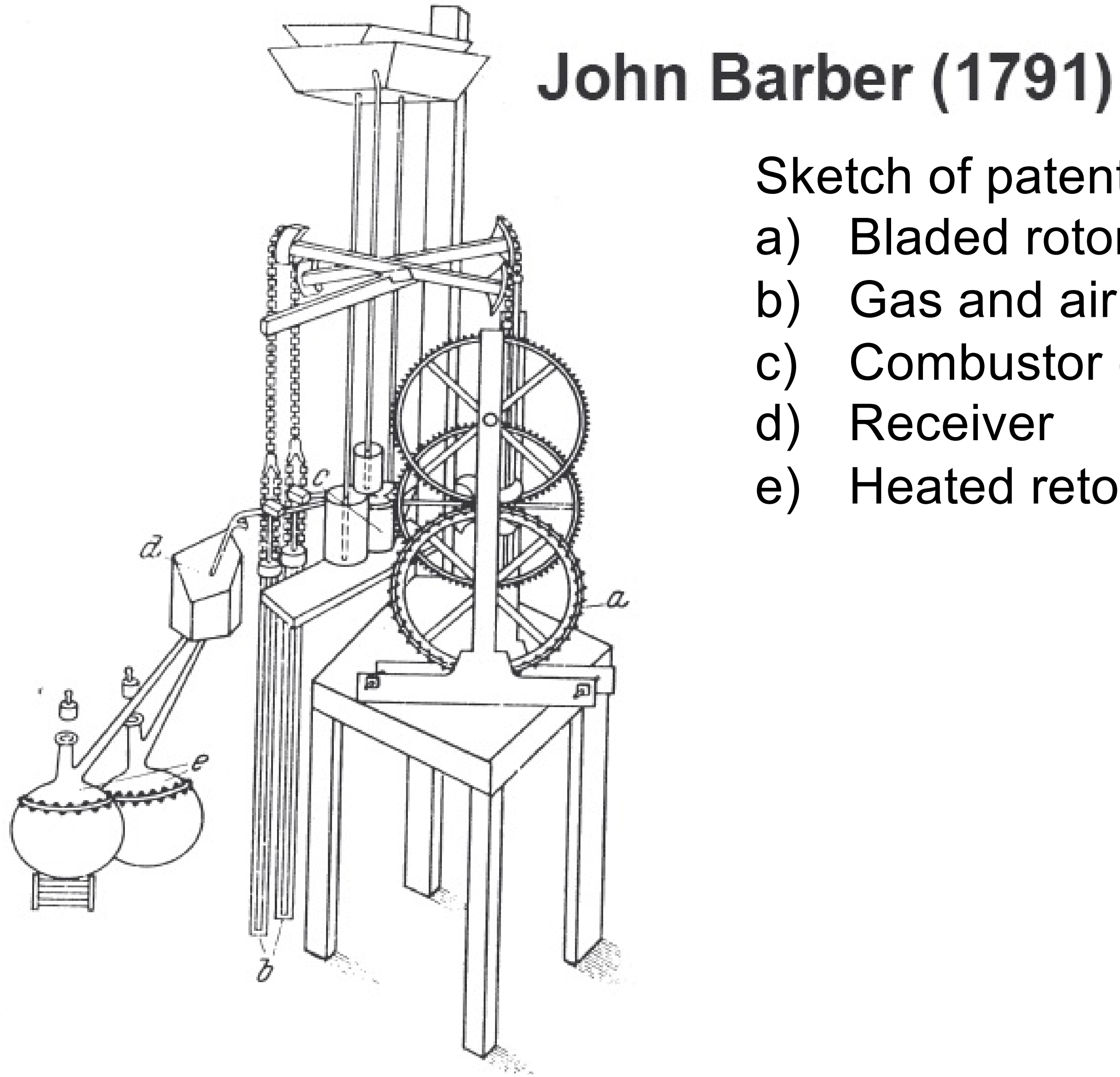


Historical Retrospection

Year	Event / Introduction
1687	Isaac Newton: Formulation of the principle of linear momentum, idea of a steam car



Patent for a „Gas Turbine Device“

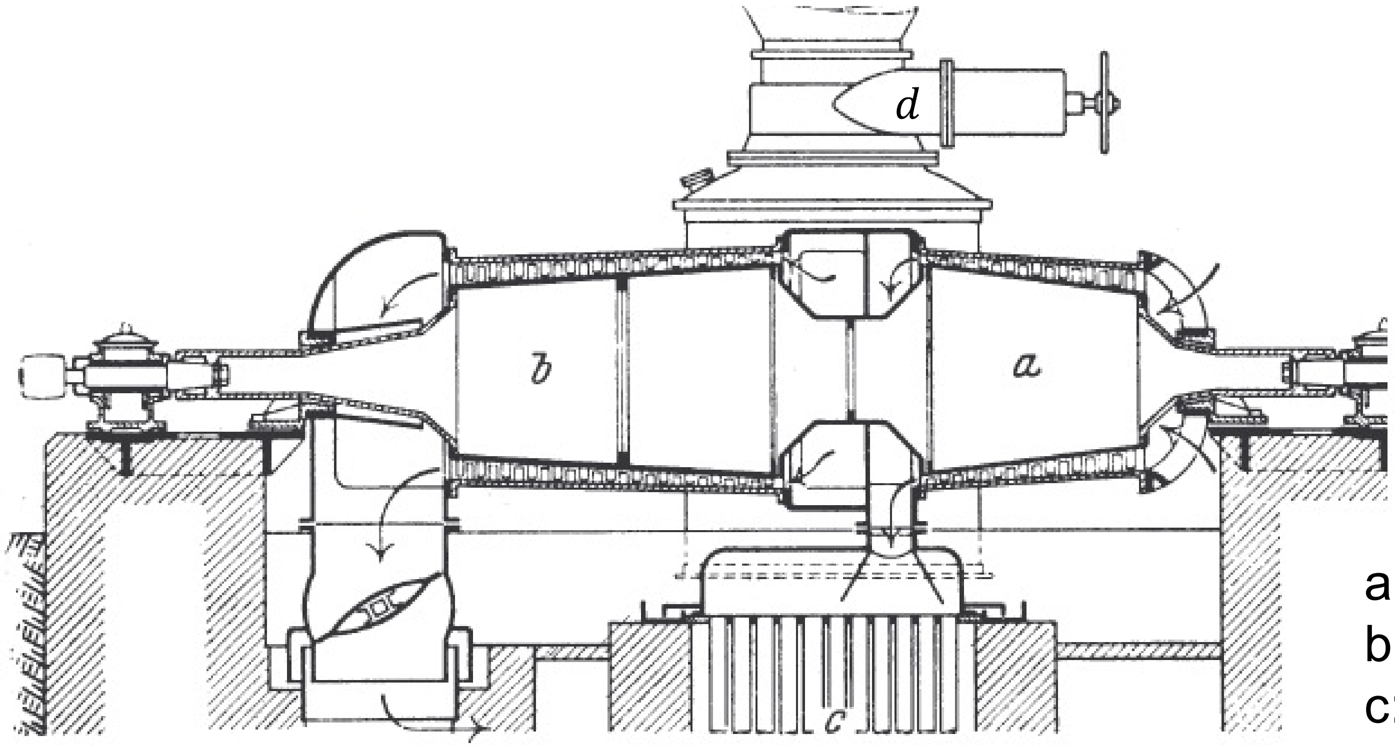


Sketch of patent application:

a) Bladed rotor
b) Gas and air compressor
c) Combustor (exploder)
d) Receiver
e) Heated retorts for gas generation

Historical Retrospection

Year	Event / Introduction
1824	Nicolas Carnot: ideal thermodynamic process
1874	Franz Stolze: Patent of a gas turbine arrangement with axial compressor and turbine (testet in 1900)



a: Axial compressor
b: Axial turbine
c: Heat exchanger
d: Combustor

Historical Retrospection

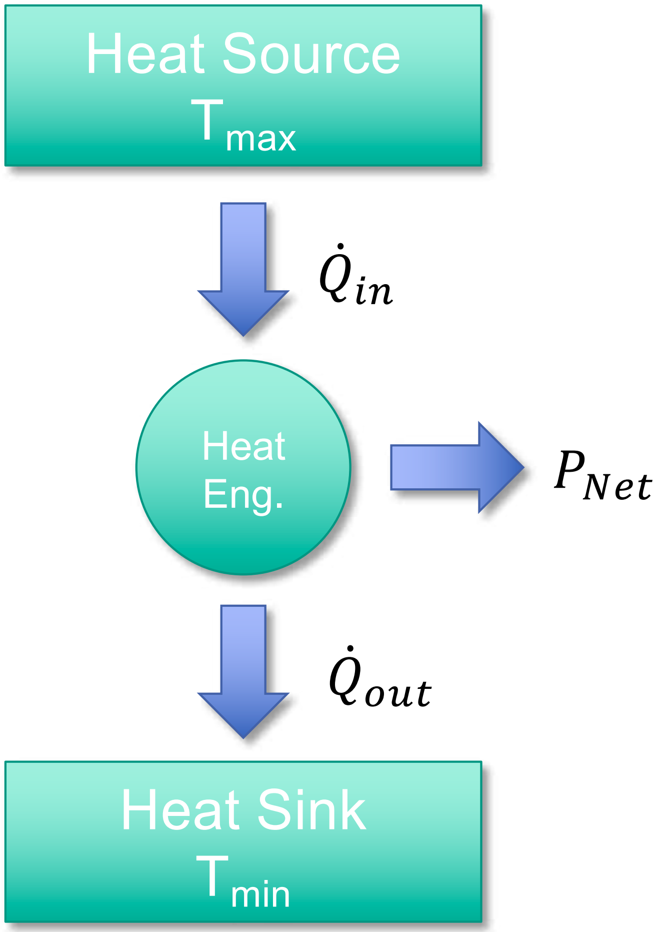
Jahr	Event / Introduction
1883/84	Carl Gustav Patrik de Laval: impulse turbine Charles Parsons: reaction turbine
1898	Armengaud Brothers: Operation of first gas turbine
1900	Charles Gordon Curtis: Turbine with velocity staging
1905	A. Bürchi: Turbo charger patent
1908	Hans Holzwarth: Gas turbine with constant volume combustion
1913	René Laurin: Patent for ram jet engine
1930	Frank Whittle: Patent application for a turbo jet engine
27.8.1939	First jet powered flight, Heinkel He-178, engine designer: Hans Joachim Pabst v. Ohain
1947	First ship with gas turbine propulsion
1950	First car with gas turbine (Rover) - demonstrator
1969	Concorde: first supersonic civil aircraft

Structure of TT I:

- Thermodynamic idea (overall concept)
  - Entire Plant / Device
    - Machine, e.g. turbine
      - Stage
        - Cascade

1.2 Thermodynamic Considerations

- Principle: conversion of thermal energy in mechanical energy utilising a thermodynamic cycle



Heat input at high temperature

- Questions:
  - Thermal efficiency/ Options to increase η
  - Specific power
  - Basic thermodynamic requirements
  - Technical feasibility
  - Economical feasibility

Heat output at low temperature

Thermodynamic Properties (Steady Processes)

Property	total	specific
Work	W	$w = \frac{W}{m}$
Power	P	$w = \frac{P}{\dot{m}}$
Enthalpy	$H = U + p \cdot V$	$h = \frac{H}{m} = u + p \cdot v$
Heat	Q	$q = \frac{Q}{m}$
Enthalpy flux	$\dot{H} = \dot{U} + p \cdot \dot{V}$	$\frac{\dot{H}}{\dot{m}} = \frac{H}{m} = h$
Heat flux	$\dot{Q}$	$\frac{\dot{Q}}{\dot{m}} = \frac{Q}{m} = q$

