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Renewable Energy

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Content Chapter 2

- Thermodynamics revision
  - Definitions
  - 1st law (energy conservation)
  - 2nd law (entropy)
  - "1st Law minus 2nd Law" => Exergy

- Review of thermodynamic power cycles
  - Rankine, Brayton, combined cycles, engines

- Thermodynamic power cycles relevant for renewable energy applications

- Review of thermodynamic heat pump and refrigeration cycles
  - ORC

Learning outcomes

- Understand and apply 1st and 2nd law of thermodynamics, and exergy concept to relevant systems and cycles
- Apply theory to thermodynamic cycles relevant for renewable energy sources

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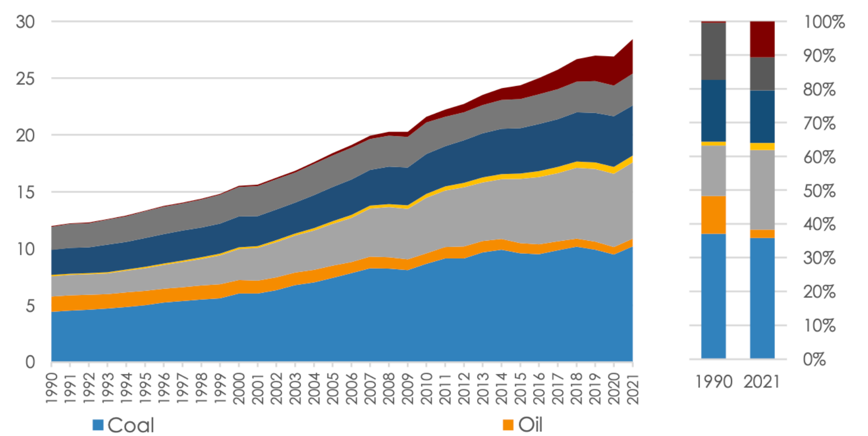
Context

Energy statistics
Pocketbook 2024

- Current global power production

28’428 TWh => 3245 GW (100% annual load factor)
In reality more power is installed as the annual load factor is of course <100%.

38. World electricity generation by source, 1990-2021
Petawatt hours and percentage



39. World electricity generation by source, 1990, 2000, 2010, 2020 and 2021
Terawatt hours

Source	1990	2000	2010	2020	2021
Thermal	7,701.0	10,112.2	14,792.6	17,183.1	18,187.0
- Coal	4,441.6	6,042.1	8,667.2	9,483.5	10,185.0
- Oil	1,339.1	1,198.6	919.3	660.7	694.0
- Natural gas	1,789.2	2,707.2	4,863.8	6,442.5	6,699.5
- Biofuels and waste	131.2	164.2	342.3	596.4	608.5
Nuclear	2,019.8	2,589.0	2,756.3	2,676.4	2,798.9
Hydro	2,193.0	2,706.8	3,528.6	4,463.4	4,408.3
Solar, wind and other sources[4]	61.5	103.8	510.9	2,565.4	3,034.3
Total	**11,975.3**	**15,511.9**	**21,588.3**	**26,888.3**	**28,428.5**

(4) See notes on pages 68-74.

→ Steam cycles (Coal)
→ Gas + combined cycles (Natural gas)
→ Integrated steam cycles (Biofuels and waste)
→ Steam cycle (Nuclear)
→ incl. Rankine cycles (Solar, wind and other sources)

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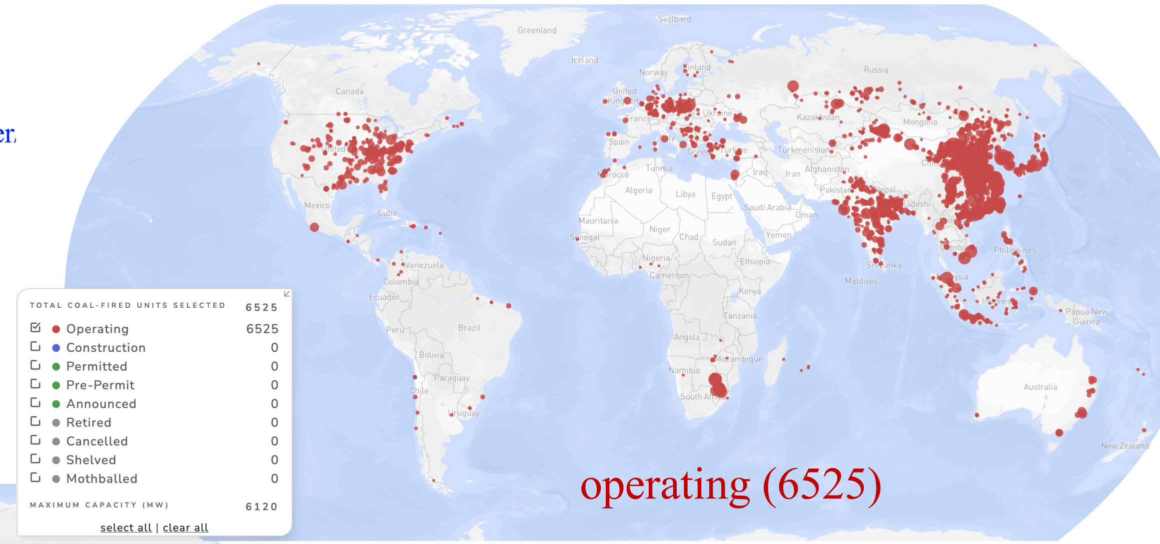
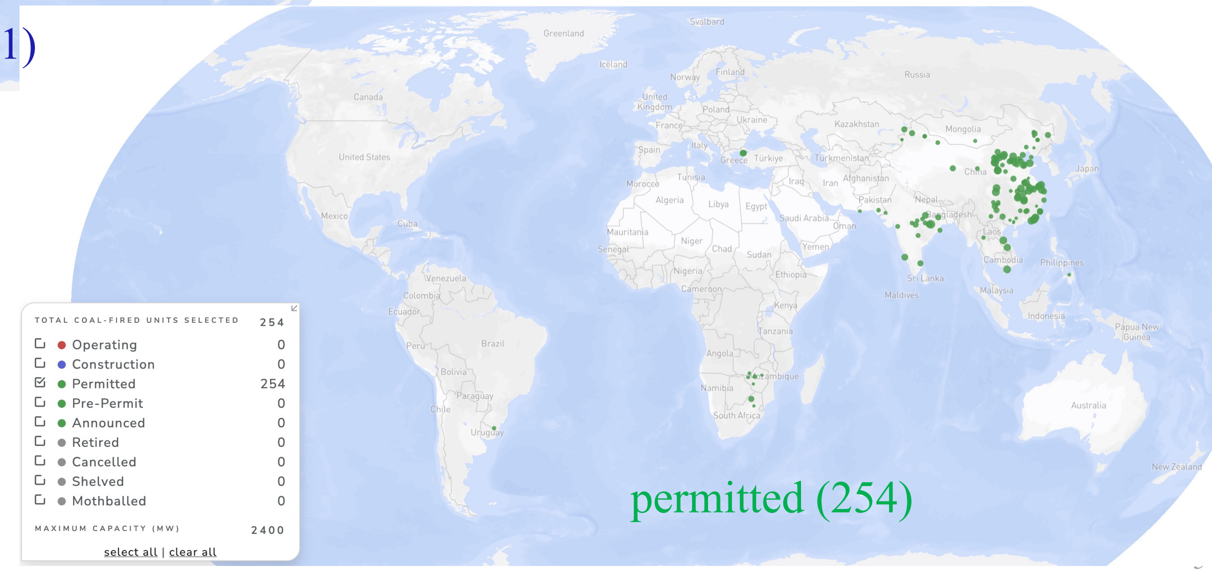
https://globalenergymonitor.org/projects/global-coal-plant-tracker/tracker/

Example : coal plants





Context

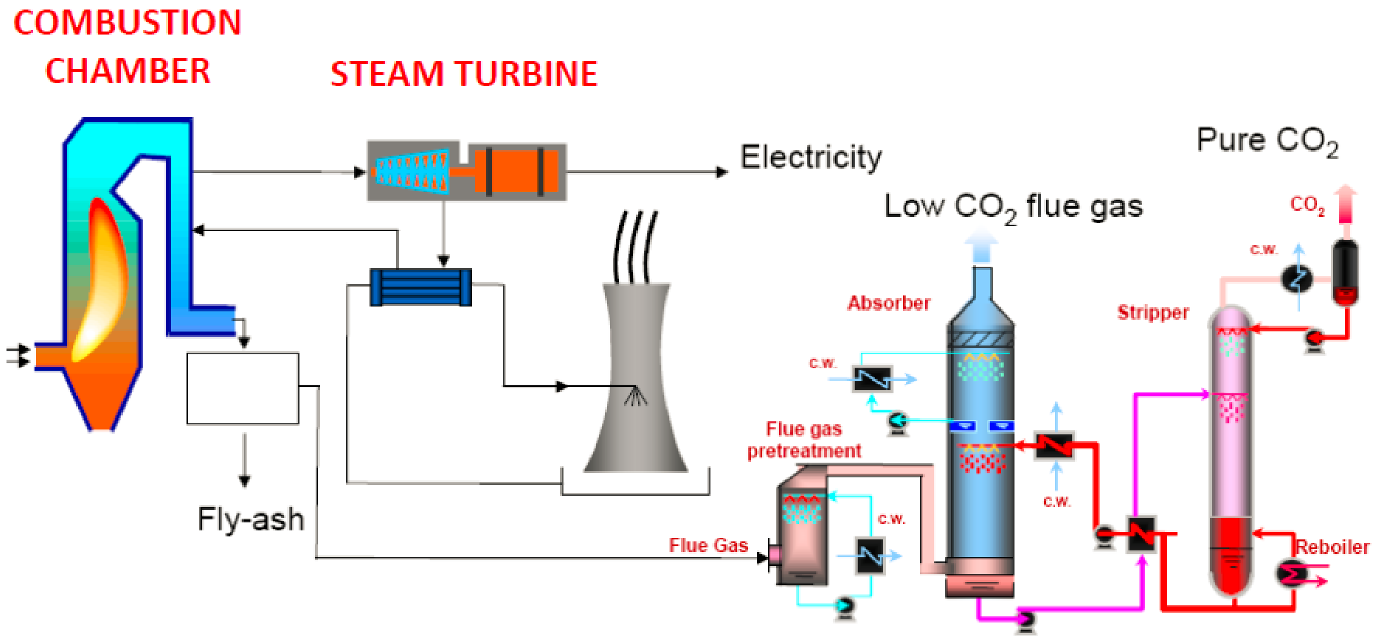
- Energy conversion systems overview:

Service	'Traditional' systems	'Advanced' (or 'new') systems
HEAT (low temperature)	Combustion (fossil fuel, wood) Electrical	Heat pumps Solar thermal Cogeneration
HEAT (high temperature)		Efficient clean combustion Cogeneration Concentrated solar thermal
MOBILITY	Internal combustion engines Electrical (train, bus) Aviation turbines	High efficiency engines Hybrid drives Fuel Cell vehicles, E-vehicles Liquid biofuels
ELECTRICITY	Fossil thermal (coal, gas) Nuclear (PWR, BWR) Hydro (river, dams)	**Optimised fossil & biomass power plants** **Nuclear Generation-IV** **Hydro (tidal, wave)** **Solar (photovoltaics)** **Solar (concentrated thermal)** **Wind turbines**

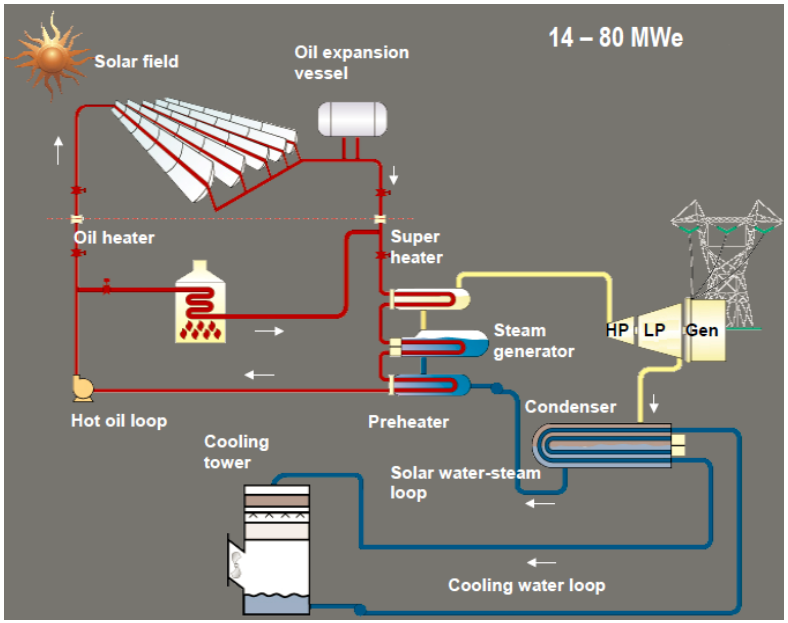
- Systems rely on power cycles and turbomachinery: heat → mechanical energy → electricity
- Heating/cooling applications rely on heat/refrigeration pumping cycles