Rem.: for heat transfer considerations $\dot{q}$ is usually defined as area specific heat flux $\dot{q} = \frac{\dot{Q}}{A}$

(Specific) Power and Thermal Efficiency of a Heat Engine

Power derived from the first principle of thermodynamics:

$$\boxed{|P| = \dot{Q}_{in} - \dot{Q}_{out}}$$

or specific

$$\boxed{|w| = q_{in} - q_{out}}$$

Thermal Efficiency:

$$\boxed{\eta_{th} = \frac{P_N}{\dot{Q}_{in}} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}}$$

or specific:

$$\boxed{\eta_{th} = \frac{w_N}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}}$$

Illustration in T,S-Diagram 1/2

- Changes of state within thermodynamic cycle in T,S diagram
  - Added or released heat (-fluxes) depicted as areas
    - dS > 0 : heat input
    - dS < 0 : heat output

For reversible heat transfer:

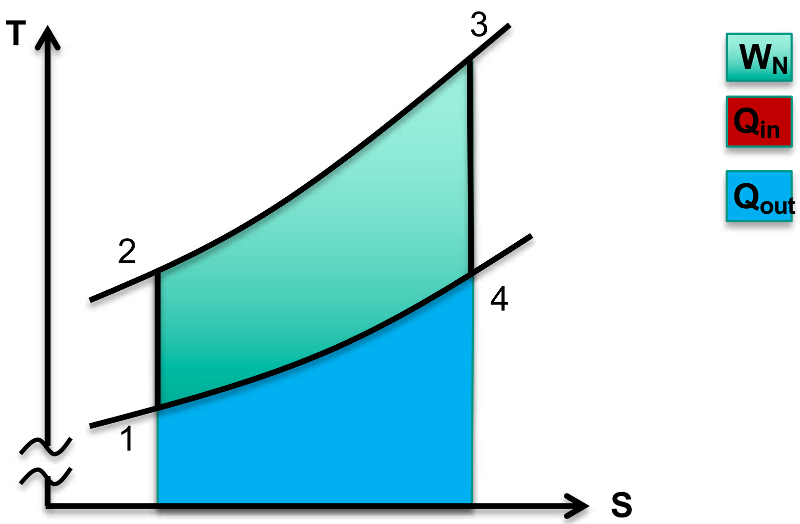
$$\boxed{T \cdot dS = dQ}$$

Integration yields:

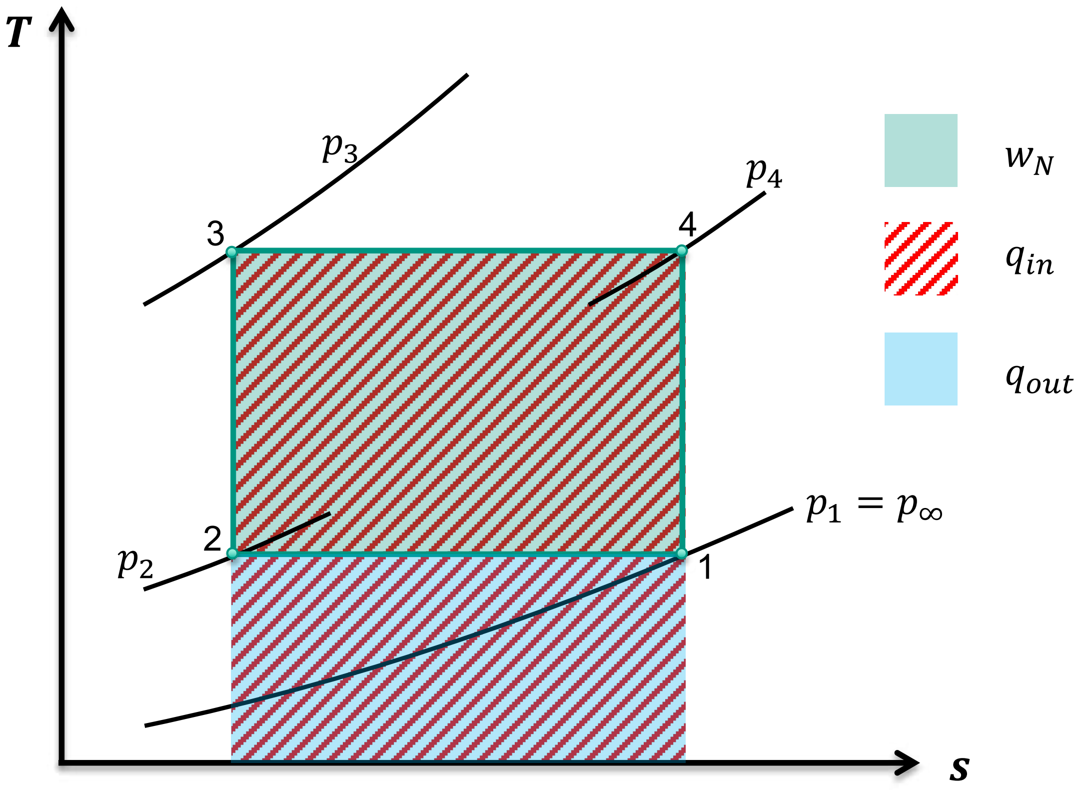
$$\boxed{\int_{S_1}^{S_2} T(S) \cdot dS = Q}$$

Illustration in T,S-Diagram 2/2

- Illustration of losses during changes of state
  - E.g. compression in compressor, expansion in turbine
  - dS = 0 : ideal, inviscid, adiabatic change of state (reversible, adiabatic => isentropic)
  - dS > 0 : change of state with losses (irreversible)
- For reversible changes of state only:
  - Confined area in T,S diagram corresponds to net work (power) of thermodynamic cycle
  - For all processes (including irreversible) the 1. law of thermodynamics yields:
    - Net work corresponds to difference of the areas Q_{in} and Q_{out}.



The Carnot Cycle - T,s- Diagramm



$1 \rightarrow 2$:	isothermal compression
$2 \rightarrow 3$:	isentropic compression
$3 \rightarrow 4$:	isothermal expansion
$4 \rightarrow 5$:	isentropic expansion

Carnot Cycle: Thermal Efficiency 1/2

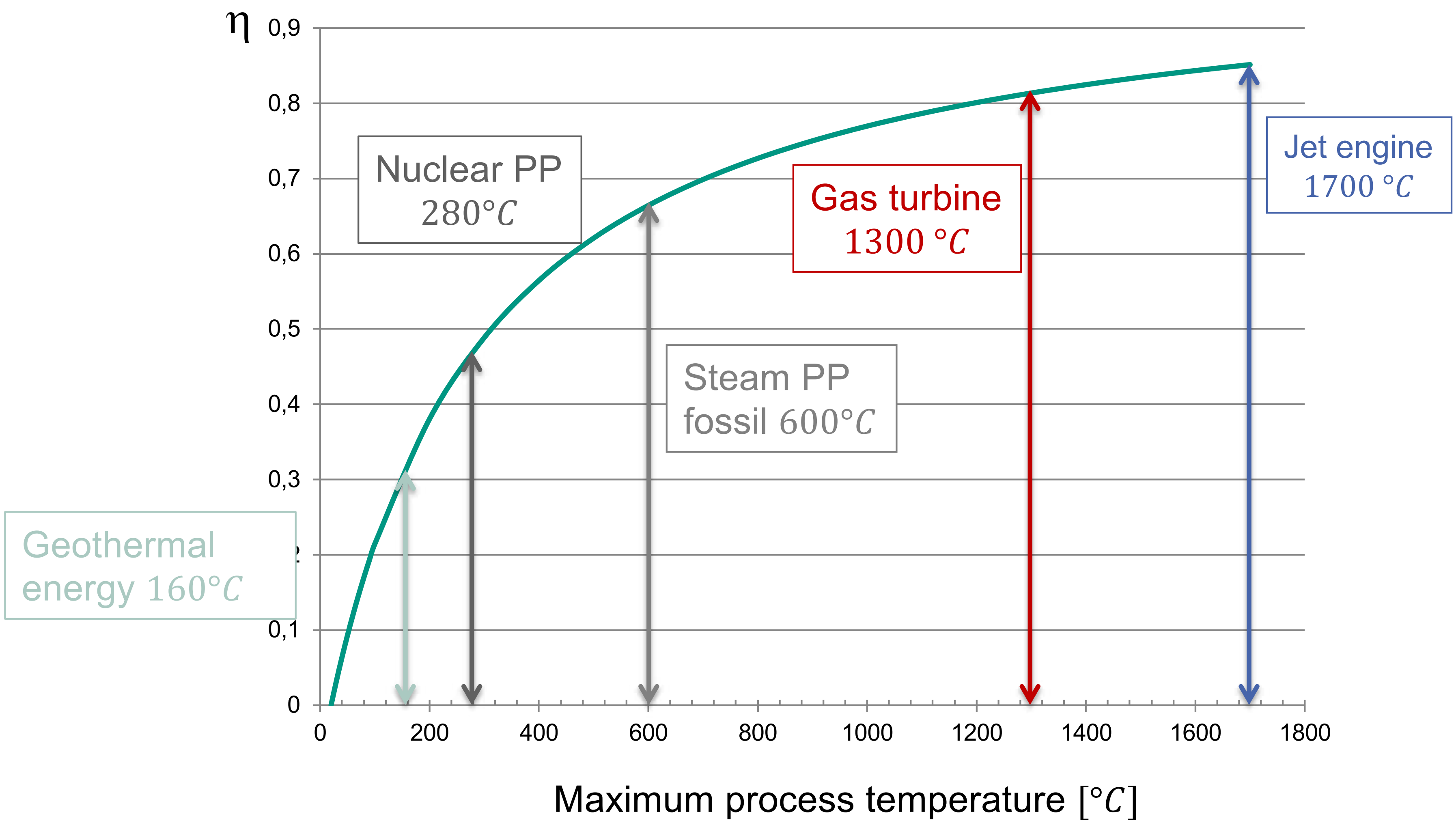
$$|q_{in}| = \left| \int_3^4 T_{max} \cdot ds \right| = T_{max}(s_4 - s_3) = T_{max} \cdot \Delta s$$

$$|q_{out}| = \left| \int_1^2 T_{min} \cdot ds \right| = T_{min}(s_1 - s_2) = T_{min} \cdot \Delta s$$

$$\boxed{\eta_{th,Carnot} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_{min}}{T_{max}}}$$

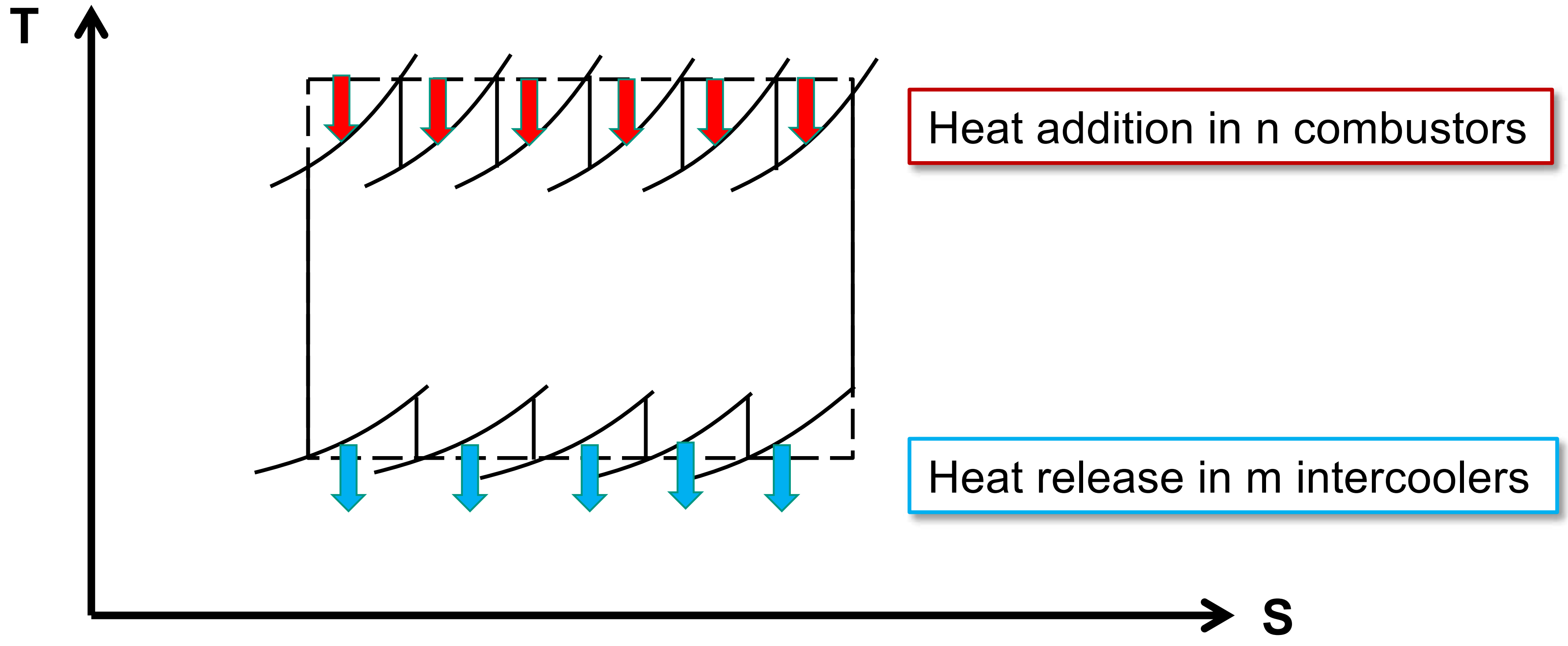
- Highest thermal efficiency for given temperature levels
- Increase of efficiency
  - Decrease of T_{min} (Ambient T !)
  - Increase of T_{max}
- Technical implementation (design)
  - Isothermal expansion/compression difficult to realise
  - In turbo machines heat addition/release at constant pressure
- Carnot cycle: ideal reference cycle

Carnot Cycle: Thermal Efficiency 2/2
Efficiency Potential at $20°C$ Ambient Temperature



Carnot Cycle: Technical Realisation / Approximation

- Approximation of
  - Isothermal expansion: multiple isobaric heat addition (reheat)
  - Isothermal compression: multiple isobaric intercooling

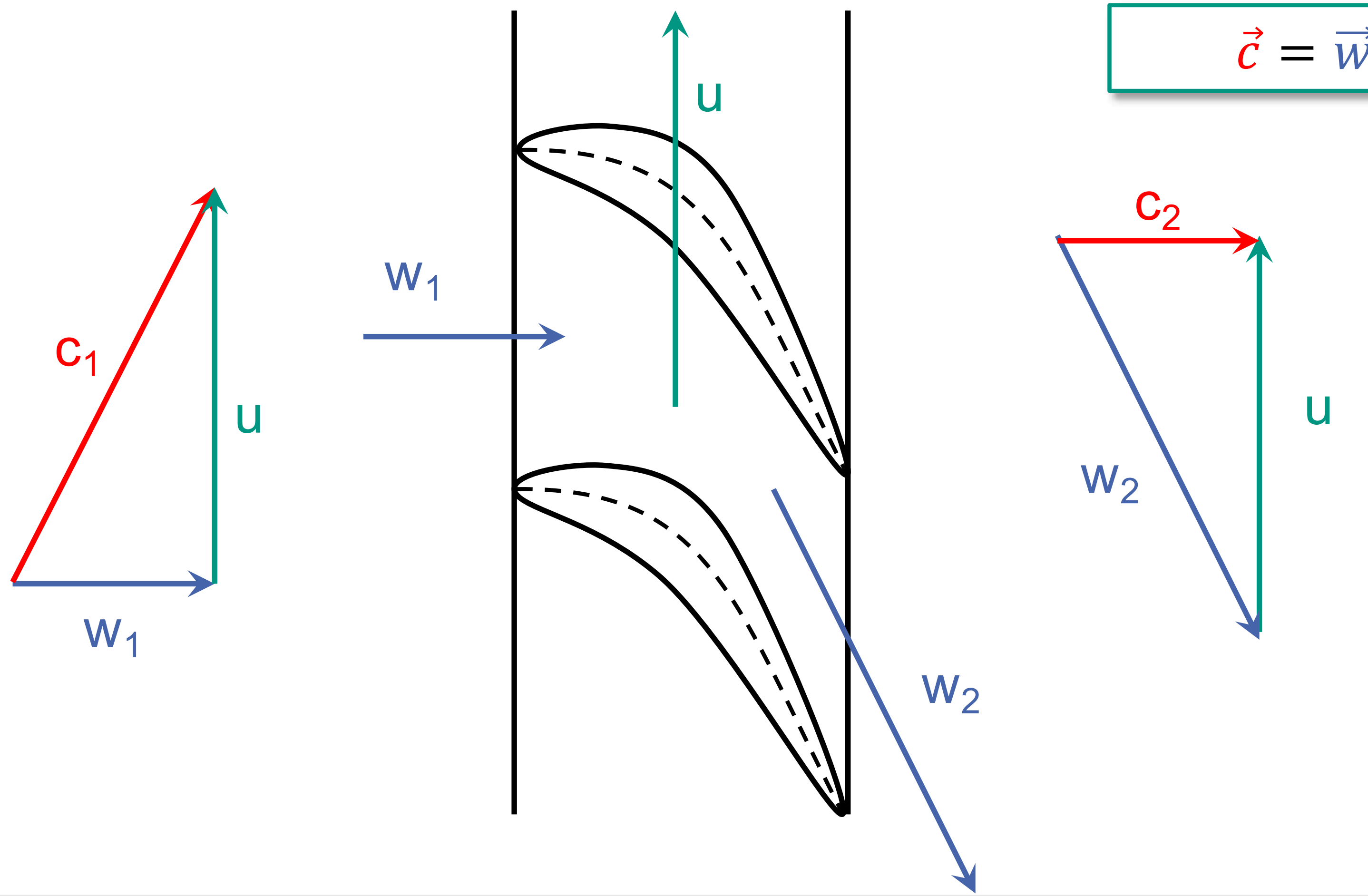


1.3 Fluid Mechanical Principle

Turbine: enthalpy → mechanical energy

Example: Rotor cascade of an axial turbine

$$\vec{c} = \vec{w} + \vec{u}$$



Energy conversion in turbines and compressors (per stage)

Turbine:

Thermal energy (Enthalpy)

↓ Acceleration

Kinetic energy

↓ Momentum exchange

Mechanical energy

Compressor:

Mechanical energy

↓ Momentum exchange

Kinetic energy

↓ Deceleration

Thermal energy / Pressure increase

Principle of Linear Momentum

Basic principle for the calculation of energy conversion:

$$\boxed{\sum \vec{F} = \frac{d\vec{I}}{dt} = \underbrace{\frac{\partial}{\partial t}\iiint_V \varrho \cdot \vec{v} \cdot dV}_{unsteady} + \underbrace{\iint_A \varrho \cdot \vec{v} \cdot (\vec{v} \cdot \vec{n}) dA}_{steady}}$$

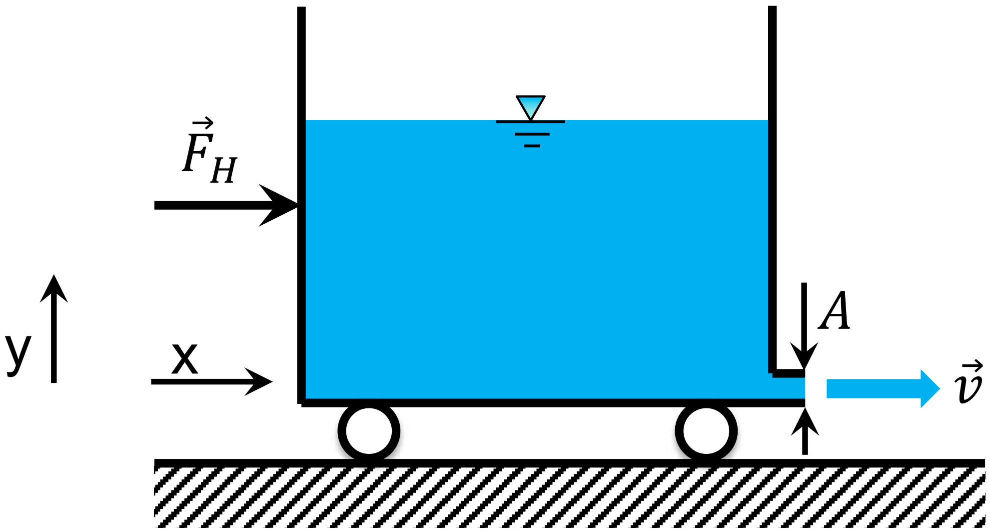
$$\boxed{\sum \vec{F} = \underbrace{\vec{F}_P}_{pressure\ forces} + \underbrace{\vec{F}_A}_{external\ forces} + \underbrace{\vec{F}_H}_{retention\ forces}}$$

Additionally mass conservation (continuity) to be considered:

$$\boxed{0 = \frac{dM}{dt} = \underbrace{\frac{\partial}{\partial t}\iiint_V \varrho \cdot dV}_{unsteady} + \underbrace{\iint_A \varrho \cdot \vec{v} \cdot \vec{n} \cdot dA}_{steady}}$$

Normal unit vector $\vec{n}$ perpendicular to A and pointing outward of control volume

Example 1: Reaction (Flow Accelaration)



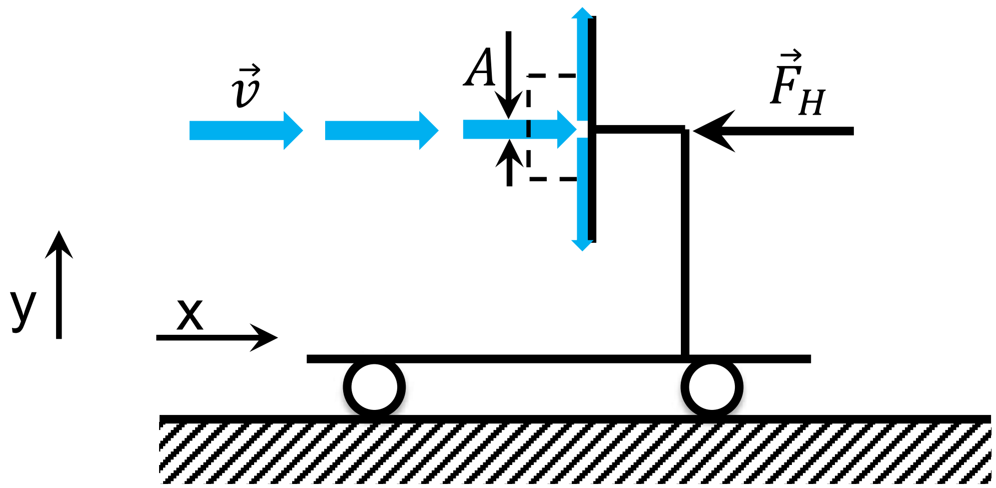
Force balance in x direction:

$$\vec{F} = \varrho \cdot \vec{v} \cdot v \cdot A = \varrho \cdot v \cdot v \cdot A \cdot \vec{e}_x$$

$$\vec{F} = \dot{m} \cdot \vec{v}$$

Corresponds to Reaction Turbine („Überdruckturbine“)