Examples

– Coal plant with CO_2 separation

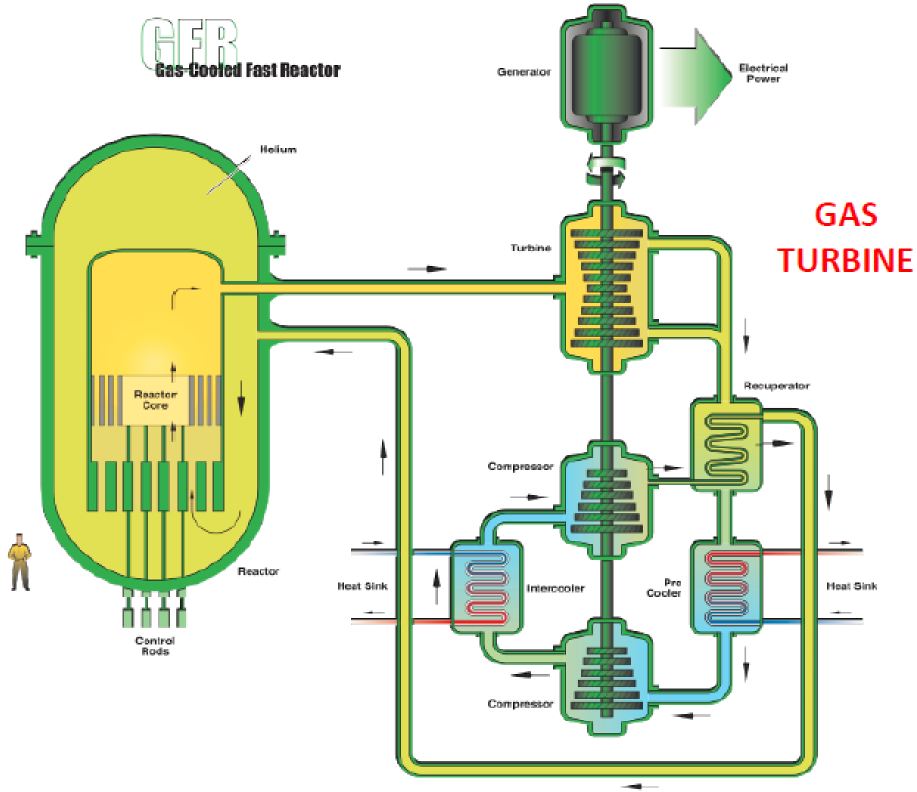


– Concentrated solar power

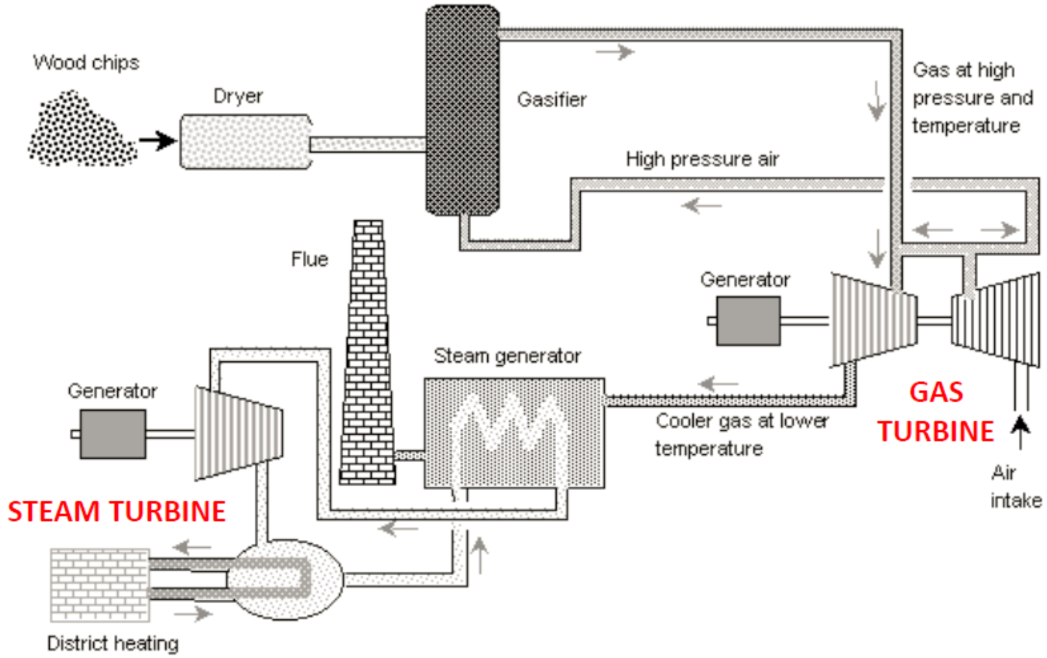


Examples

– (Advanced) nuclear

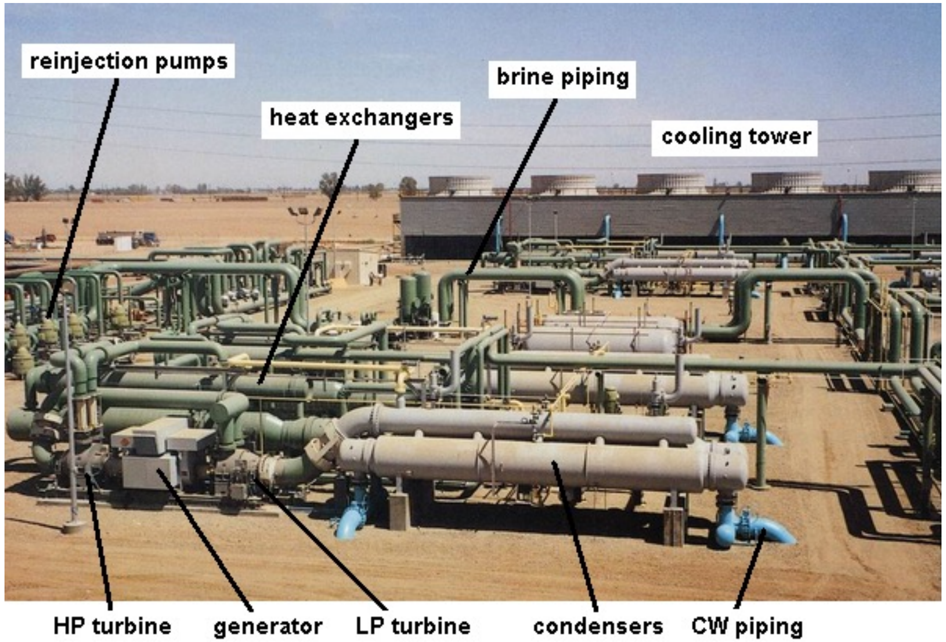


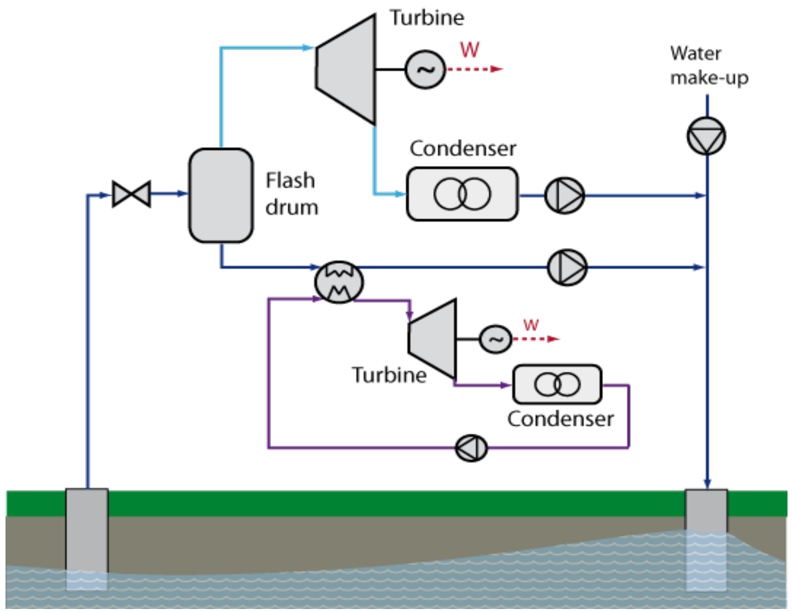
Biomass-fired combined cycle:



Examples

– Enhanced geothermal systems (EGS)





1st law for closed and open systems

- Energy conservation for **open** systems:

$$\Delta E = \underbrace{\Delta U}_{internal} + \underbrace{\Delta PE}_{potential} + \underbrace{\Delta KE}_{kinetic} = \overbrace{Q_{12}}^{heat} - \overbrace{W_{12}}^{work} + \overbrace{E_{\text{in}} - E_{\text{out}}}^{enthalpy}$$

$$\begin{bmatrix} \text{time rate of change} \\ \text{of the energy contained} \\ \text{within the control volume} \\ \text{at time } t \end{bmatrix} = \begin{bmatrix} \text{net rate of energy} \\ \text{transferred in across} \\ \text{system boundary by heat transfer} \\ \text{at time } t \end{bmatrix} - \begin{bmatrix} \text{net rate of energy} \\ \text{transferred out across} \\ \text{system boundary by work transfer} \\ \text{at time } t \end{bmatrix} + \begin{bmatrix} \text{net rate of energy} \\ \text{transfered into the} \\ \text{control volume} \\ \text{accompanying mass flow} \end{bmatrix}$$

1st law for open systems

- Energy conservation for open systems: (i.e. with mass transfer / enthalpy)
  - Requires mass conservation:

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

  - Energy conservation:

$$\frac{dE_{CV}}{dt} = \dot{Q} - \underbrace{\dot{W}}_{\text{total work}} + \sum_i \dot{m}_i \left(u_i + \frac{w_i^2}{2} + g z_i \right) - \sum_e \dot{m}_e \left(u_e + \frac{w_e^2}{2} + g z_e \right)$$

(w = fluid speed)

$$\frac{dE_{CV}}{dt} = \dot{Q}_{cv} - \underbrace{\dot{W}_{cv}}_{\text{effective work}} + \sum_i \dot{m}_i \left(h_i + \frac{w_i^2}{2} + g z_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{w_e^2}{2} + g z_e \right)$$

enthalpy $h = u + pV$ (work term due to mass transfer in/out))

(cv : control volume)

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1st law for closed and open systems

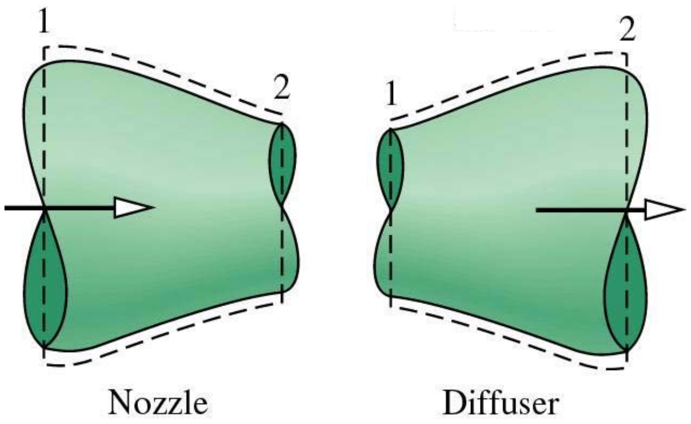
- Energy conservation for open systems: Applications:
  - Nozzle, diffusor

$$h_i + \frac{w_i^2}{2} = h_e + \frac{w_e^2}{2}$$

(w = fluid speed)

total enthalpy is conserved

$P_i > P_e$ *acceleration* $P_i < P_e$ *deceleration*

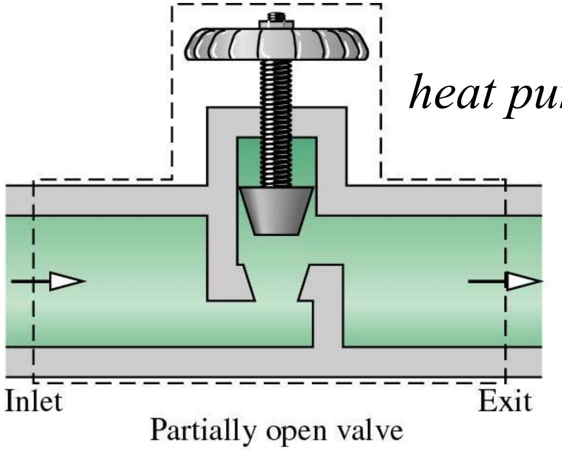


turbines

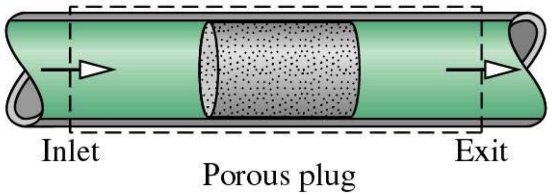
  - Throttling valves

$$h_i = h_e$$

$h = u + Pv$



heat pumps, ORC



$P_i > P_e \Rightarrow v_i < v_e \Rightarrow w_i < w_e$

1st law for closed and open systems

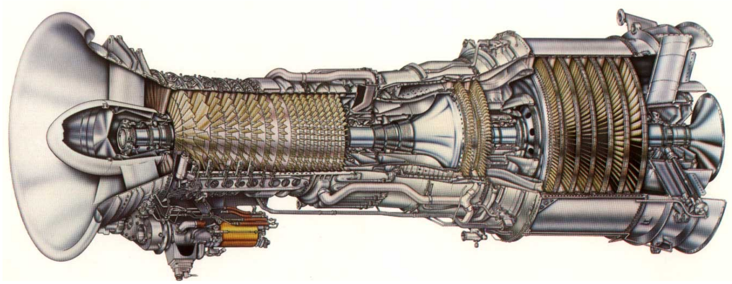
- Energy conservation for open systems: Applications:
  - Turbine, compressor, pump, fan

$$0 = -\dot{W} + \dot{m}\left(h_i + \frac{w_i^2}{2} + gz_i\right) - \dot{m}\left(h_e + \frac{w_e^2}{2} + gz_e\right)$$

work = Δh_{fluid}

(~adiabatic)

GE, Roots* API 617 OIB

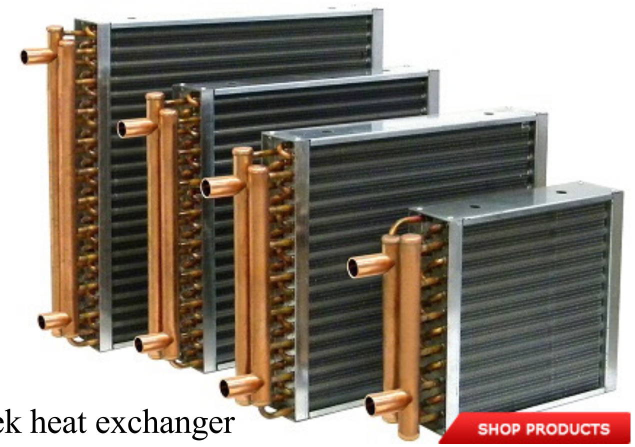


GE, LM2500 gas turbine, ships, ca. 30 MW

Voith-Kaplan turbine, 200 MW, diameter 10.5m

  - Heat exchanger

$$0 = \sum_{\text{inlets}:i} \dot{m}_i h_i - \sum_{\text{outlets}:j} \dot{m}_j h_j$$



Brazetek heat exchanger

Efficiency

- Energy efficiency or performance metric can be introduced for single components or complete systems
  - always need a proper definition!
  - indicates how well an energy conversion or transfer process is accomplished

- General:

$$\text{Efficiency} = \frac{\text{desired output}}{\text{required input}}$$

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Efficiency

- Example - Efficiency of *combustion systems*:

Efficiency of combustion processes is related to the *heating value of a fuel*, which is the amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to room temperature.

- Combustion efficiency:

$$\eta_{\text{combustion}} = \frac{\text{amount of heat released during combustion}}{\text{heating value of the fuel burned}} = \frac{\dot{Q}}{\dot{m}\text{HV}}$$

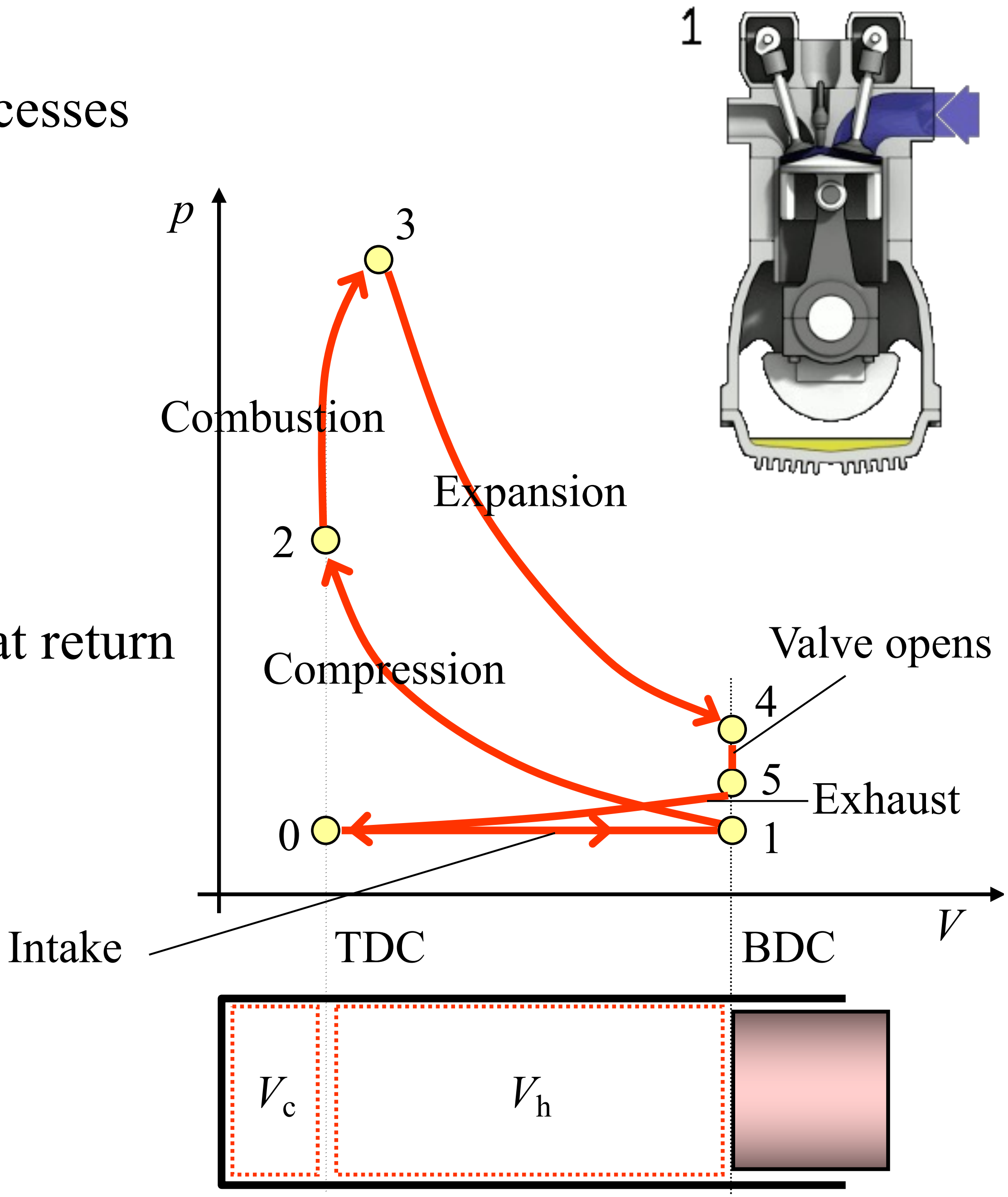
- Heating values (HV):
  - Higher heating values (HHV): water is condensed (boilers etc.)
  - Lower heating values (LHV): water exhaust remains vapor (cars, jet engines, etc.)