Example 2: Action (Flow Deflection)



Force balance in x direction:

$$-\vec{F} = -\varrho \cdot \vec{v} \cdot v \cdot A$$

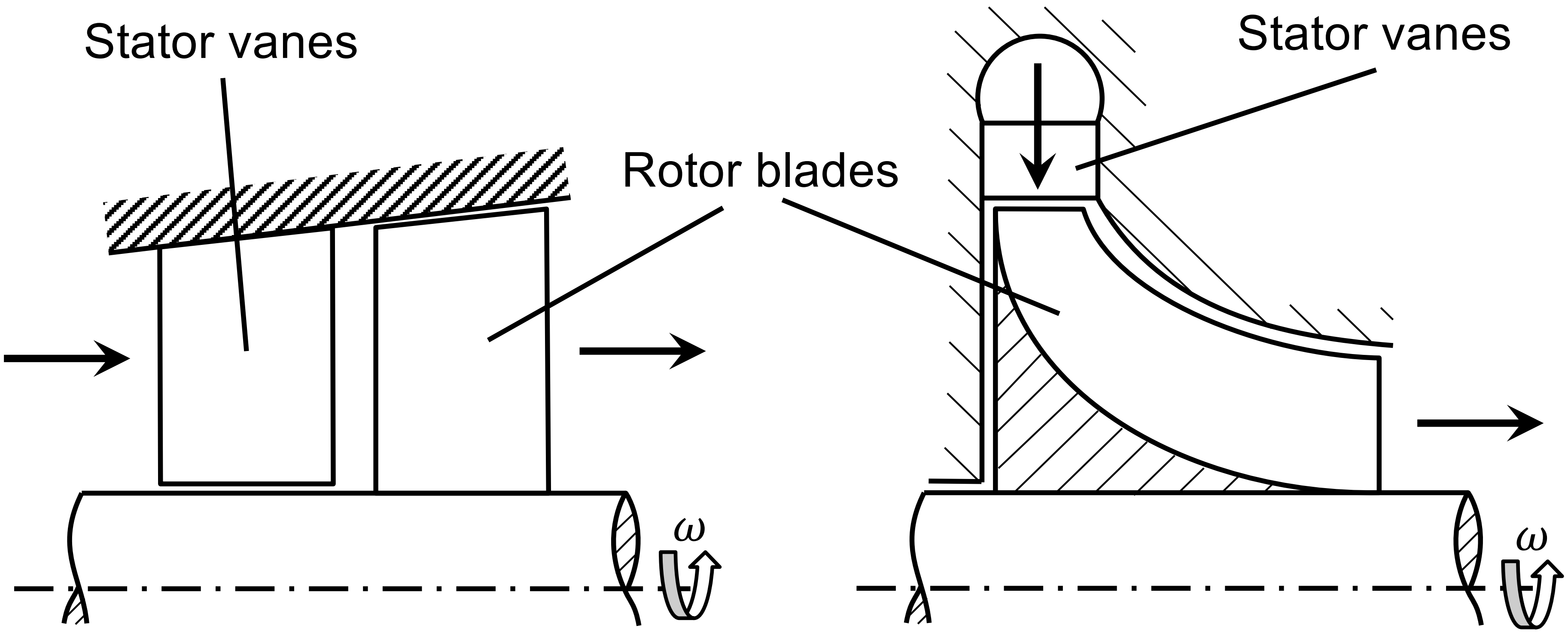
$$\vec{F} = -\dot{m} \cdot v \cdot \vec{e}_x$$

Corresponds to Impulse Turbine („Gleichdruckturbine“)

1.4 Relevance of Steam and Gas Turbines
1.4.1 Typical Designs

Axial flow turbines

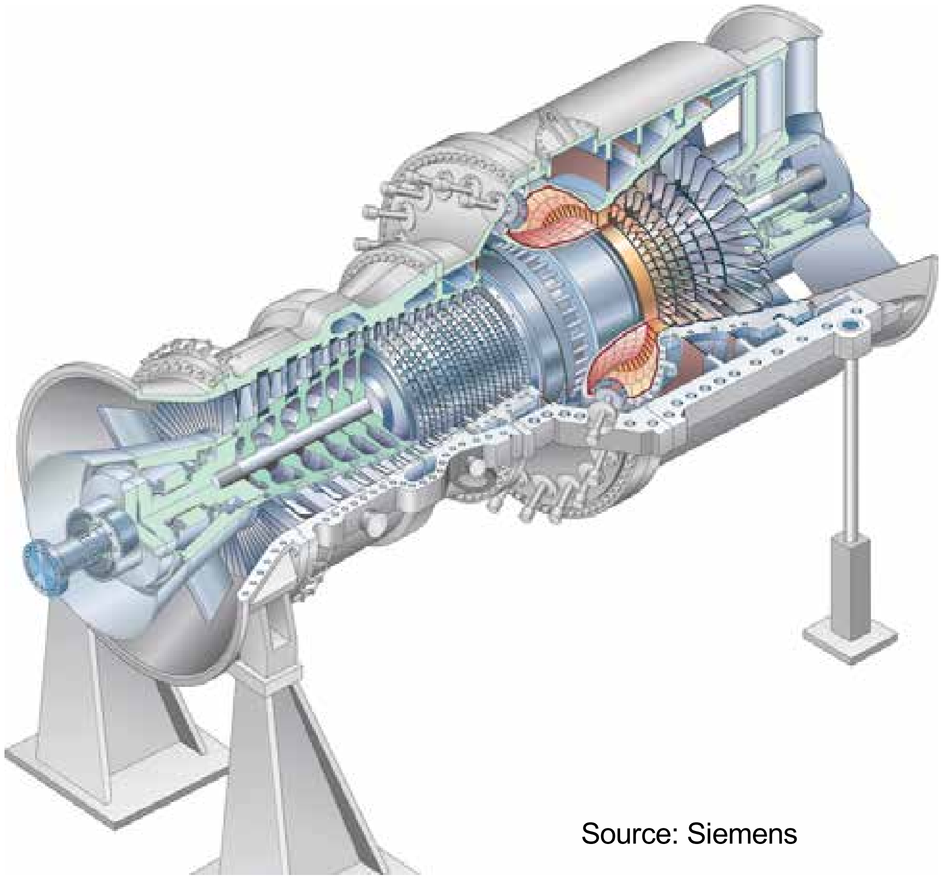
Radial flow turbines



Intermediate design: „diagonal flow turbines“

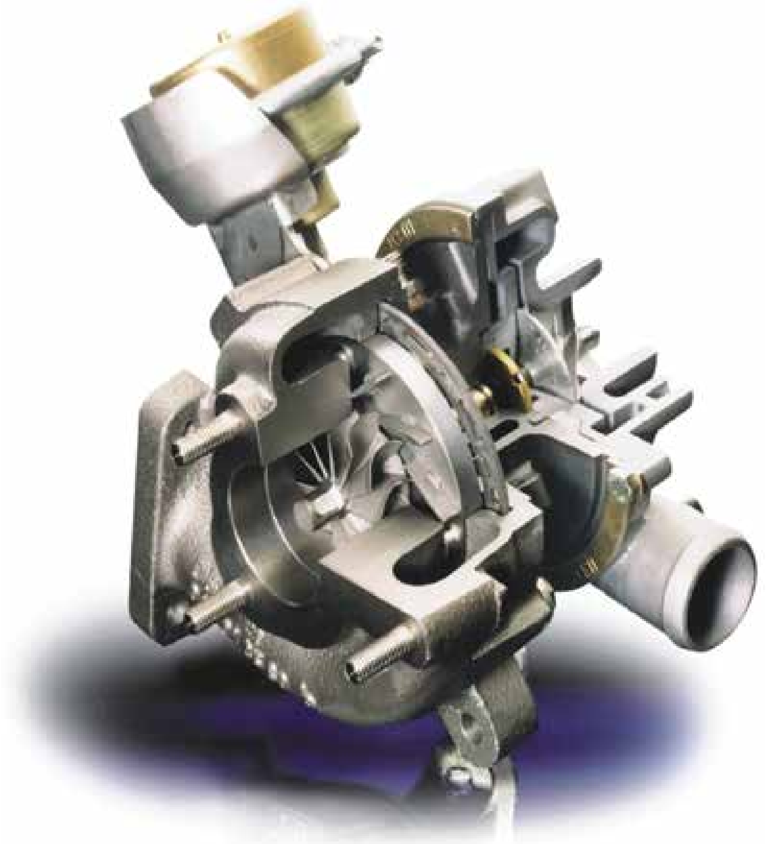
Typical Designs

Axial flow turbine



Source: Siemens

Radial flow turbine



Source: Borg Warner

1.4.2 Advantages of Turbo Machines

- High rotational speeds
  $\rightarrow$ high power output for a given (small) size / weight
  $\rightarrow$ high power density
- Large units with high power output (up to 1.6 GW), parallel arrangement of multiple stages on the same shaft
- No oscillating forces or moments
- Expansion to low pressure levels (ambient, vacuum) linked with high specific volumes feasible
  $\rightarrow$ high thermal efficiency, large units
- High reliability and availability, long engine life
- No direct contact between working fluid and lubricant
- Use of different working fluids possible
- High flexibility, adaptation to a variety of applications
- Excellent maintainability

1.4.3 Main Areas of Application

- Electric power generation
  - Permanent operation (base load)
  - Intermediate load
  - Peak load
  - Economical considerations determine type of power plant
  - Distributed generation (micro gas turbines) / CHP (combined heat & power)
- Aircraft propulsion
- Industrial applications
  - Mechanical / electric energy
  - Process heat / steam (CHP)
- Propulsion of land based vehicles and marine propulsion
- Turbo chargers
- Turbo compressors

Main Areas of Application

- Power range from some 100 W to 1.6 GW
- Power per blade up to several hundreds of kW
- Outage of an 800 MW power plant generates losses of approx. 1 Mio € / day
- Hot gas temperature in NGVs of jet engines several hundred K higher than melting point of Ni based super alloys
- Centrifugal forces at the HPT blade root corresponds to the weight of a double decker bus
- World market for turbo chargers > 30 Mio units / a
- 70% of electrical energy in Germany provided by thermal power plants utilising turbo machines
- Globally app. 25,000 aircrafts with turbo propulsion systems in use

1.4.4 Environmental Impact

- Fuel
  - Fossil (coal, natural gas) → pollutant emissions, greenhouse effect
  - Nuclear → radioactivity (waste)
- Jet engines, aircrafts
  - Contrails, cirrus clouds (radiative forcing)
- Heat release
  - Cooling towers (plumes), rivers (heat load, temperature)
  - Example nuclear power plant

$$\eta_{th} = 33\%$$

$$P_{el} = 1.500\ MW \qquad \eta_{el} = \frac{P_{el}}{P_N} \approx 1$$

$$\eta_{th} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}} = \frac{P_N}{\dot{Q}_{in}}$$

$$\dot{Q}_{out} = \frac{1-\eta}{\eta} = \frac{2/3}{1/3} \cdot P_N = 3.000 MW$$

Environmental Impact

- Noise
  - Jet engines
  - Gas turbines, fans
- Aesthetics
  - Buildings, cooling towers, chimneys
  - Plumes
  - Electric power transmission lines & poles
- Pollutant emissions
  - NO_x, formation at high temperatures
  - UHC (C_xH_y), burning efficiency, quenching
  - CO, combustion efficiency, quenching
  - SO_x for coal and heavy crude oil
  - Particulate matter: ash, soot
- Mitigation
  - Gas turbines: control of combustion process
  - Steam power plants: exhaust gas treatment, control of combustion