Fuel	HHV MJ/kg	LHV MJ/kg
Hydrogen	141.80	119.96
Methane	55.50	50.00
Ethane	51.90	47.80
Propane	50.35	46.35
Butane	49.50	45.75
Gasoline	47.30	44.4
Kerosene	46.20	43.00
Diesel	44.80	43.4
Coal (Anthracite)	32.50	
Coal (Lignite)	15.00	
Wood	21.7	20

Processes and Cycles

- Definitions:
  - Process: special types of processes
    - Isothermal (T = constant)
    - Isobaric (p = constant)
    - Isochoric (v = constant)
    - Isentropic (s = constant)
    - Adiabatic ($\dot{Q} = 0$)
  - Cycle: series of processes that return a system to its initial state

    E.g. 4-stroke engine



(TDC: top dead center)
(BDC: bottom dead center)

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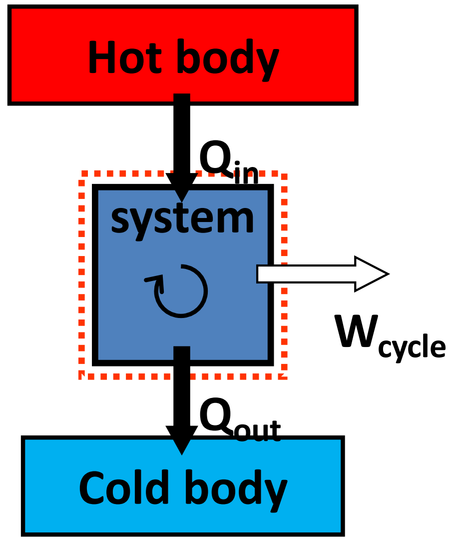
Energy for closed systems

- Cycle analysis:

$$\Delta E = 0 = Q_{\mathrm{cycle}} - W_{\mathrm{cycle}}$$

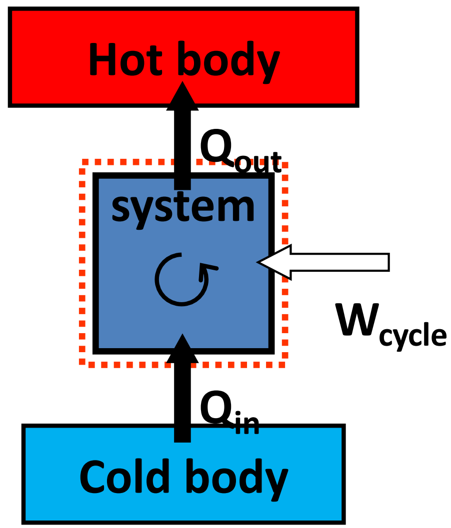
  – Power cycles:



$$\eta_{\mathrm{th}} = \frac{W_{\mathrm{cycle}}}{Q_{\mathrm{in}}} = 1 - \frac{|Q_{\mathrm{out}}|}{Q_{\mathrm{in}}}$$

Carnot

  – Refrigeration and heat pump cycles:



Q_{in}: Heat extracted at cold source

$$\mathrm{COP}_{\mathrm{cm}} = \frac{Q_{\mathrm{in}}}{|W_{\mathrm{cycle}}|} = \frac{Q_{\mathrm{in}}}{|Q_{\mathrm{out}}| - Q_{\mathrm{in}}}$$

Q_{out}: Heat rejected at hot source

$$\mathrm{COP}_{\mathrm{hm}} = \frac{Q_{\mathrm{out}}}{W_{\mathrm{cycle}}} = \frac{|Q_{\mathrm{out}}|}{|Q_{\mathrm{out}}| - Q_{\mathrm{in}}} = \mathrm{COP}_{\mathrm{cm}} + 1$$

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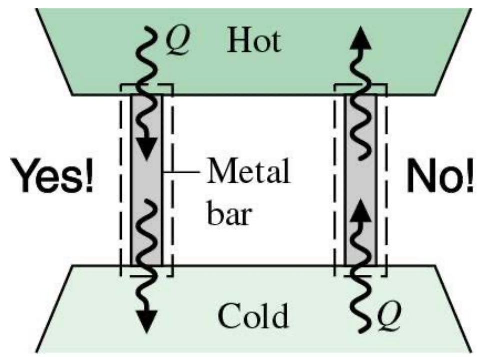
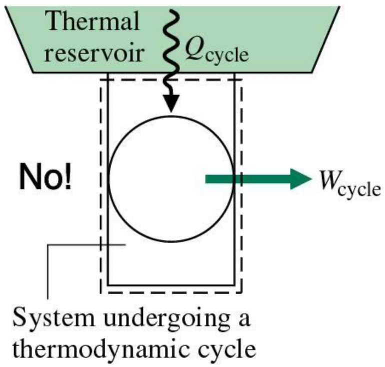
2^{nd} law of thermodynamics

- It is impossible for a system to operate in such a way that the only result would be an energy transfer by heat from a cooler to a hotter body.



- It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surrounding while receiving energy by heat transfer from a single thermal reservoir.



- It is impossible for any system to operate in a way that system entropy is destroyed.

$$S_2 - S_1 = \sum_j \frac{Q_j}{T_j} + \sigma$$

σ: >0 irreversibilities; =0 no irreversibilities; <0 impossible

internal entropy production

Entropy balance – closed systems

$$\begin{bmatrix}\text{change in the} \\ \text{amount of entropy} \\ \text{contained within system} \\ \text{during time interval}\end{bmatrix} = \begin{bmatrix}\text{net amount of entropy} \\ \text{transferred in across} \\ \text{system boundary} \\ \text{during time interval}\end{bmatrix} + \begin{bmatrix}\text{amount of entropy} \\ \text{produced within} \\ \text{system during} \\ \text{time interval}\end{bmatrix}$$

- General:

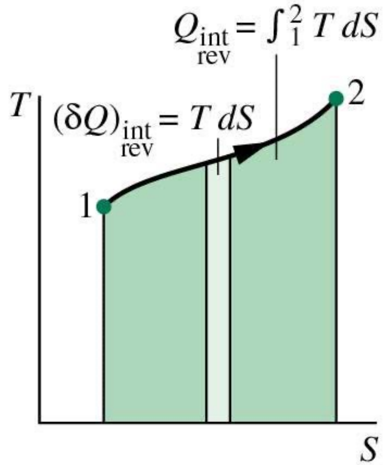
$$S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_b + \sigma = \sum_j \frac{Q_j}{T_j} + \sigma \qquad \frac{dS}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \dot{\sigma}$$

- Internally reversible processes:

$$S_2 - S_1 = \left(\int_1^2 \frac{\delta Q}{T}\right)_{\substack{\text{int}\\ \text{rev}}} \qquad \frac{dS}{dt} = \left(\sum_j \frac{\dot{Q}_j}{T_j}\right)_{\substack{\text{int}\\ \text{rev}}}$$

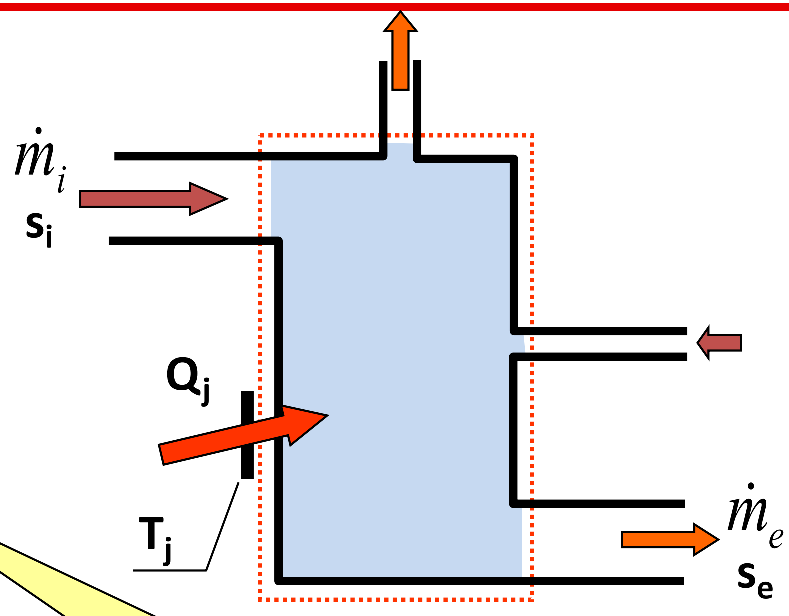
S = State function: process **independent**

heat transfer : process **dependent**



Entropy balance – open systems

- Entropy balance for an open system:



$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \underbrace{\sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e} + \dot{\sigma}_{cv}$$

Rate of entropy change in control volume

Entropy transfer due to heat transfer (in or out) over system boundary

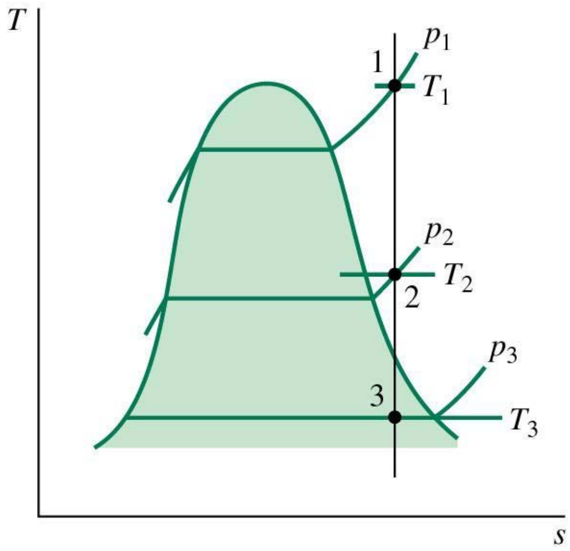
Convective entropy transport

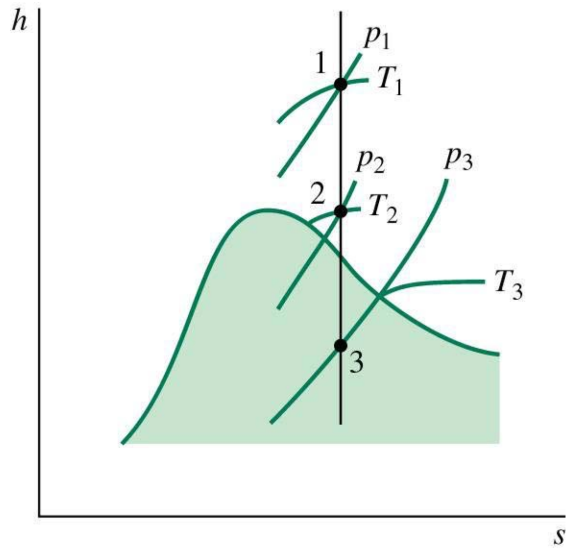
Entropy production within the control volume

- Simplifications for steady state systems, or systems with only one inlet/outlet

Isentropic processes

- Isentropic = constant entropy.
- Isentropic processes are processes where the entropy at the initial and final state are equal.
- Isentropic processes, e.g.: closed system, reversible and adiabatic process





- Isentropic (turbine) efficiencies:

$$\eta_{t,s} = \frac{\dot{W}/\dot{m}}{\left(\dot{W}/\dot{m}\right)_s} = \frac{h_1 - h_2}{h_1 - h_{2,s}}$$

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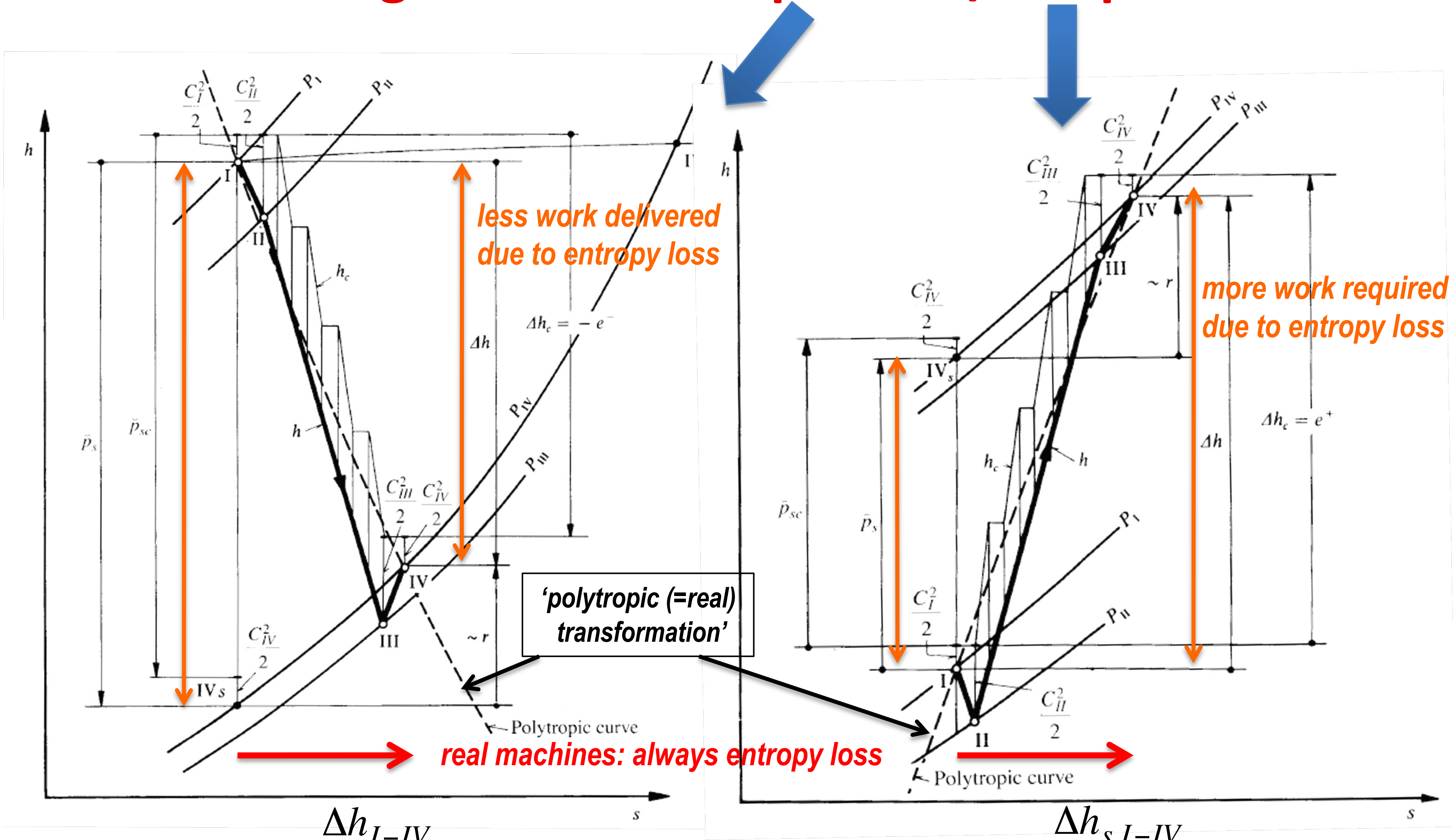
h-s diagram of fluid expansion/compression



$$\eta_{Ts} = \frac{\Delta h_{I-IV}}{\Delta h_{s,I-IV}}$$

isentropic turbine efficiency

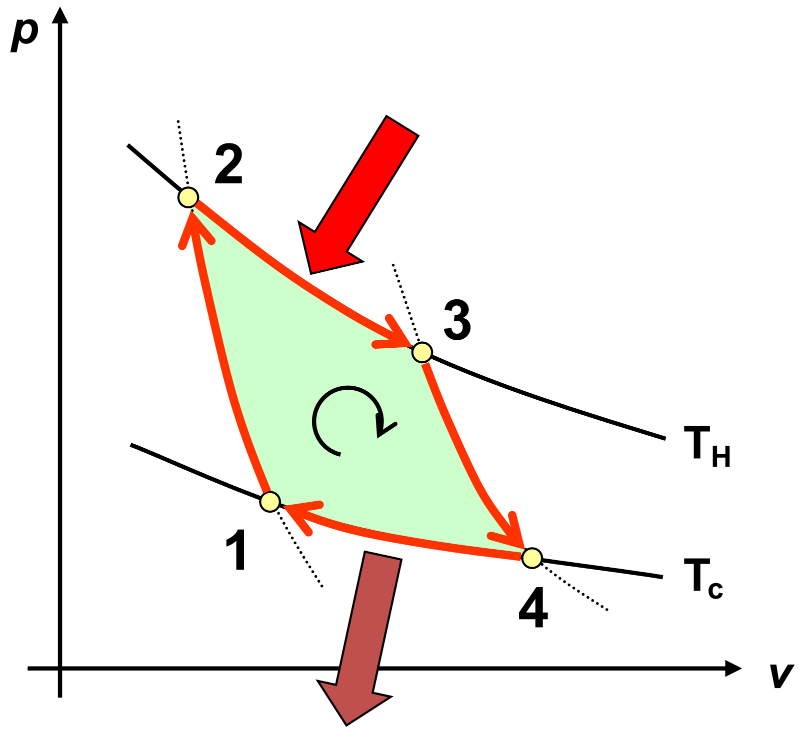
$$\eta_{Cs} = \frac{\Delta h_{s,I-IV}}{\Delta h_{I-IV}}$$

isentropic compressor efficiency

Carnot cycle

- Carnot cycle:
  cycle that undergoes four reversible processes

- Two isothermal processes at two different temperature levels.
  Require heat to be delivered or rejected



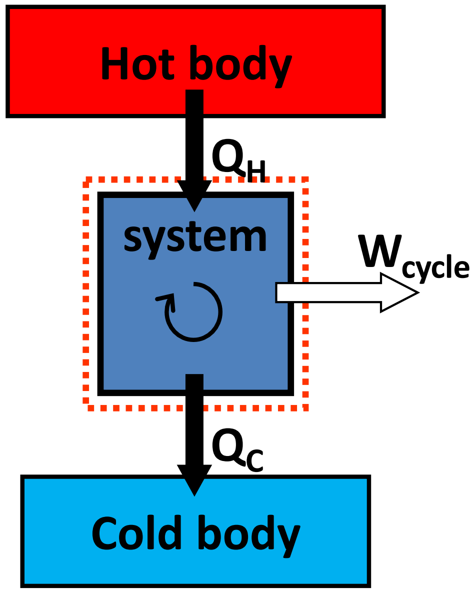
- Two isentropic processes

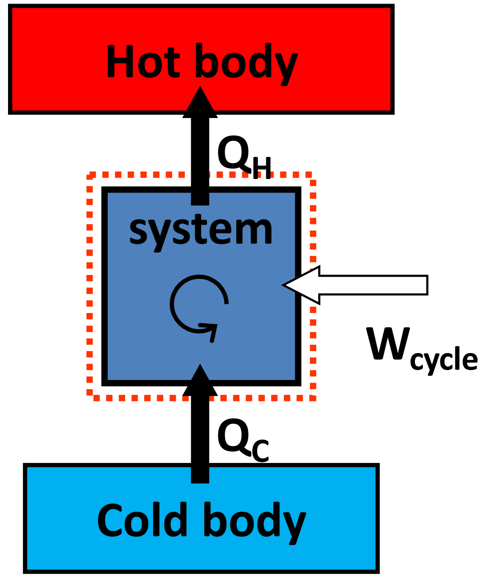
- Reverse direction => refrigeration or heat pump cycle

- Efficiency given by Carnot efficiency or COP

Carnot efficiency

- Maximum efficiencies of power and refrigeration/heat pump cycles:





Efficiency	$\eta_{\text{th}} = \dfrac{W_{\text{cycle}}}{Q_{\text{H}}} = 1 - \dfrac{Q_{\text{C}}}{Q_{\text{H}}}$	$\text{COP}_{\text{cm}} = \dfrac{Q_{\text{C}}}{W_{\text{cycle}}} = \dfrac{Q_{\text{C}}}{Q_{\text{H}} - Q_{\text{C}}}$	$\text{COP}_{\text{hm}} = \dfrac{Q_{\text{H}}}{W_{\text{cycle}}} = \dfrac{Q_{\text{H}}}{Q_{\text{H}} - Q_{\text{C}}}$
Max. efficiency (Carnot)	$\eta_{\text{th,max}} = 1 - \left(\dfrac{Q_{\text{C}}}{Q_{\text{H}}}\right)_{\substack{\text{rev}\\ \text{cycle}}} = 1 - \dfrac{T_{\text{C}}}{T_{\text{H}}}$	$\text{COP}_{\text{cm,max}} = \dfrac{T_{\text{C}}}{T_{\text{H}} - T_{\text{C}}}$	$\text{COP}_{\text{hm,max}} = \dfrac{T_{\text{H}}}{T_{\text{H}} - T_{\text{C}}}$

Efficiency independent of process, components, fluids, only dependent on temperature of reservoirs
Best case -> exergy efficiency = 1 -> delivered work equals received heat exergy

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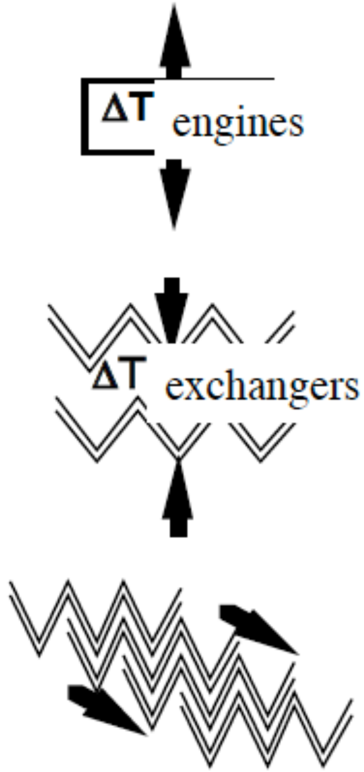
Consequences of the 2nd Law

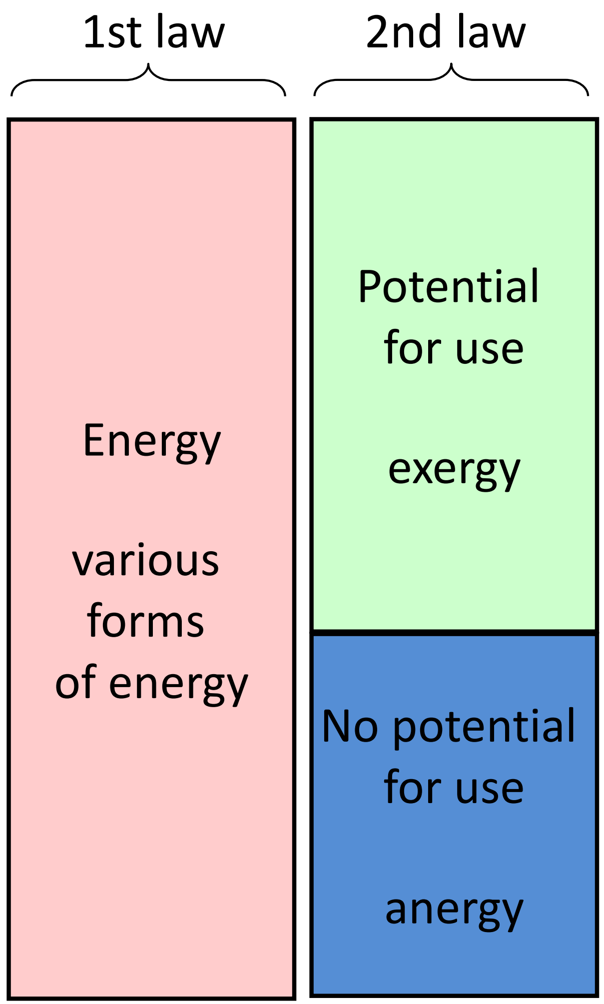
Practical implications from the second law:

- **Increase the temperature differences of the engine cycles.** (Superposed cycles, increased higher temperature)
- **Limit the temperature drop during heat transfer** (Increase the heat exchange surfaces (but take care of the pressure drop), counter current heat exchange)
- **Multiply the use of a same thermal source** (Cogeneration, heat exchanger cascade, extraction in turbine, superposed cycles)



Exergy

- What is the potential for use?



Exergy

- Exergy – Definition:

$$Ex = U - U_0 + KE + PE - T_0\left(S - S_0\right) + p_0\left(V - V_0\right)$$

- Specific exergy:

$$ex = u - u_0 + ke + pe - T_0\left(s - s_0\right) + p_0\left(v - v_0\right)$$

- Exergy difference between two states:

$$Ex_2 - Ex_1 = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) - T_0\left(S_2 - S_1\right) + p_0\left(V_2 - V_1\right)$$

- Specific exergy difference between two states:

$$ex_2 - ex_1 = (u_2 - u_1) + (ke_2 - ke_1) + (pe_2 - pe_1) - T_0\left(s_2 - s_1\right) + p_0\left(v_2 - v_1\right)$$

Exergy balance - open systems

- Open systems – Exergy:

$$\frac{dEx}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \left(\dot{W} - p_0 \frac{dV}{dt}\right) + \sum_i \dot{m}_i ex_{f,i} - \sum_e \dot{m}_e ex_{f,e} - T_0 \dot{\sigma}$$

Change in exergy within the volume	=	**Exergy transfer via heat transfer**	-	**Exergy transfer** via work	+	**Convective exergy transfer at the inlets and outlets**	-	**Exergy destruction due to irreversibilities**

- With flow exergy:

$$ex_f = u - u_0 + ke + pe - T_0\left(s - s_0\right) + p_0\left(v - v_0\right) + (p - p_0)v$$

$$ex_f = h - h_0 + ke + pe - T_0\left(s - s_0\right)$$

$$ex_f = ex + (p - p_0)v$$

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Exergy efficiency

- Exergy efficiency expresses the work-equivalent efficiency of energy resource utilization

$$\varepsilon_{ex} = \frac{\text{used exergy}}{\text{provided exergy}}$$

$$\eta = \frac{\text{used energy}}{\text{provided energy}}$$

energy efficiency

- Components:
  - Turbine:

$$\varepsilon_{ex} = \frac{\left(\dot{W} / \dot{m}\right)}{ex_{f,i} - ex_{f,e}}$$

  - Compressor/pump:

$$\varepsilon_{ex} = \frac{ex_{f,e} - ex_{f,\mathrm{i}}}{\left(-\dot{W}_{\mathrm{cv}} / \dot{m}\right)}$$

  - Heat exchanger: (non/mixing)

$$\varepsilon_{ex} = \frac{m_c(ex_{f,e,c} - ex_{f,i,c})}{m_h(ex_{f,i,h} - ex_{f,e,h})} \qquad \varepsilon_{ex} = \frac{m_2(ex_{f,3} - ex_{f,2})}{m_1(ex_{f,1} - ex_{f,3})}$$

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Turbine

Work **OUTPUT** (enthalpy balance):

$$\dot{E}^- = \dot{Y}^+ - \dot{Q}_a^- = \sum_j \left[h_{cj} \dot{M}_j^+ \right] - \dot{Q}_a^-$$

M: steam mass flow rate

$$\dot{E}^- = \dot{M}_1 h_{c1} - \dot{M}_2 h_{c2} - \dot{M}_3 h_{c3} - \dot{M}_4 h_{c4} - \dot{M}_5 h_5 - \dot{M}_6 h_6 - \dot{Q}_a^-$$

$$\dot{E}^- = \dot{E}_y^+ - \dot{L}$$

Exergy **balance**:

$$\dot{E}_y^+ = \sum_j \left[k_{czj} \dot{M}_j^+ \right] = \dot{M}_1 k_{c1} - \dot{M}_2 k_{c2} - \dot{M}_3 k_{c3} - \dot{M}_4 k_{c4} - \dot{M}_5 k_5 - \dot{M}_6 k_6$$

Exergy efficiency:

$$\eta = \frac{\dot{E}^-}{\dot{E}_y^+} = 1 - \frac{\dot{L}}{\dot{E}_y^+} = \frac{\sum_j \left[h_{cj} \dot{M}_j^+ \right] - \dot{Q}_a^-}{\sum_j \left[k_{cj} \dot{M}_j^+ \right]}$$

Exergy loss:

$$\dot{L} = T_a \sum_j \left[s_j \dot{M}_j^- \right] + \dot{Q}_a^-$$

$$\dot{L} = \underbrace{T_a (\dot{M}_2 s_2 + \dot{M}_3 s_3 + \dot{M}_4 s_4 + \dot{M}_5 s_5 + \dot{M}_6 s_6 - \dot{M}_1 s_1)}_{} + \dot{Q}_a^-$$

dissipation in the steam network (inlet, outlet, blades, channels, labyrinth seals)

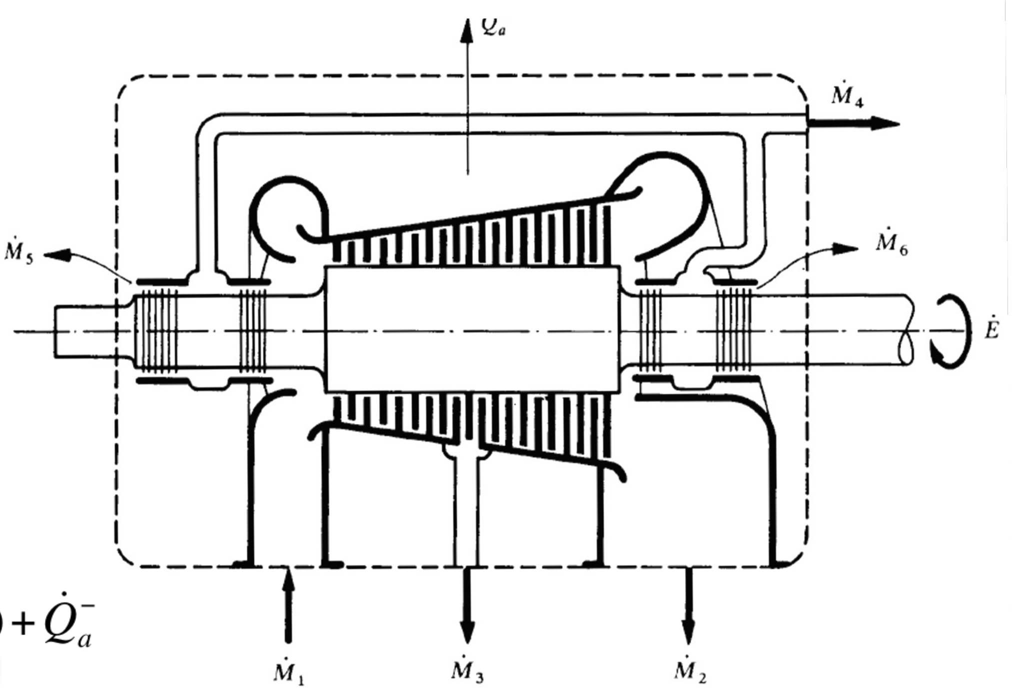


Fig. 10.42 A schematic representation of a steam turbine with extraction.