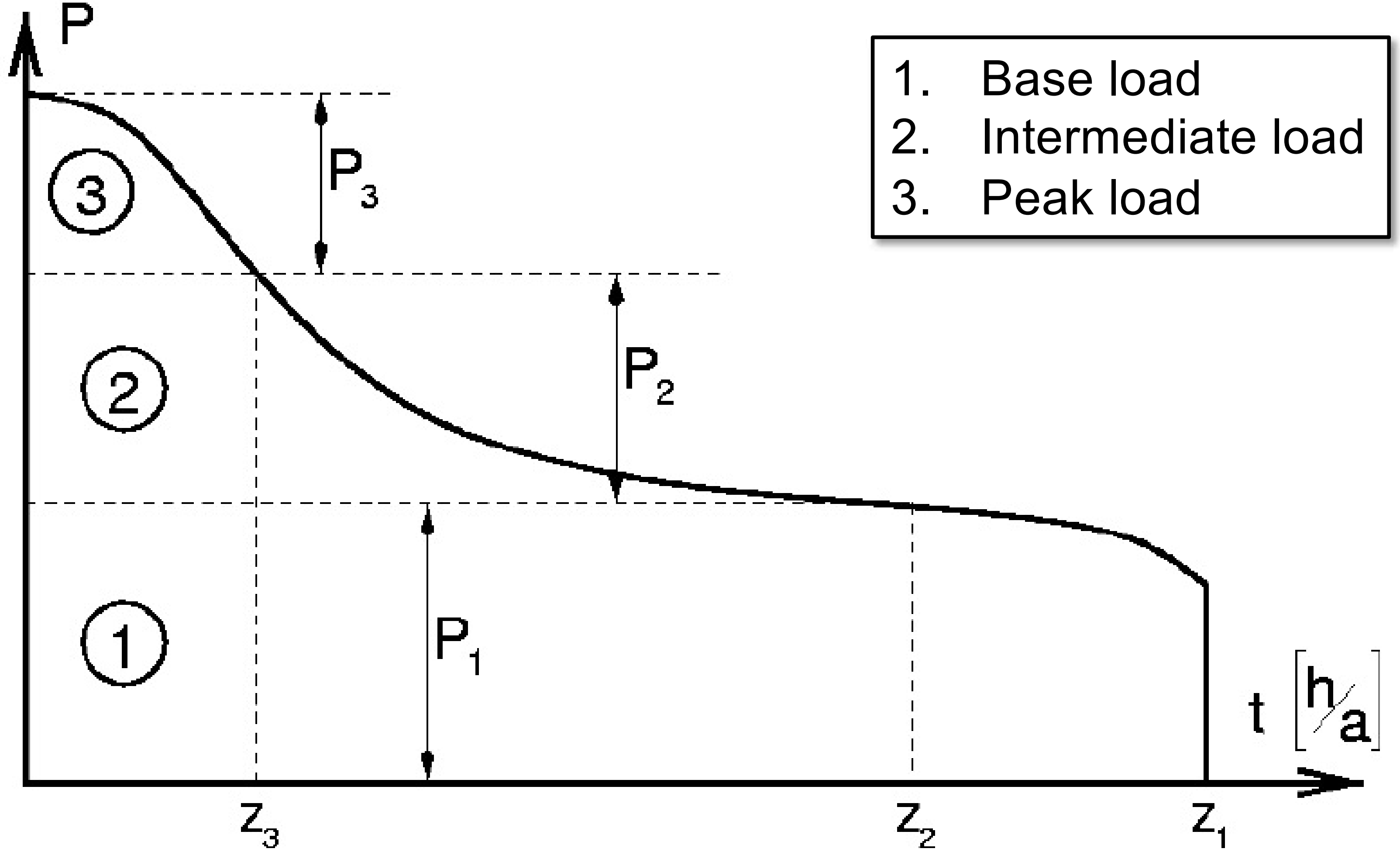
1.4.5 Economic Considerations (comp. lecture „Kraft- und Wärmewirtschaft“)

- Electricity generation costs comprise:
  - Fixed Costs:
    - Capital costs
      - Amortisation of loan capital (depreciation, part I)
      - Return on loan capital (interests)
      - Amortisation of equity (depreciation, part II)
      - Return on equity capital (profit)
      - Taxes on profit
    - Costs related to ensuring operation
      - Personal costs
      - License costs
      - Insurances
      - Provisions (e.g. decommissioning costs)
      - …
- See next slide

Economic Considerations

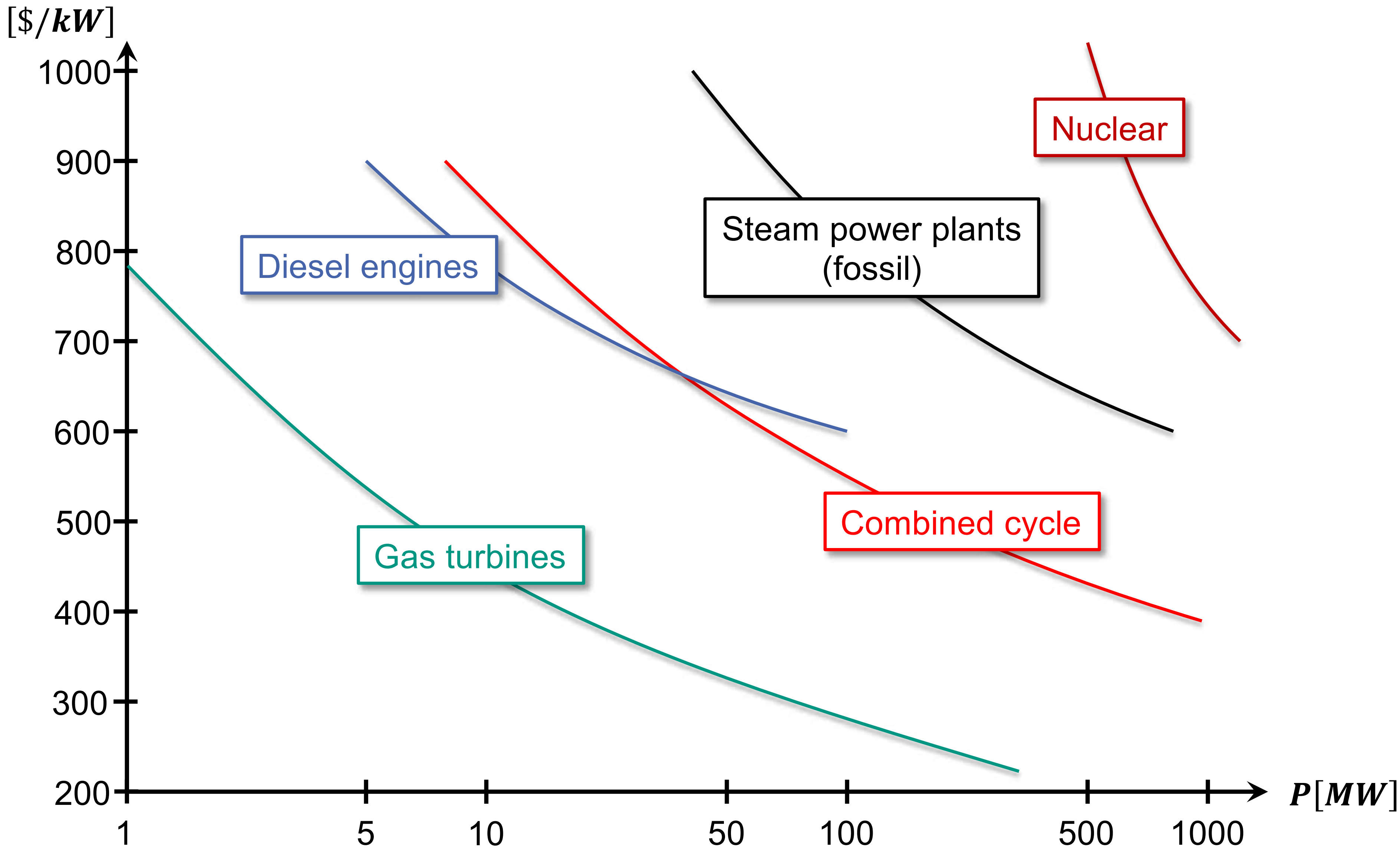
- Electricity generation costs comprise (ctd.):
  - Variable Costs:
    - Costs of operation
      - Fuel costs (efficiency, fuel price)
      - Consumables (exhaust gas cleaning!)
      - CO_2-certificates
      - Maintenance and overhaul
      - Personal costs (partial)
- For a given load , utilisation of the power plant with lowest (specific) electricity generation costs
  - Base load (nuclear, lignite, run-of-river)
  - Intermediate load (hard coal, combined cycle)
  - Peak load(gas turbine, hydro pump storage)

Regular Annual Load Diagram



1. Base load
2. Intermediate load
3. Peak load

Specific Investment Costs Depending on Unit Size (Economy of Scale!)



Investment Costs vs. Operational Costs

- Lowest specific investment costs for single cycle gas turbine but high operational costs
    - Moderate efficiency
    - High fuel price (natural gas)
  - „Peaker“ (peak load power plant)
- Highest specific investment cost for nuclear power plants but low operational costs
    - Low efficiency
    - Extremely low fuel price (U-235)
  - Base load power plant (s. HB 2.1)

Investment Cost Split of a Large Steam Power Plant (Fossil)

Boiler & heat exchangers (without cooling tower)	~ 30 %
Turbo machines	~ 20 %
Pipes	~ 15 %
Building	~ 12 %
Generator	~ 12 %
Auxilary units	~ 8 %
Process control system	~ 3 %
Flue gas cleaning, additional	~ 30 %

1.4.6 Cost Calculation

Annuity

Fixed costs:

$$K_A\left[\frac{€}{a}\right] = p \cdot K_I + \frac{K_I}{n} + \cdots$$

$$K_A = K_I \frac{p(1+p)^n}{(1+p)^n - 1}$$

K_I: Investment costs

n: Recovery period $[a]$

p: interest rate

Variable costs:

$$K_B\left[\frac{€}{a}\right] = K_b\left[\frac{€}{kWh}\right] \cdot z\left[\frac{kWh}{a}\right]$$

$$= q\left[\frac{kJ}{kWh}\right] \cdot b\left[\frac{€}{kJ}\right] \cdot P_{el}[kW] \cdot t\left[\frac{h}{a}\right]$$

q: specific heat requirement $\sim \frac{1}{\eta}$

P_{el}: net electric power

b: specific fuel price

t: annual hours of operation

Total costs:

$$K = K_A + K_B = K_A + q \cdot b \cdot P_{el} \cdot t$$

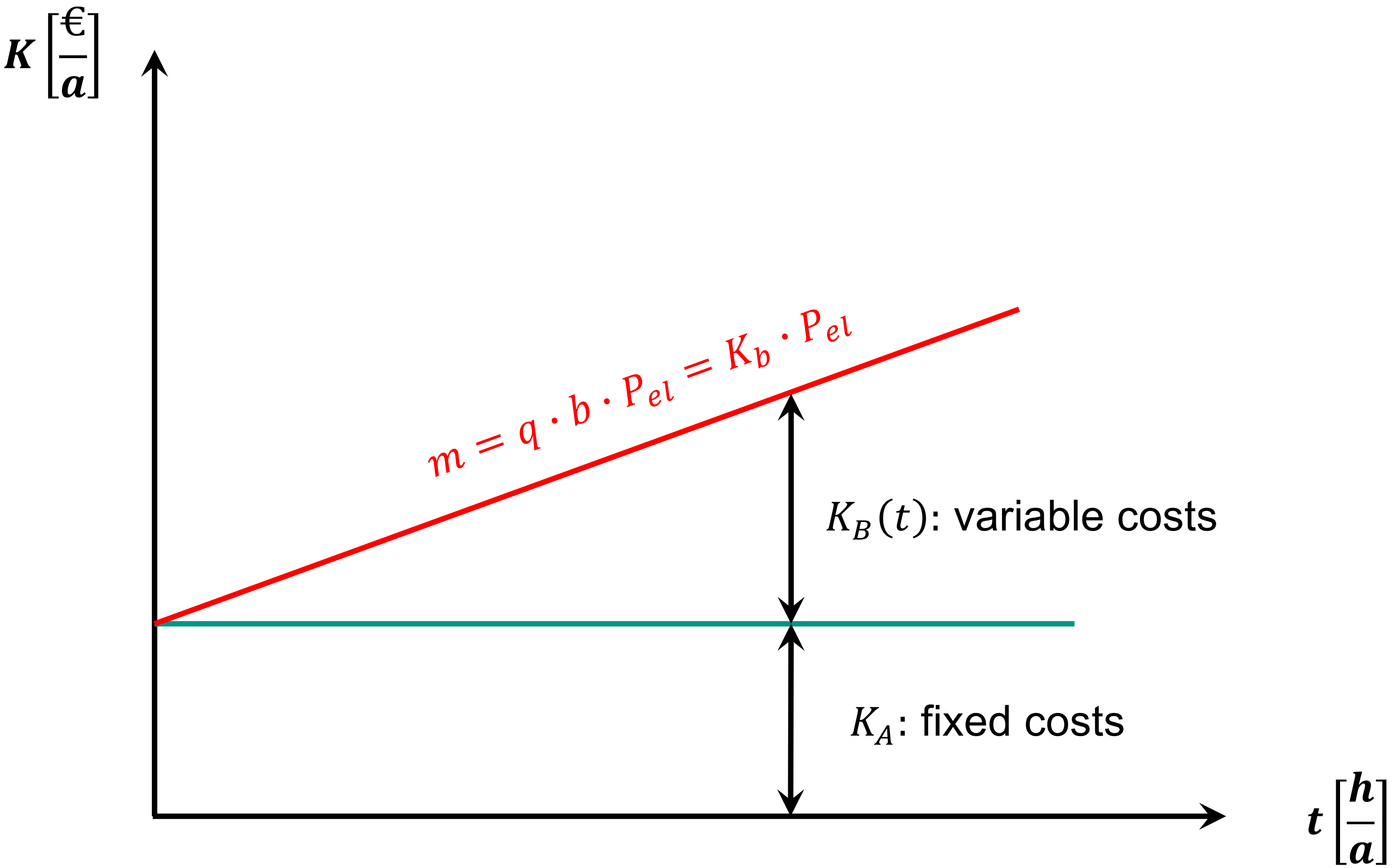
Annuity Factors

$$\frac{p(1+p)^n}{(1+p)^n - 1}$$

	Interest (p)							
Period (n)	1%	2%	3%	4%	5%	10%	15%	20%
1	1,01000	1,02000	1,03000	1,04000	1,05000	1,10000	1,15000	1,20000
2	0,50751	0,51505	0,52261	0,53020	0,53780	0,57619	0,61512	0,65455
3	0,34002	0,34675	0,35353	0,36035	0,36721	0,40211	0,43798	0,47473
4	0,25628	0,26262	0,26903	0,27549	0,28201	0,31547	0,35027	0,38629
5	0,20604	0,21216	0,21835	0,22463	0,23097	0,26380	0,29832	0,33438
6	0,17255	0,17853	0,18460	0,19076	0,19702	0,22961	0,26424	0,30071
7	0,14863	0,15451	0,16051	0,16661	0,17282	0,20541	0,24036	0,27742
8	0,13069	0,13651	0,14246	0,14853	0,15472	0,18744	0,22285	0,26061
9	0,11674	0,12252	0,12843	0,13449	0,14069	0,17364	0,20957	0,24808
10	0,10558	0,11133	0,11723	0,12329	0,12950	0,16275	0,19925	0,23852
11	0,09645	0,10218	0,10808	0,11415	0,12039	0,15396	0,19107	0,23110
12	0,08885	0,09456	0,10046	0,10655	0,11283	0,14676	0,18448	0,22526
13	0,08241	0,08812	0,09403	0,10014	0,10646	0,14078	0,17911	0,22062
14	0,07690	0,08260	0,08853	0,09467	0,10102	0,13575	0,17469	0,21689
15	0,07212	0,07783	0,08377	0,08994	0,09634	0,13147	0,17102	0,21388
16	0,06794	0,07365	0,07961	0,08582	0,09227	0,12782	0,16795	0,21144
17	0,06426	0,06997	0,07595	0,08220	0,08870	0,12466	0,16537	0,20944
18	0,06098	0,06670	0,07271	0,07899	0,08555	0,12193	0,16319	0,20781
19	0,05805	0,06378	0,06981	0,07614	0,08275	0,11955	0,16134	0,20646
20	0,05542	0,06116	0,06722	0,07358	0,08024	0,11746	0,15976	0,20536
30	0,03875	0,04465	0,05102	0,05783	0,06505	0,10608	0,15230	0,20085
40	0,03046	0,03656	0,04326	0,05052	0,05828	0,10226	0,15056	0,20014
50	0,02551	0,03182	0,03887	0,04655	0,05478	0,10086	0,15014	0,20002