Compressor

Work **INPUT** (enthalpy balance):

$$\dot{E}^+ = \dot{Y}^- = \sum_j \left[h_{cj}\dot{M}_j^-\right] = \dot{M}_2 h_{c2} + \dot{M}_3 h_3 + \dot{M}_4 h_4 - \dot{M}_1 h_{c1}$$

Exergy : $\dot{E}_y^- = \sum_j \left[k_{cj}\dot{M}_j^-\right] = \dot{M}_2 k_{c2} + \dot{M}_3 k_3 + \dot{M}_4 k_4 - \dot{M}_1 k_{c1}$

Balance : $\dot{E}_y^- = \dot{E}^+ - \dot{L}_r$

Exergy efficiency:

$$\eta = \frac{\dot{E}_y^-}{\dot{E}^+} = 1 - \frac{\dot{L}_r}{\dot{E}^+} = \frac{\sum_j \left[k_{cj}\dot{M}_j^-\right]}{\sum_j \left[h_{cj}\dot{M}_j^-\right]}$$

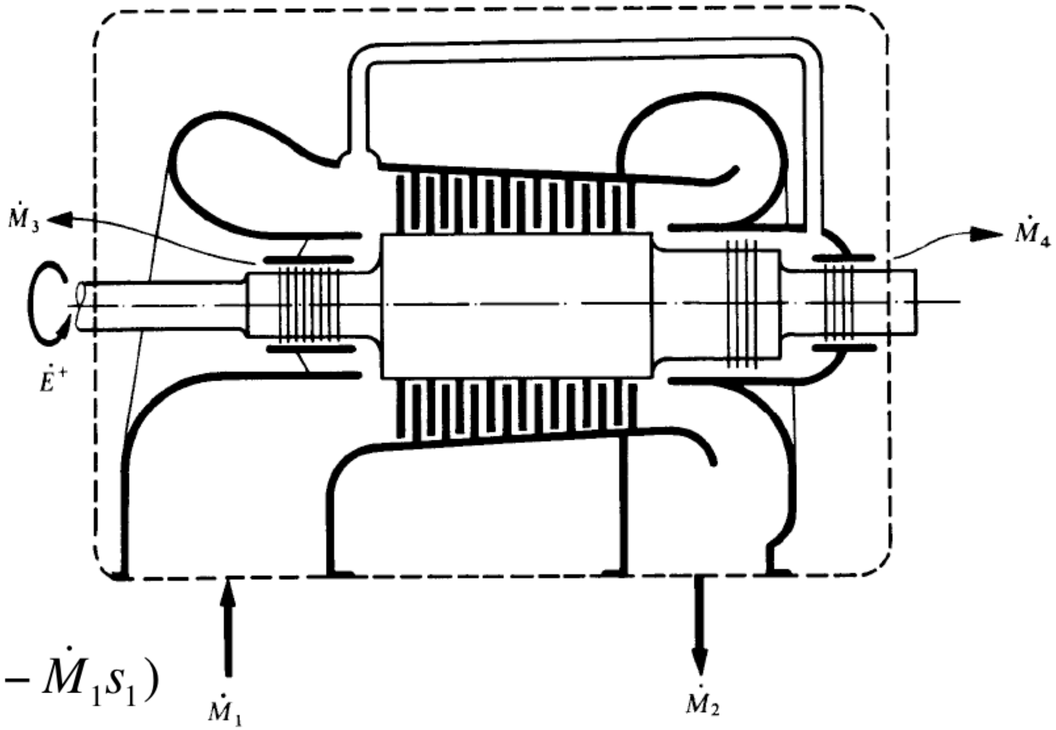


Fig. 10.43 A schematic representation of an axial compressor.

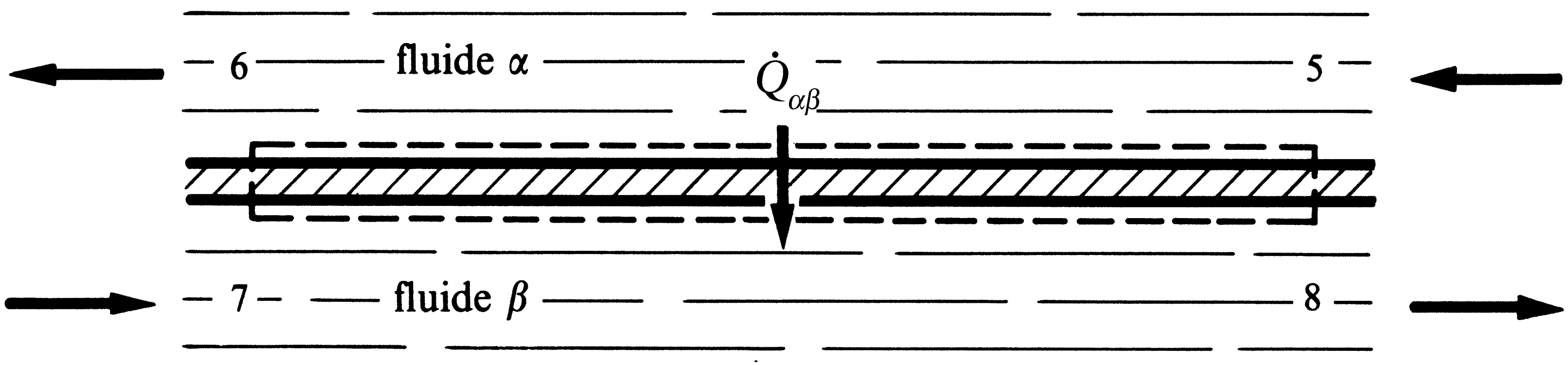
Exergy loss:

$$\dot{L}_r = T_a \sum_j \left[s_j \dot{M}_j^-\right] = T_a(\dot{M}_2 s_2 + \dot{M}_3 s_3 + \dot{M}_4 s_4 - \dot{M}_1 s_1)$$

fluid dissipation in the network (inlet, outlet, blades, channels, labyrinth seals)

Example of countercurrent HEX (steady state)

Heat transfer in counter-current between two fluids, steady state.
f.ex. fluid β heats up, evaporates, and superheats
(application: steam generator fluid (β) heated by exit gas (α) of a gas turbine)



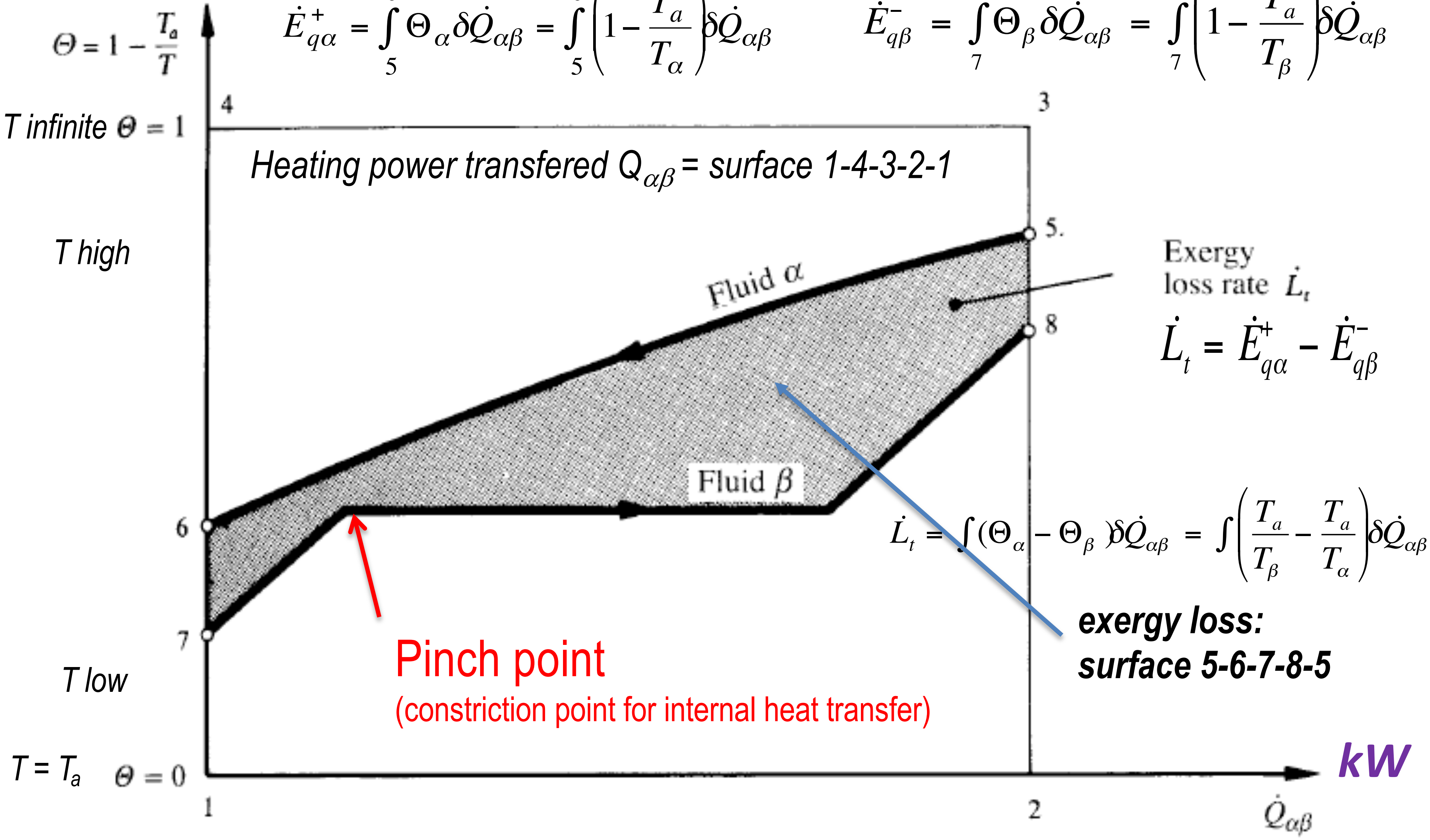
=> graphical representation, in terms of power (kW)

Heat-exergy received from α:
surface 2-5-6-1-2

$$\dot{E}^{+}_{q\alpha} = \int_{5}^{6} \Theta_{\alpha}\delta\dot{Q}_{\alpha\beta} = \int_{5}^{6}\left(1-\frac{T_a}{T_\alpha}\right)\delta\dot{Q}_{\alpha\beta}$$

Heat-exergy given to β:
surface 1-7-8-2-1

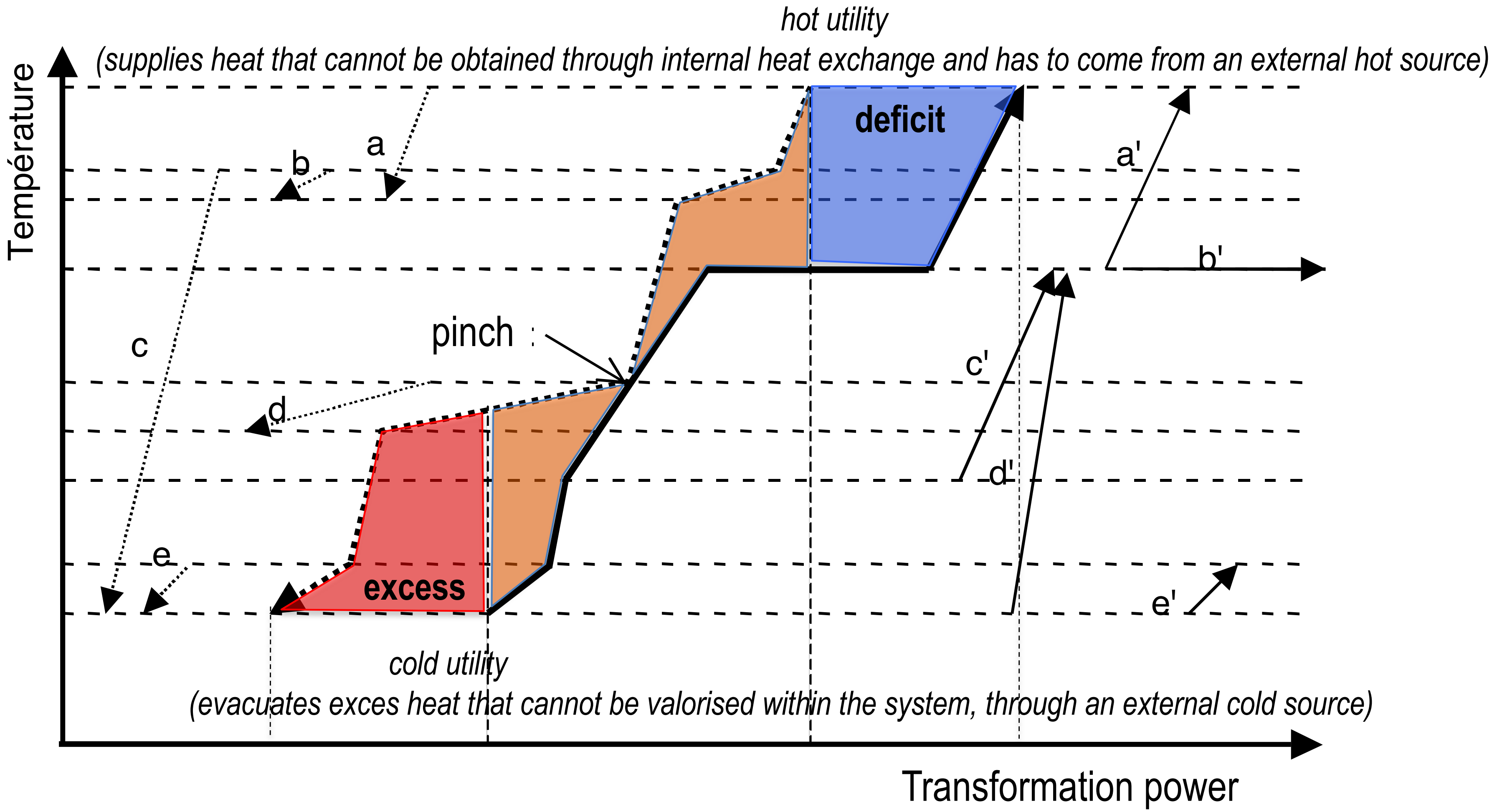
$$\dot{E}^{-}_{q\beta} = \int_{7}^{8} \Theta_{\beta}\delta\dot{Q}_{\alpha\beta} = \int_{7}^{8}\left(1-\frac{T_a}{T_\beta}\right)\delta\dot{Q}_{\alpha\beta}$$



$$\dot{L}_t = \dot{E}^{+}_{q\alpha} - \dot{E}^{-}_{q\beta}$$

$$\dot{L}_t = \int(\Theta_\alpha - \Theta_\beta)\delta\dot{Q}_{\alpha\beta} = \int\left(\frac{T_a}{T_\beta}-\frac{T_a}{T_\alpha}\right)\delta\dot{Q}_{\alpha\beta}$$

=> Pinch theory



All flows a, b, c, d, e are to cool → hot composite curve

All flows a',b',c',d',e' are to heat → cold composite curve

Goal = maximise the internal heat transfer between the 2 composite curves

(the orange zone represents the exergy losses due to <u>internal</u> heat transfer)

Comments

→ basis for the conception of heat exchanger networks (HEN), and of the identification of hot and cold utilities; also indicates the possibility to introduce heat pump or cogeneration units in the system

→ the pinch point fixes the limit which is possible to achieve with internal heat exchanges (crossing of the hot and cold composite curves)

→ in practice, the ΔT at the pinch cannot be zero (which would imply infinitely large heat exchanger surface); it is optimised for cost (=avoid too large heat exchanger surfaces) and pressure drop

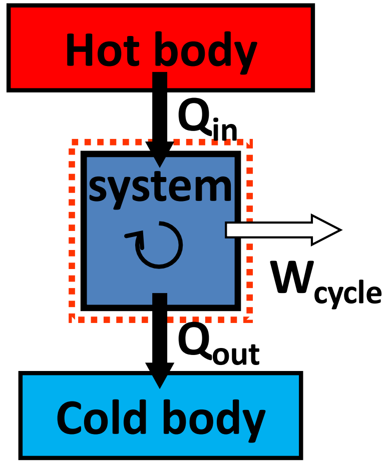
transfered power in a heat exchange = $h.A.\Delta T$, with:

h = heat transfer coefficient ($W/m^2.K$), material-dependent;