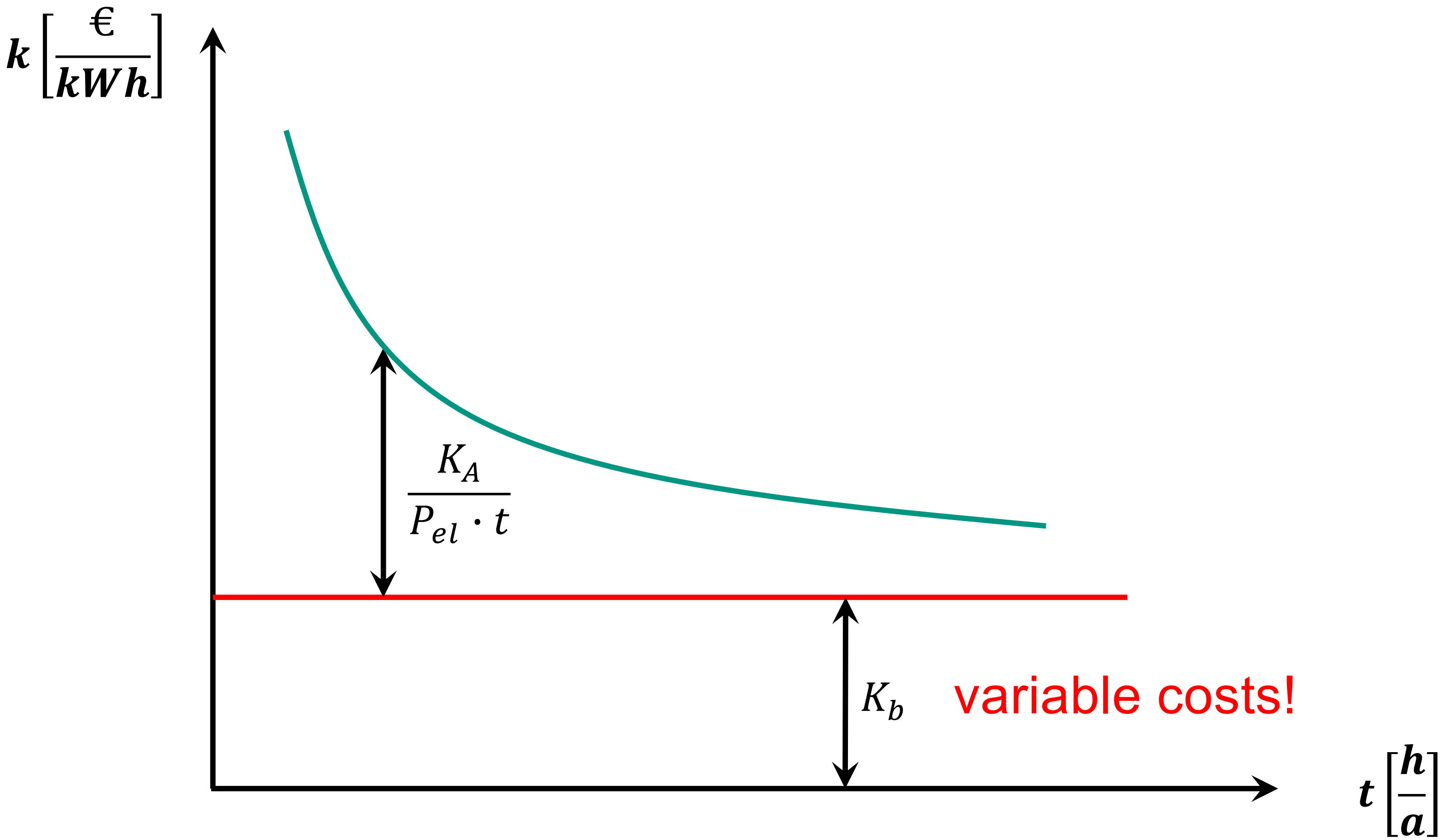
Total Costs

$$\boxed{K = K_A + K_B = K_A + q \cdot b \cdot P_{el} \cdot t}$$

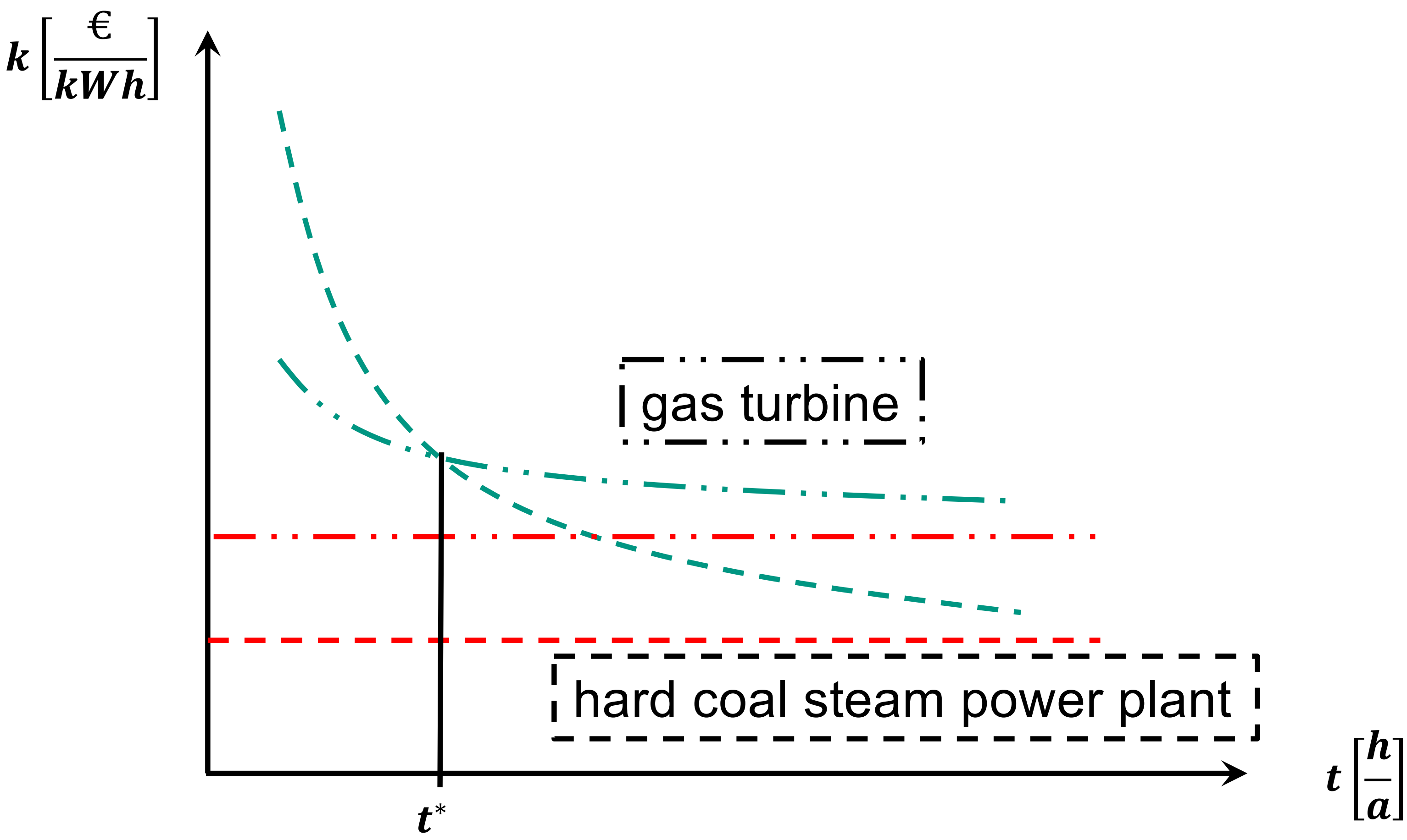


Specific Costs of Electricity Generation

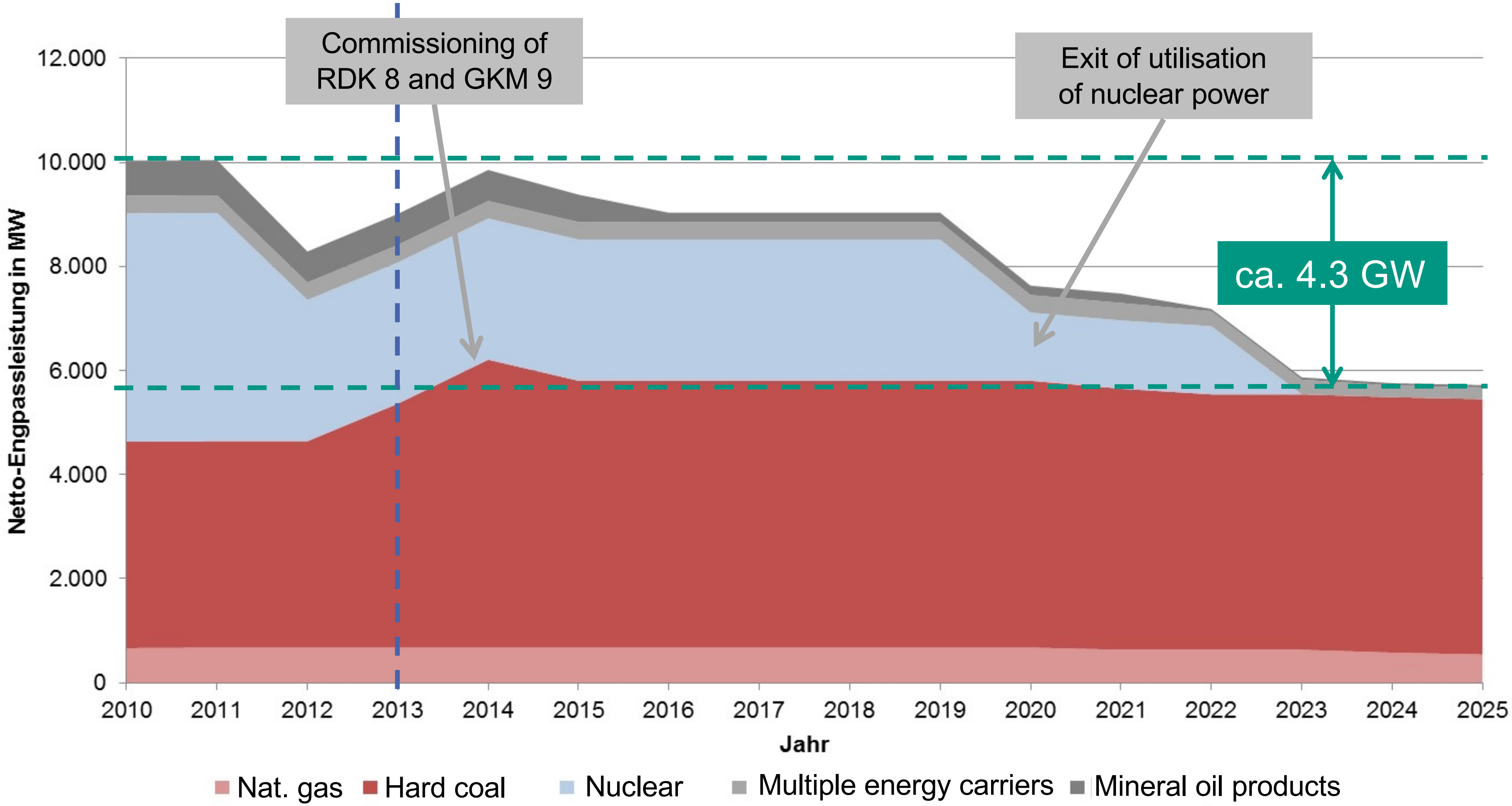
$$k\left[\frac{€}{kwh}\right] = \frac{K[€/a]}{z[kWh/a]} = \frac{K_A + K_b \cdot z}{z} = \frac{K_A}{z} + K_b = \frac{K_A}{P_{el} \cdot t} + K_b$$



Cost Comparison of Different Power Plants

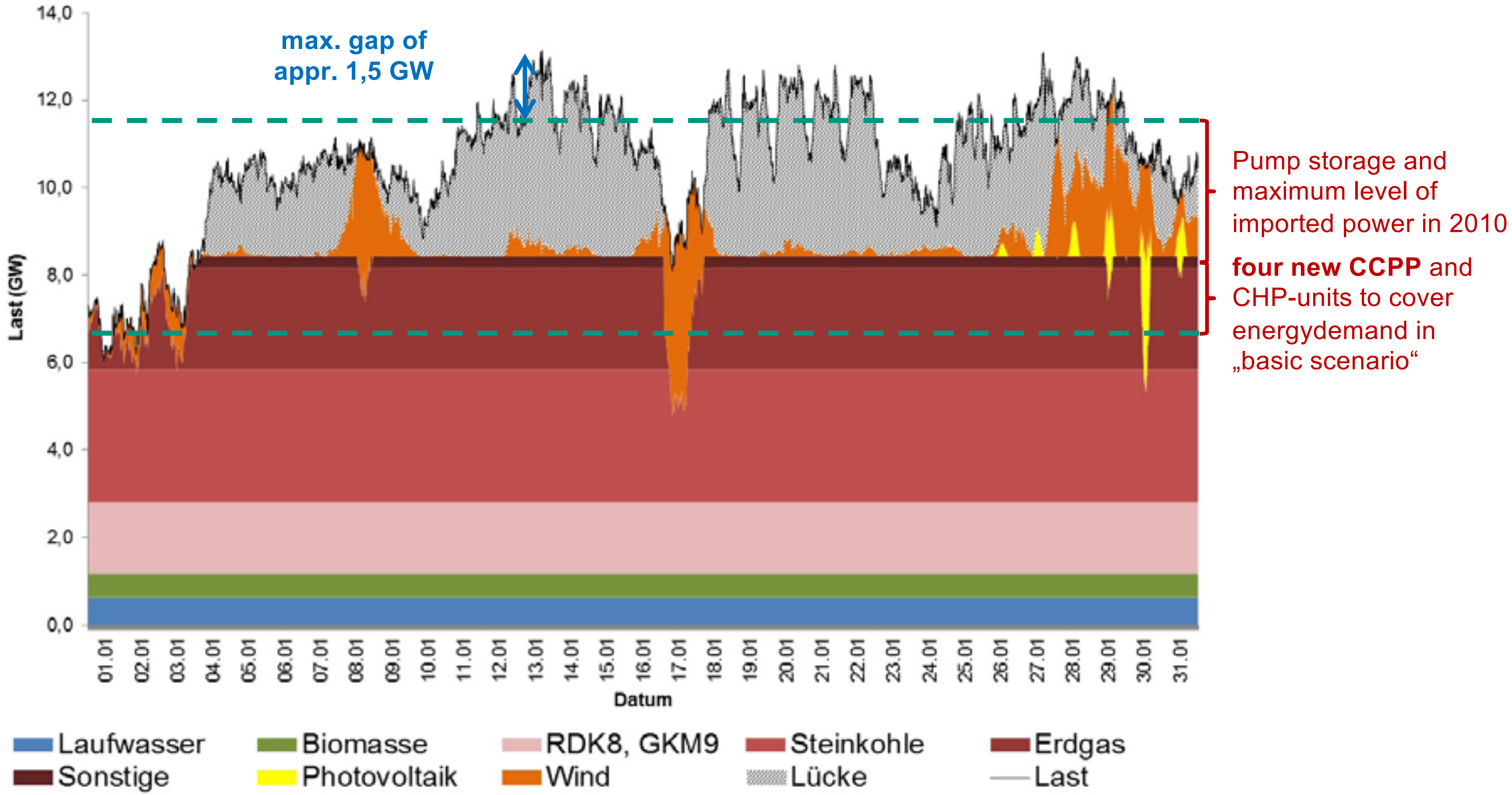


Reduction of Existing Installed Power in Baden-Württemberg until 2025



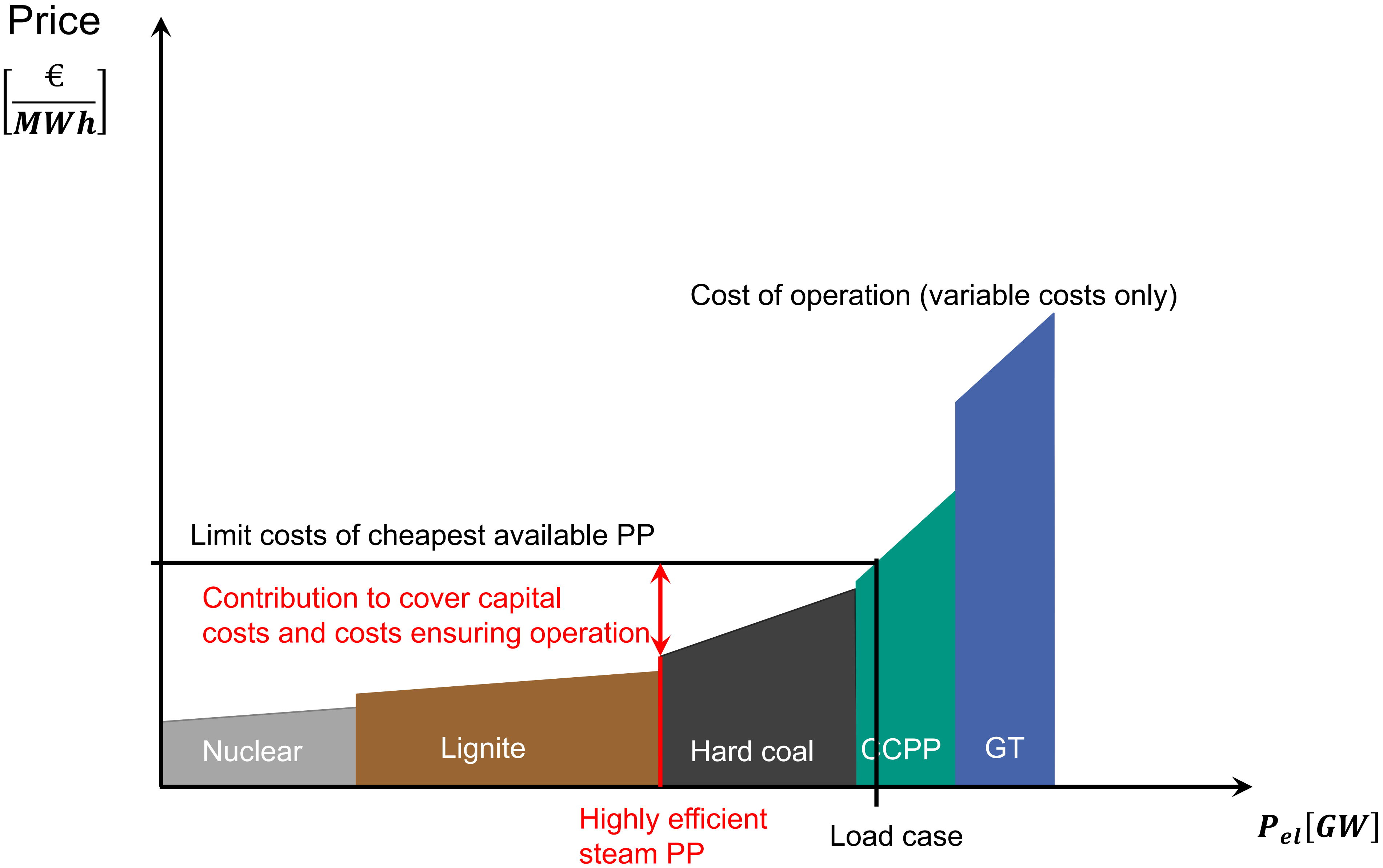
- Development of present power plant portfolio including planned and projects with high probability to be realised (e.g. RDK 8, GKM 9)

Potential Load Curve in January 2025

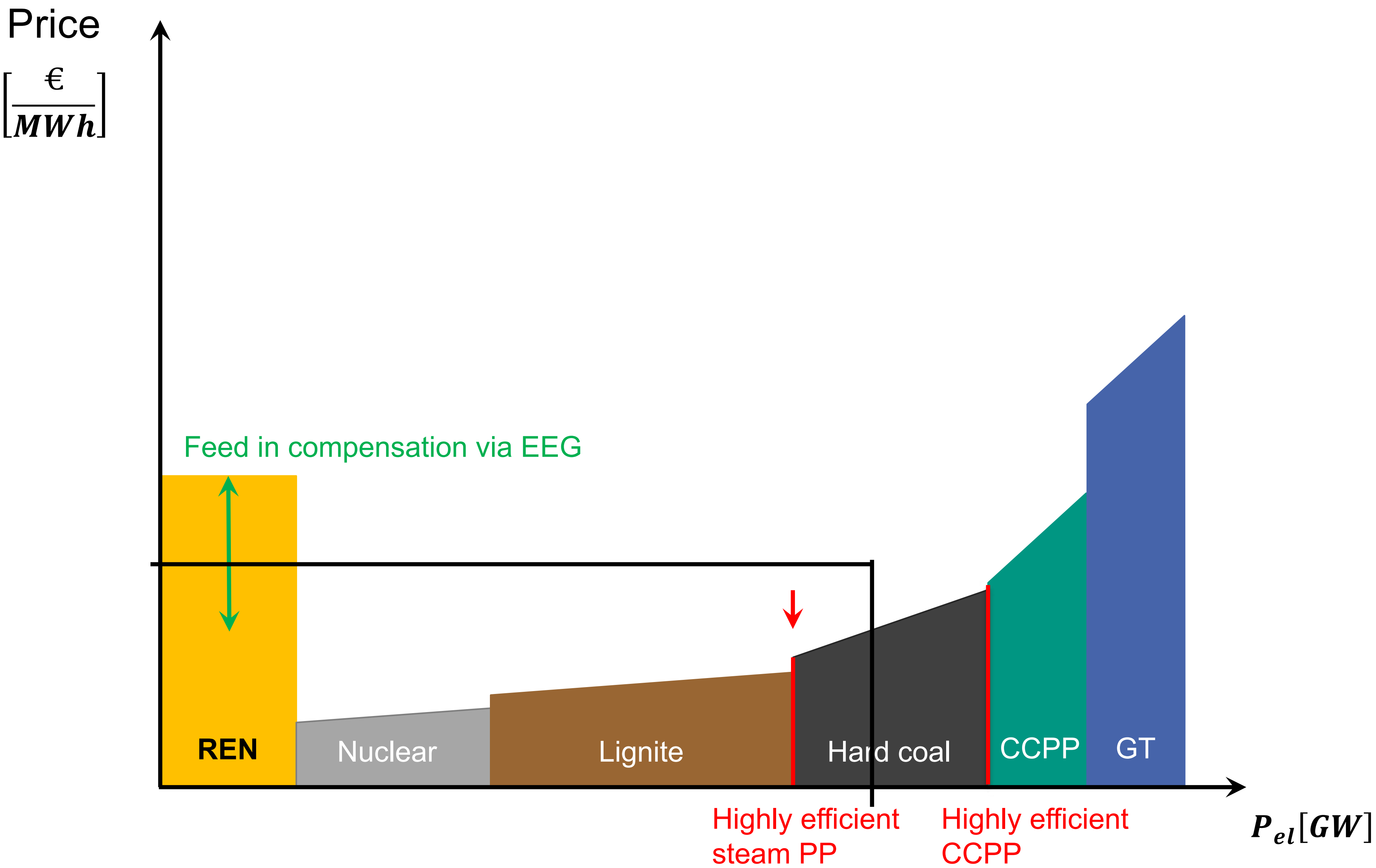


Anticipated extension of installed power not sufficient to cover extreme load scenarios

But: Missing Incentives for Investments into new PP: Price Mechanism @ EEX – Merit Order Principle



But: Missing Incentives for Investments into new PP: Price Mechanism @ EEX – Merit Order Principle



1.5 Recent Development Trends - Steam Turbines / Power Plants

- In general: quite mature, but
- Increase of thermodynamic main steam parameters
  - Presently: 280 bar / 580-600 °C
    $\eta > 46\ \%$
  - Targets: 350 bar / 700 °C, $\eta > 50\ \%$
  - High material and manufacturing costs (MoV-steel, Ni-base alloys)
    - Machinability
    - High material thickness (thermal inertia)
  - Low heat conductivity
  - High heat expansion coefficients
  - Gain in efficiency needs to (over-) compensate increased investment costs
  - CCS (alternative power plant processes and architectures)
    - EU without Germany

Recent Development Trends
- Steam Turbines / Power Plants

- Increased load flexibility (contribution of fluctuating renewables)
- Load shift: base ⇨ intermediate ⇨peak: residual load
  (Spec. costs of electricity generation)
- 3D blading in LP-, IP- and HP-turbine
  - Increased component efficiency
  - Utilisation of numerical development tools (3D CFD)
- Predictive tools for wet steam flows (erosion)
- Life prediction and failure analysis
- Ti blades in last LP stages (fossil only)
  - 16 m^2 (50 s^{-1}), 25 m^2 (half speed) per flow (double flow cylinders)
  - Increase of maximum power
  - Reduction of number of LP cylinders / flows

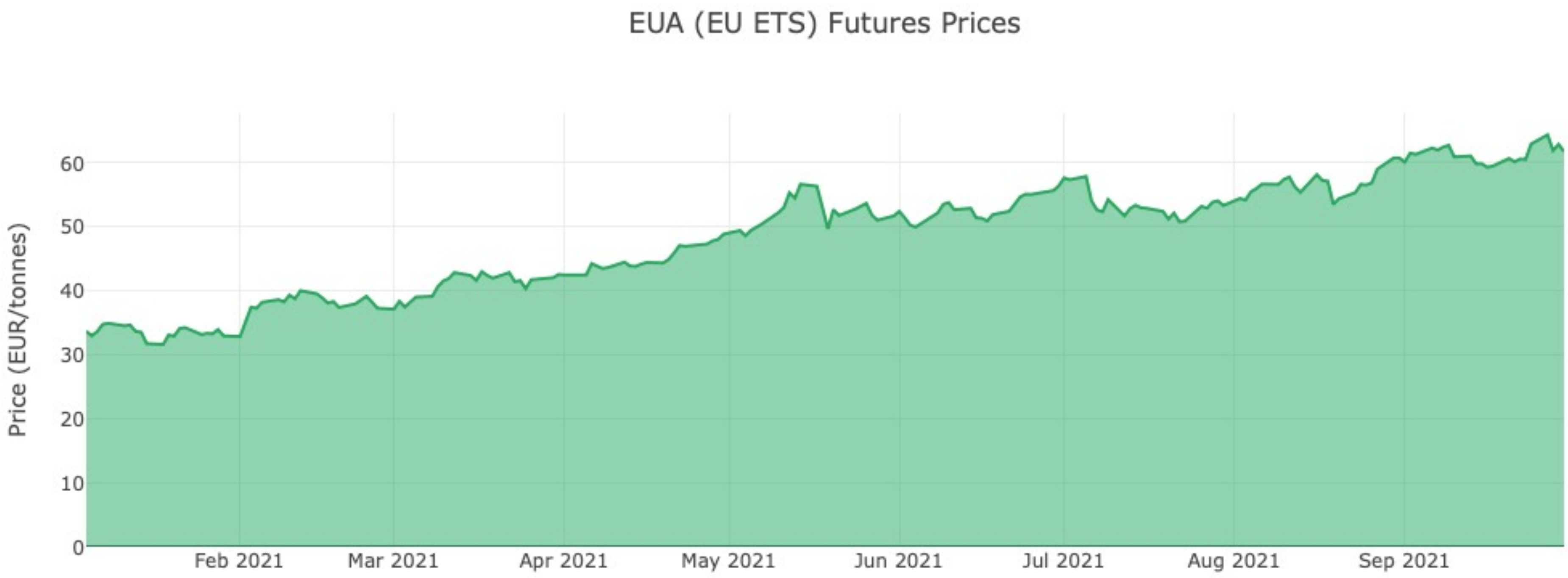
Recent Development Trends
- Gas Turbines / Power Plants

- Increase of max. power capacity (SGT5-9000 HL 567 MW)
- Increase of turbine inlet temperature and pressure ratio
- Sequential combustion (Alstom/GE GT 24/26)
- Compressor intercooling (GE, RR)
- Turbine blade & vane cooling
  - Film- / effusion cooling, laid back / fan shaped holes
  - Steam cooling (GE)
- Coatings
  - Metallic: corrosion protection
  - Ceramic: heat protection
- Compressors: „Controlled Diffusion Blading“
  - Prevention of near wall flow separation
- Turbine: end wall contouring
  - Reduction of secondary flows
- Turbine: clocking

Recent Development Trends
- Gas Turbines / Power Plants

- Combustion:
  - Lean premixed combustion („Dry Low No_x“)
    - Cooling air reduction required, no mixing ports
    - Residence time requirements (stability, efficiency)
    - Flash back and auto-ignition prevention
    - Prevention of thermo-acoustic oscillations
    - Stable combustion at part load and during transient operation
  - Fuel flexibility
    - Variation of NG composition (Wobbe Index $W_l = \frac{H_l}{\sqrt{\frac{\rho_{fuel}}{\rho_{air}}}}$)
    - Syngas combustion
      - Low heating value
      - High amount of H_2 and CO

ETS CO2 Certificates – Cost Development (9/2021)



Quelle: finanzen.net GmbH