A = exchange surface

Power systems

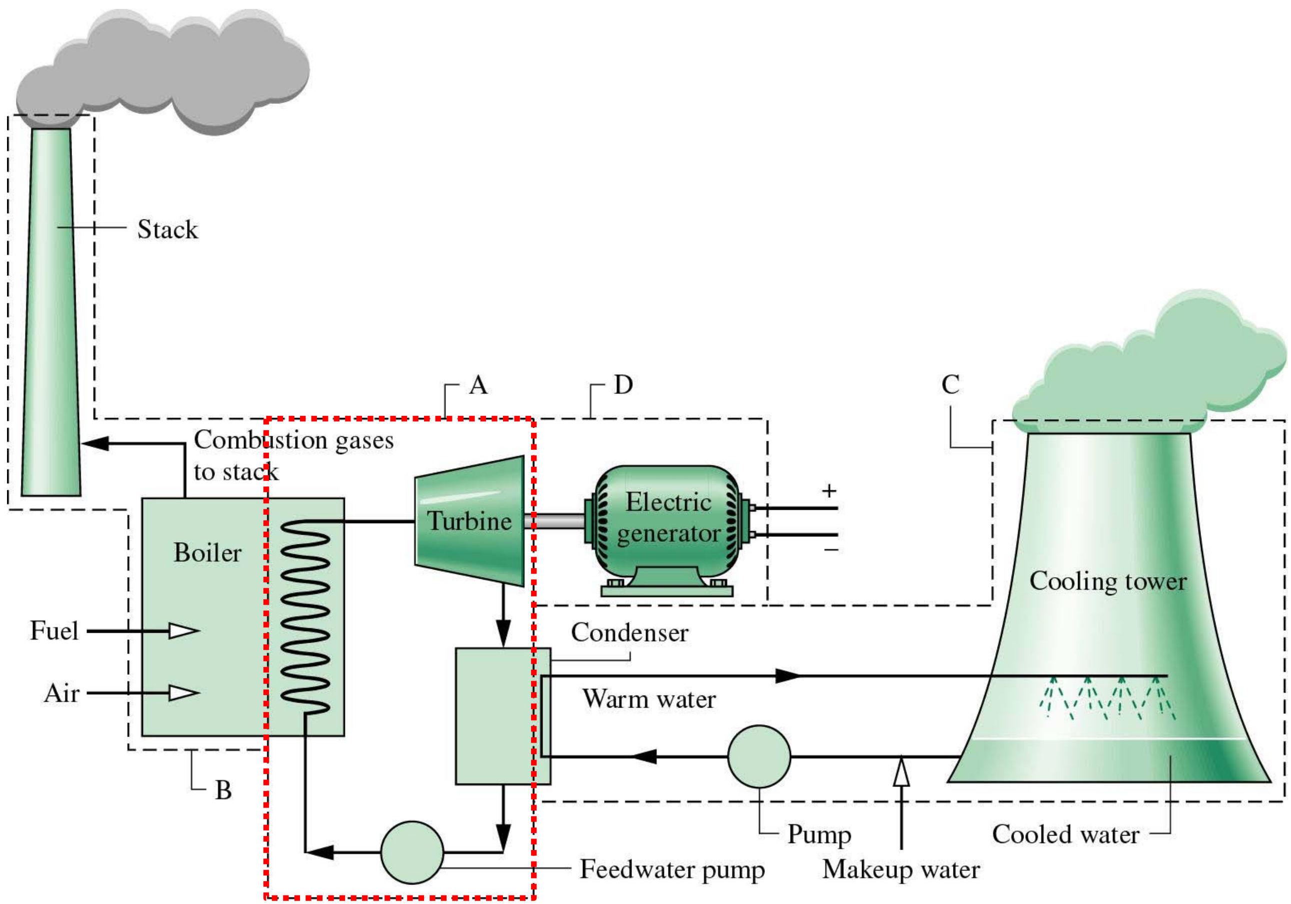
- Produce net power output from an energy source, such as (fossil/renewable) fuel, nuclear, solar, biomass,…



- Three major types of systems:
  - Vapor power plants (working fluid alternately vaporizes and condenses)
  - Gas turbine power plants (working fluid = gas, series of components)
  - Internal combustion engines (working fluid = gas, reciprocating)

Vapor power systems

- Vapor power systems:
  - Water is the working fluid, which alternately vaporizes and condenses
  - **Majority of electrical power generation** done by these systems
  - Basic components in a simple system are:
    - Boiler
    - Turbine
    - Condenser
    - Pump



Vapor power systems

- Idealized *Rankine* cycle:
  - Turbine: *isentropic* expansion (1→2)

$$\dot{W}_t / \dot{m} = (h_1 - h_2)$$

  - Condenser: *isobaric* heat transfer (2→3)

$$\dot{Q}_{out} / \dot{m} = (h_3 - h_2)$$

  - Pump: *isentropic* compression (3→4)

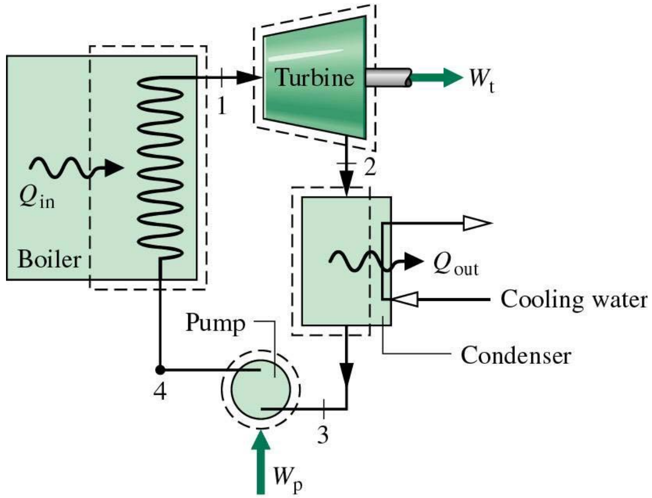
$$\dot{W}_p / \dot{m} = (h_3 - h_4)$$

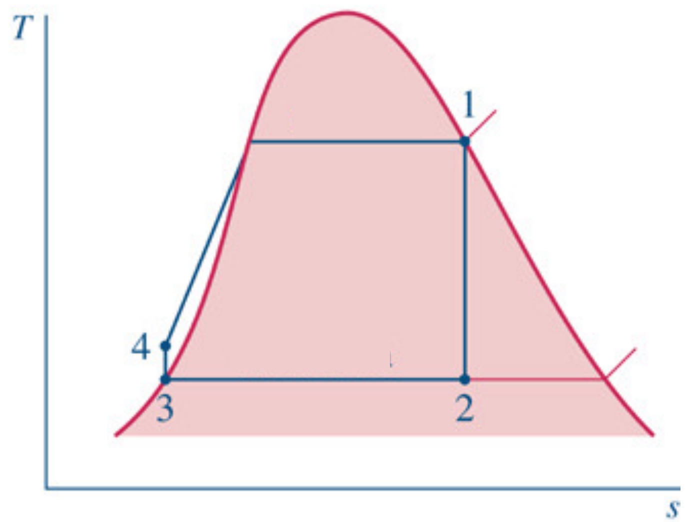
  - Boiler: *isobaric* heat transfer (4→1)

$$\dot{Q}_{in} / \dot{m} = (h_1 - h_4)$$

  - Efficiency:

$$\eta = \frac{\dot{W}_t / \dot{m} + \dot{W}_p / \dot{m}}{\dot{Q}_{in} / \dot{m}} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_4)}$$



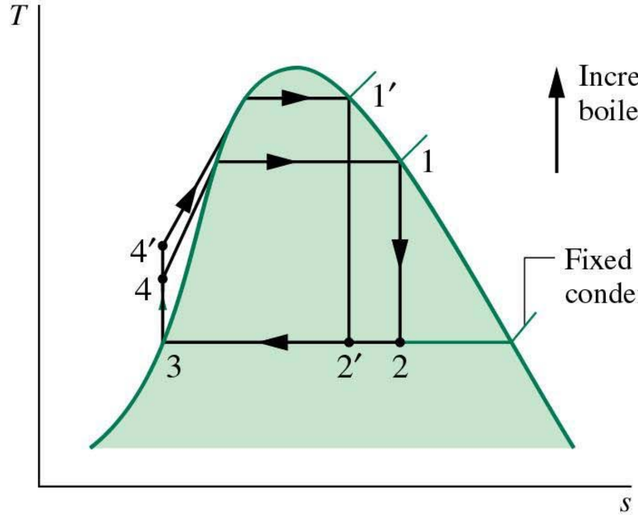


Vapor power systems

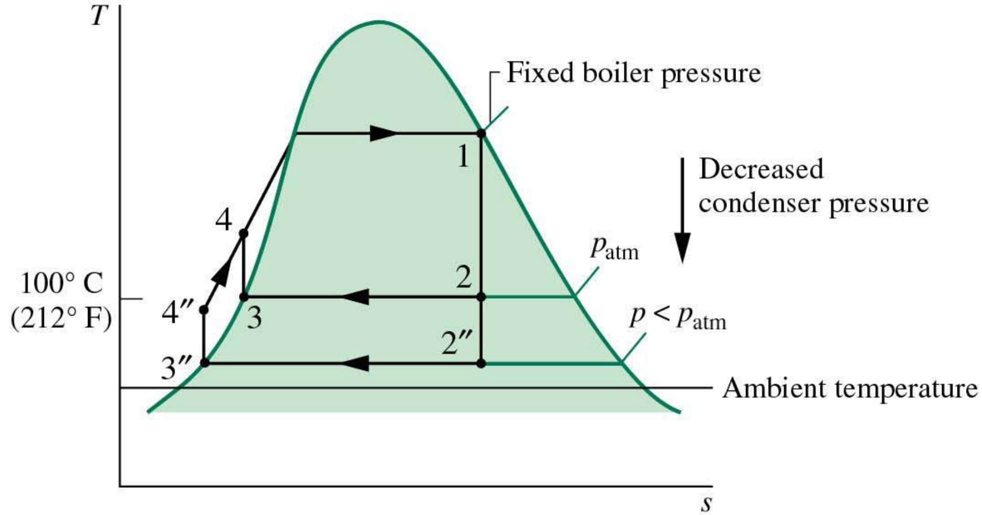
- Idealized Rankine cycle: effects of components on performance:
  - Increase of average temperature at which energy is added and decrease of average temperature at which energy is rejected leads to increased efficiency (Carnot):

$$\eta_{ideal} = \frac{(\dot{Q}_{in} / \dot{m})_{int,rev} - (\dot{Q}_{out} / \dot{m})_{int,rev}}{(\dot{Q}_{in} / \dot{m})_{int,rev}} = 1 - \frac{\overline{T}_{out}}{\overline{T}_{in}}$$

  - Increase in boiler pressure and decrease in condenser pressures:



(a)



(b)

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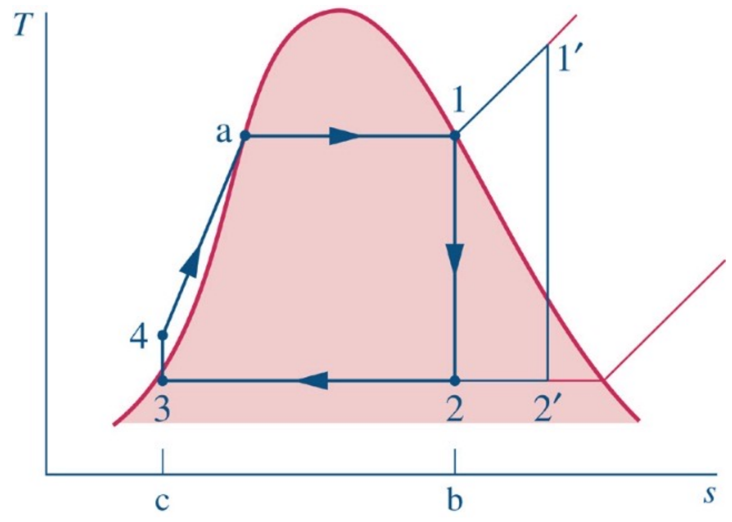
Vapor power systems

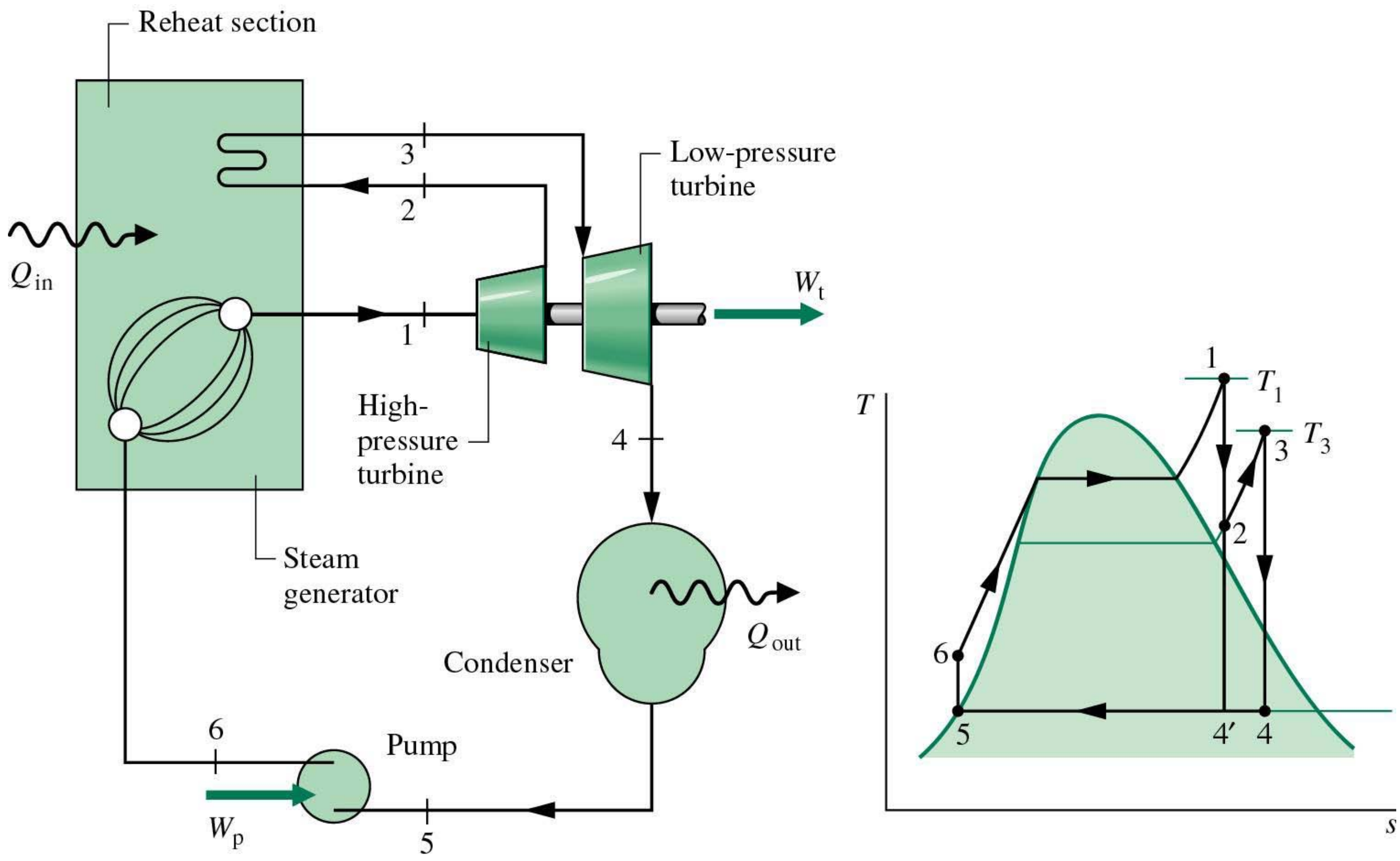
- Rankine cycle: improving performance:
  - **1.Superheating** (using additional heat exchanger, combination of boiler and heat exchanger is called steam generator)



Protects turbine (higher vapor quality *x*) & increases efficiency (higher *T*)

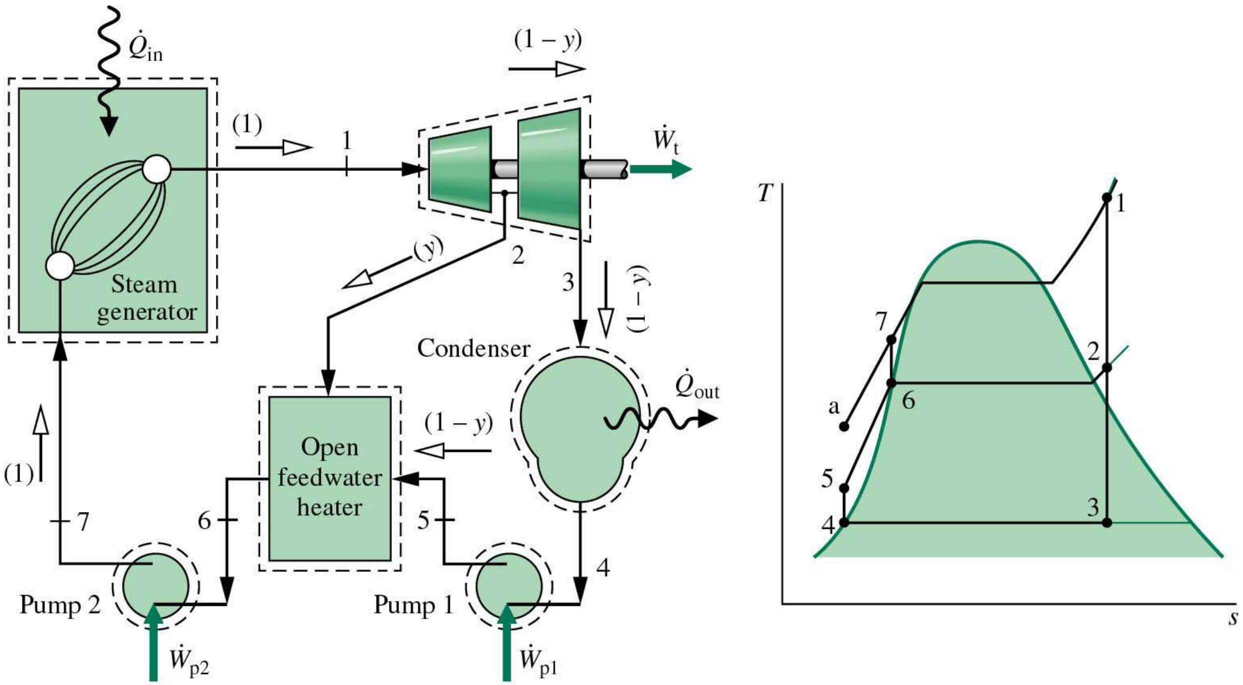
Vapor power systems

- Rankine cycle: improving performance:
  - **2.Reheating**

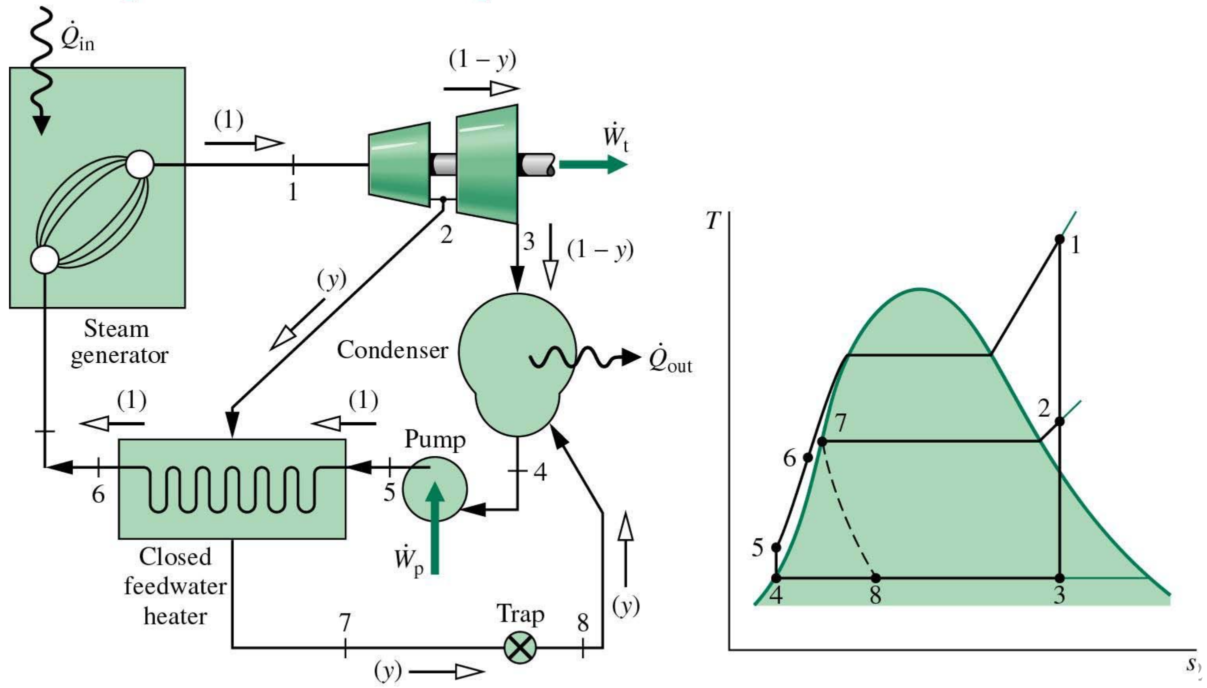


Vapor power systems

- Rankine cycle: improving performance:
  - **3.Regeneration** via open feedwater heater



closed feedwater heater



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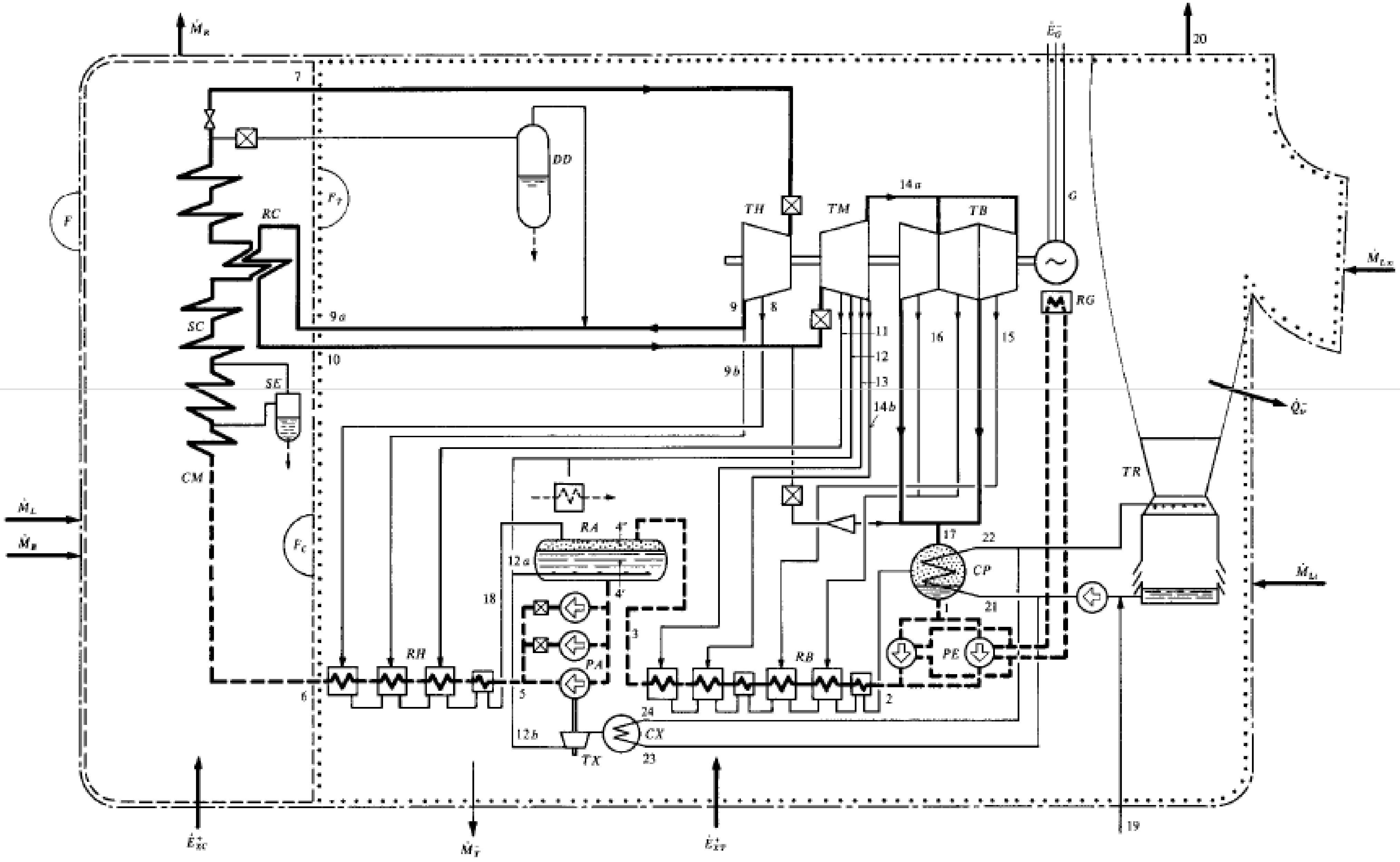
Real steam plant example:



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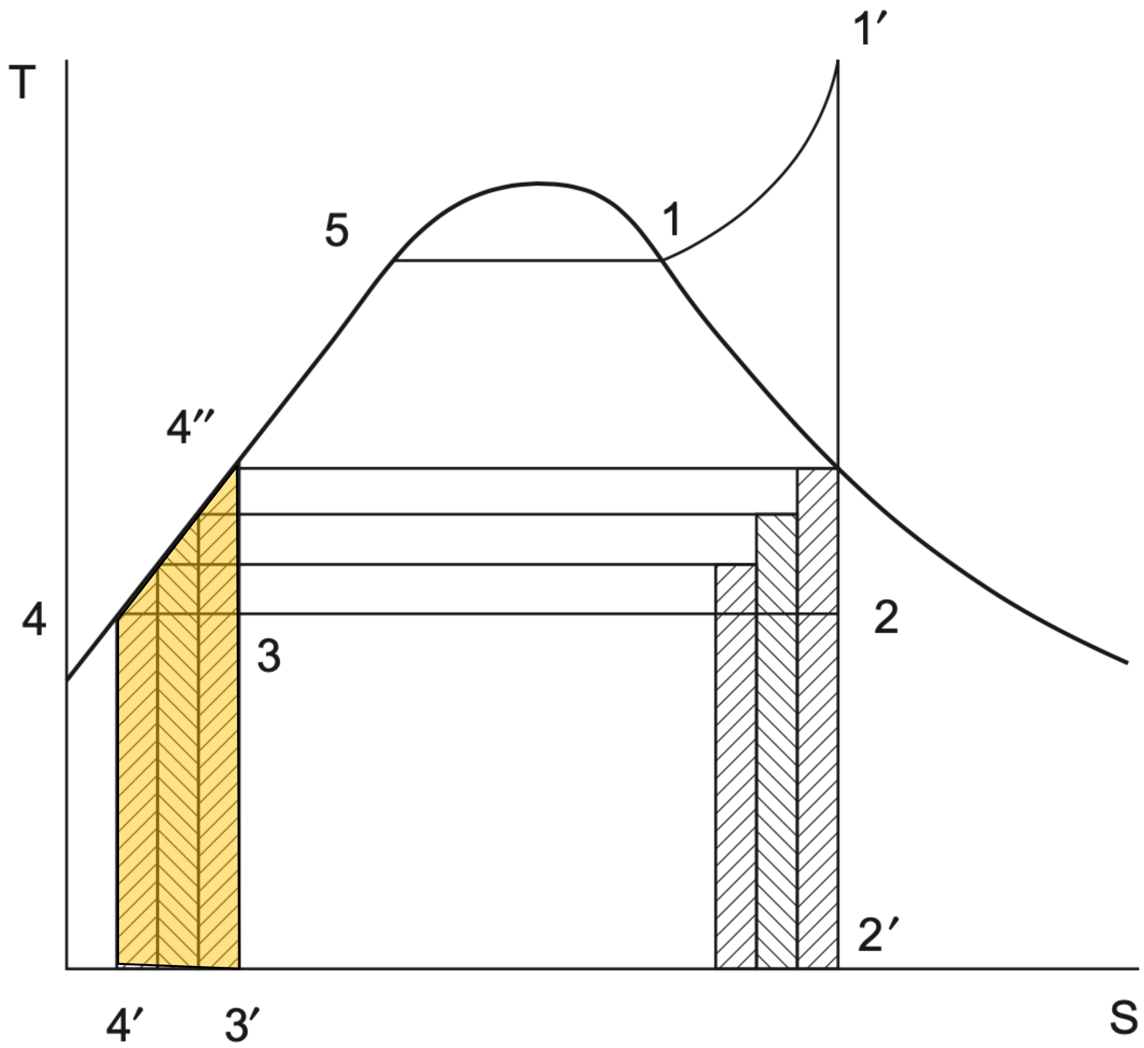
Multistage extraction



Heat addition to the cycle is reduced from the area bounded by 4’-4-4”-5-1-1’-2-2’-4’ to the area bounded by 3’-3-4”-5-1-1’-2-2’-3’, hence the heat addition to the cycle is reduced by the area 4’-4-4”-3-3’-4’, keeping the output unchanged, thereby reducing the cost of power generation.

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Real steam plant example:

- 2 * 150 MW_e
- **8 extractions**
- **1 reheater;**

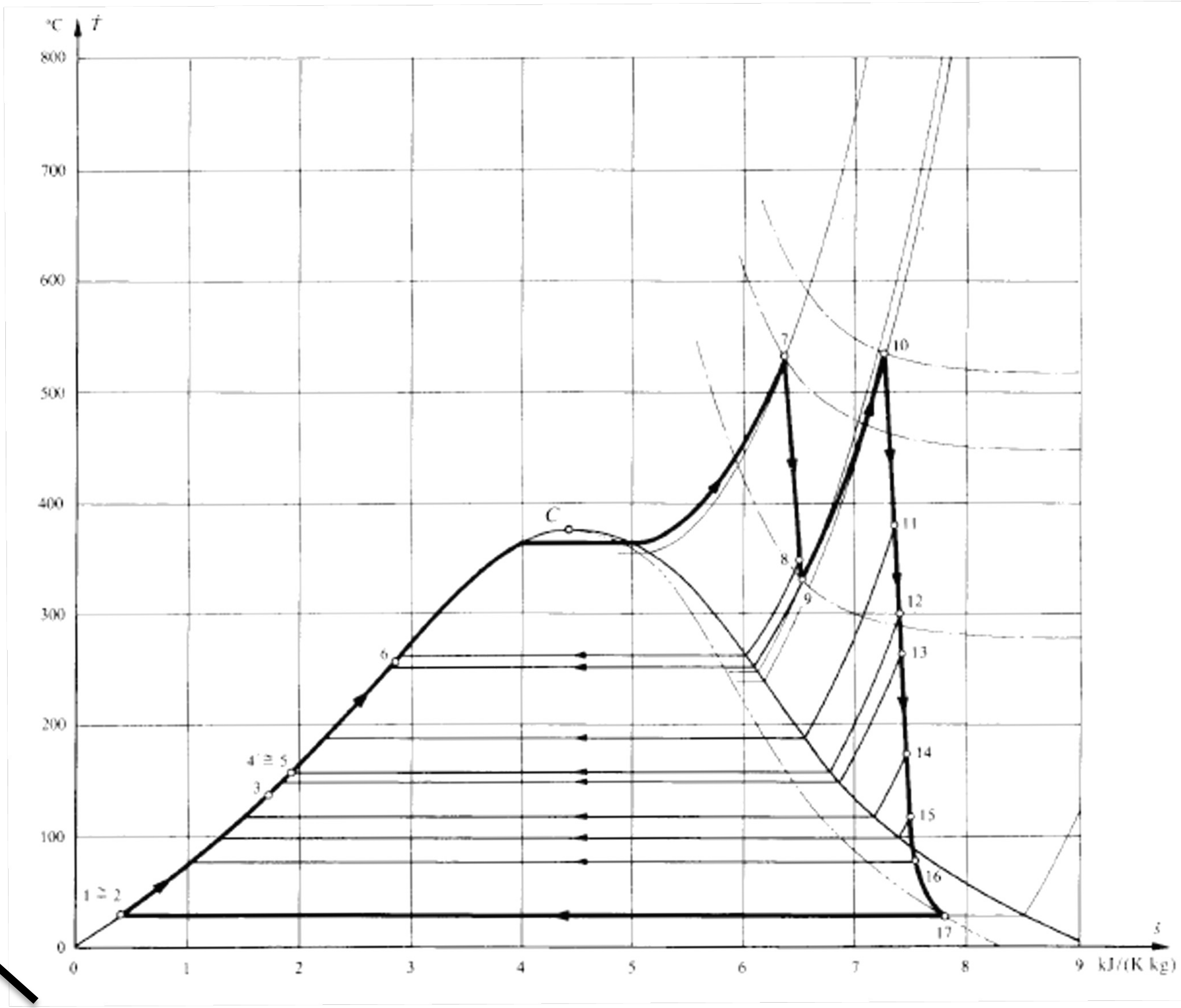
  for feed-water at HP and LP
- 5 turbines

  (1 HP, 1 MP, 3 LP)
- 2 cooling towers

$\varepsilon_{Turbogroup} = 75\%$

$\varepsilon_{Boiler} = 52\%$

$\varepsilon_{Plant} = \varepsilon_{TG} \cdot \varepsilon_{Boiler} = 39\%$



= the main exergy loss (large T drop) ←→ 1st law : 94%

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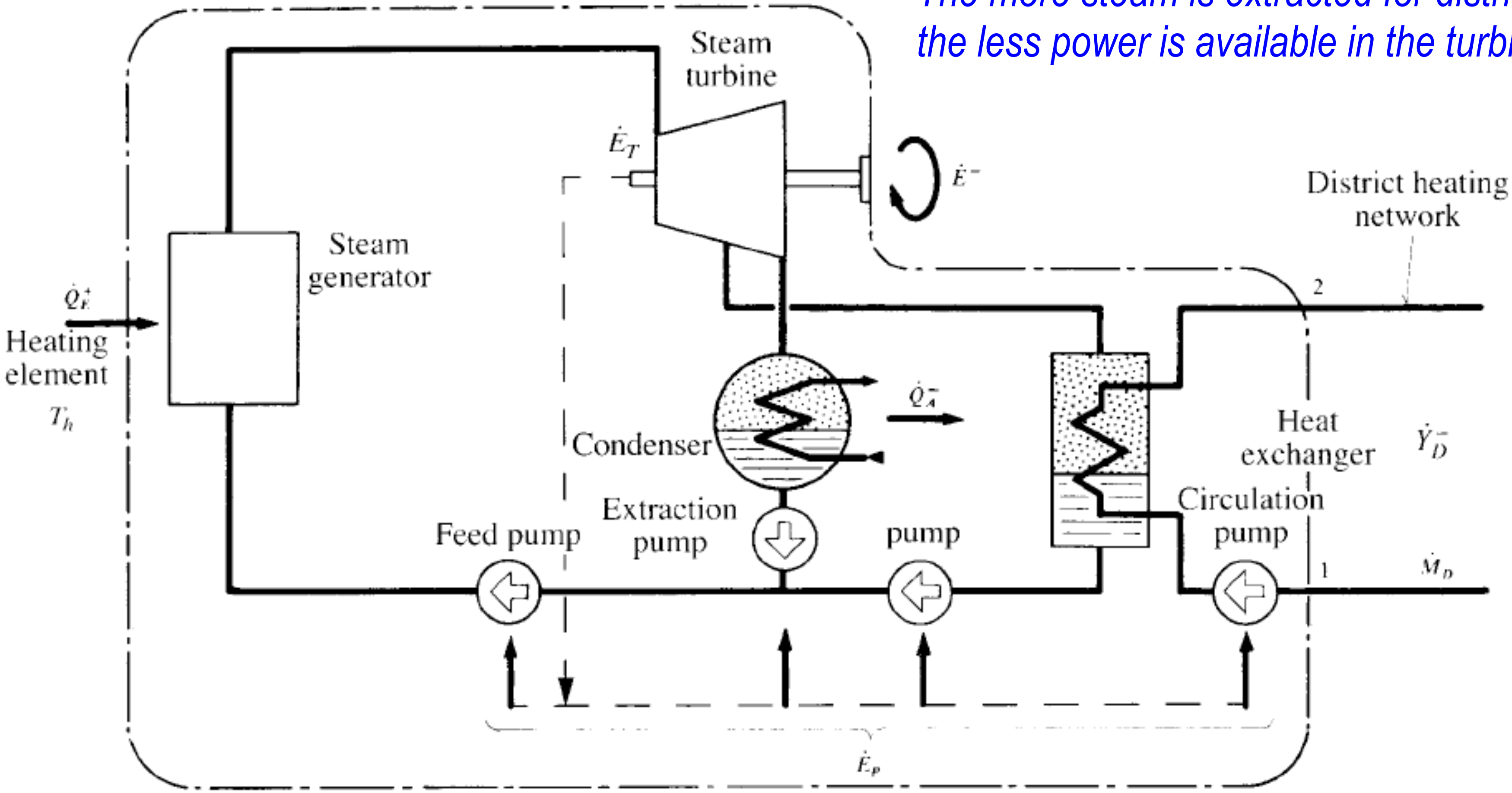
Co-generation

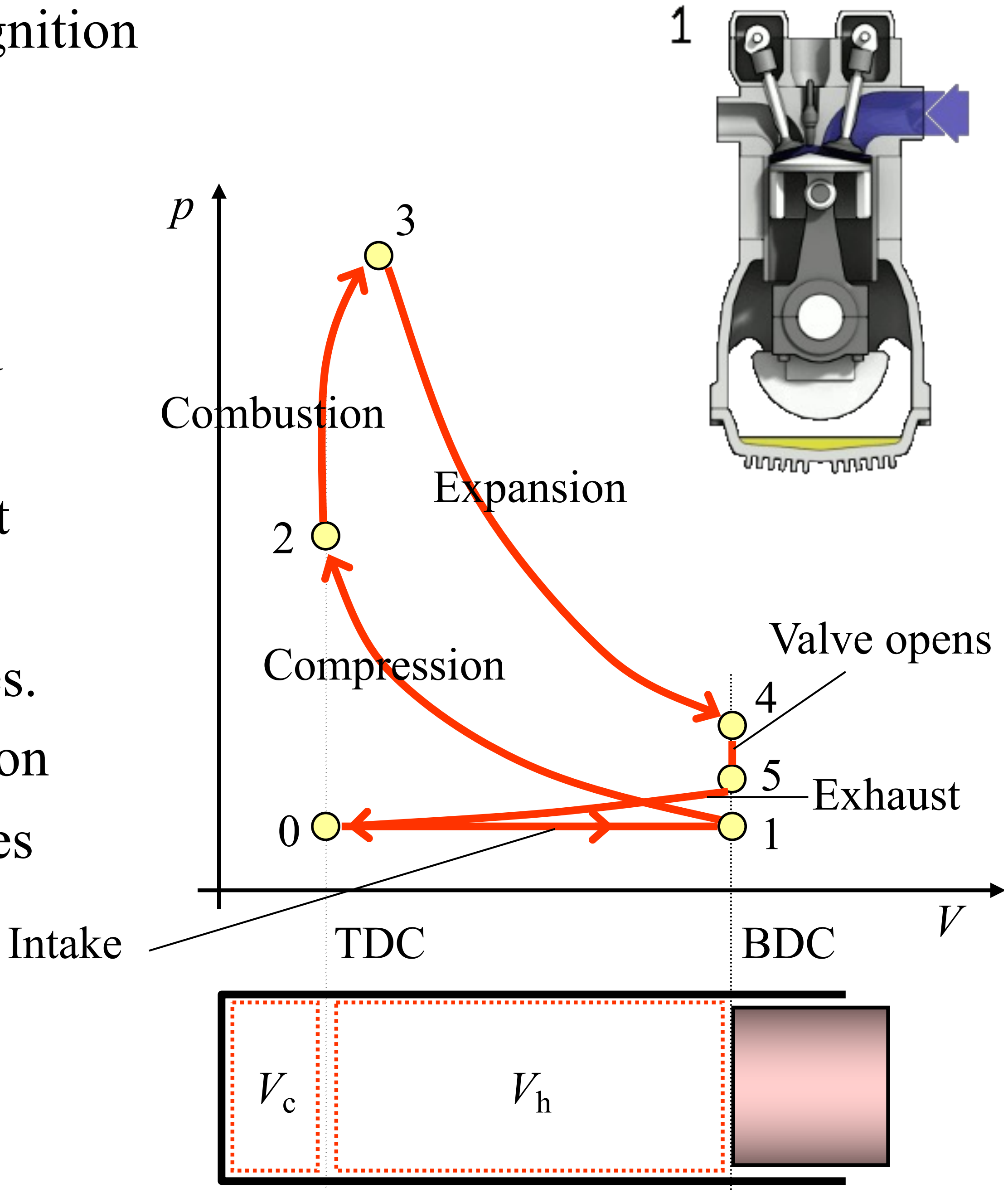
- Power and heat:
  - steam extraction to HEX for district heating (70°C)
  - output service: power E^- and enthalpy Y_D^-

The more steam is extracted for district heating, the less power is available in the turbine



Internal combustion engines

- Spark ignition or compression ignition



- *Air-standard analysis:*
  - Fixed amount of air modeled as ideal gas
  - Combustion modeled by heat transfer from external source
  - No exhaust and intake strokes. Constant volume heat rejection
  - Internally reversible processes

Internal combustion engines

- Air-standard **Otto** cycle:
  - 1-2: Isentropic compression

$$\frac{W_{12}}{m} = u_1 - u_2 \qquad (<0)$$

  - 2-3: Constant-volume heat transfer

$$\frac{Q_{23}}{m} = u_3 - u_2$$

  - 3-4: Isentropic expansion

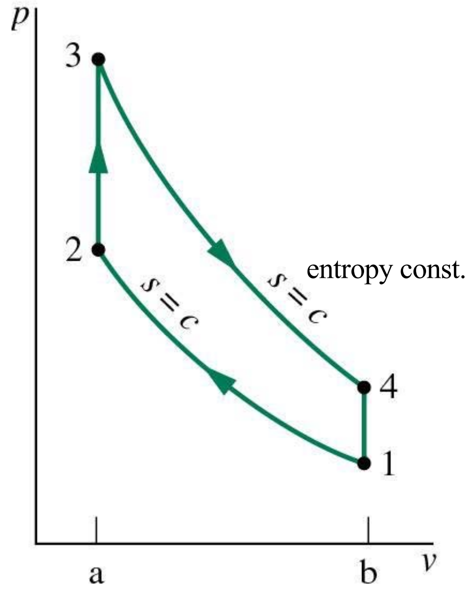
$$\frac{W_{34}}{m} = u_3 - u_4$$

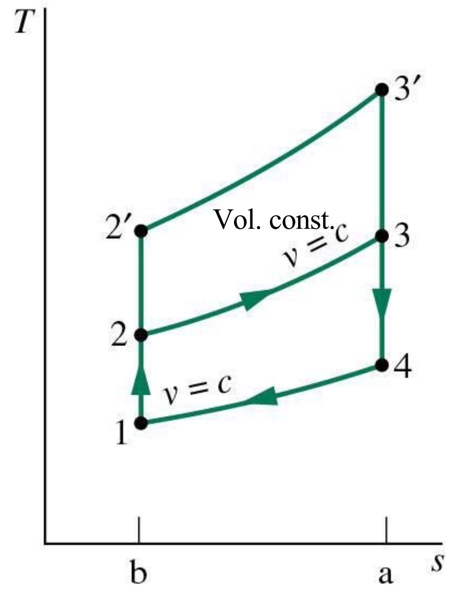
  - 4-1: Constant-volume heat rejection

$$\frac{Q_{41}}{m} = u_1 - u_4 \qquad (<0)$$

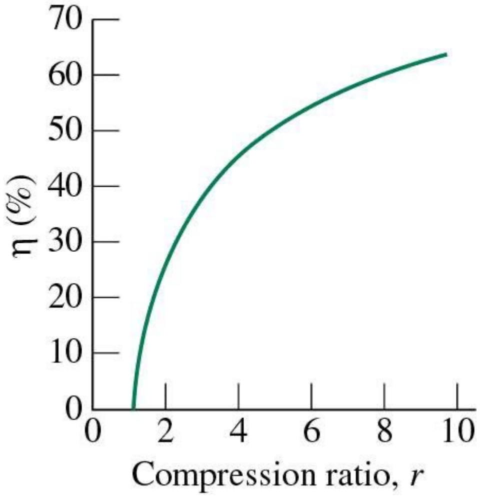
  - Cycle efficiency:

$$\eta = \frac{W_{cycle}}{Q_{23}} = \frac{u_3 - u_4 + u_1 - u_2}{u_3 - u_2}$$





Compression ratio: $r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$



Internal combustion engines

- Air-standard **Diesel** cycle:
  - 1-2: Isentropic compression

$$\frac{W_{12}}{m} = u_1 - u_2$$

  - 2-3: Constant-pressure heat transfer

$$\frac{W_{23}}{m} = p_2(v_3 - v_2) \qquad \frac{Q_{23}}{m} = u_3 - u_2 + \frac{W_{23}}{m}$$

  - 3-4: Isentropic expansion

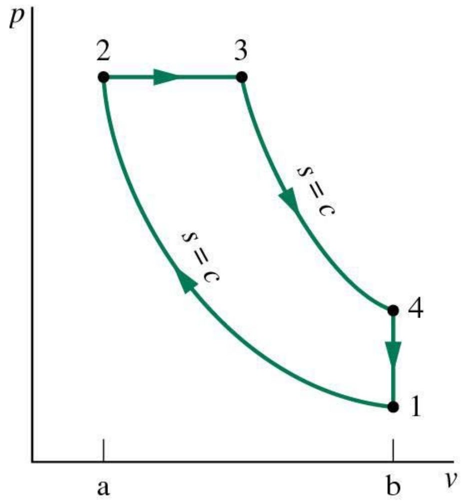
$$\frac{W_{34}}{m} = u_3 - u_4$$

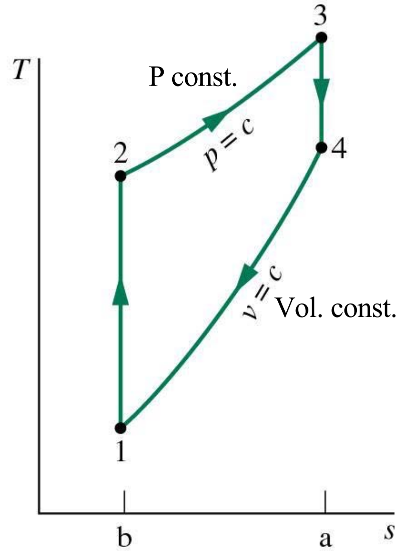
  - 4-1: Constant-volume heat rejection

$$\frac{Q_{41}}{m} = u_1 - u_4$$

  - Cycle efficiency:

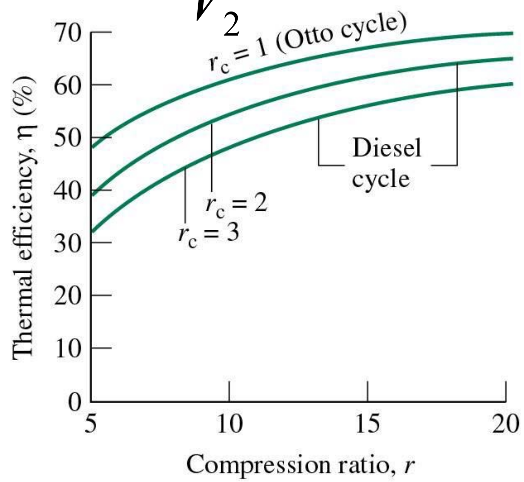
$$\eta = \frac{W_{cycle}}{Q_{23}} = \frac{h_3 - h_2 - u_4 + u_1}{h_3 - h_2}$$





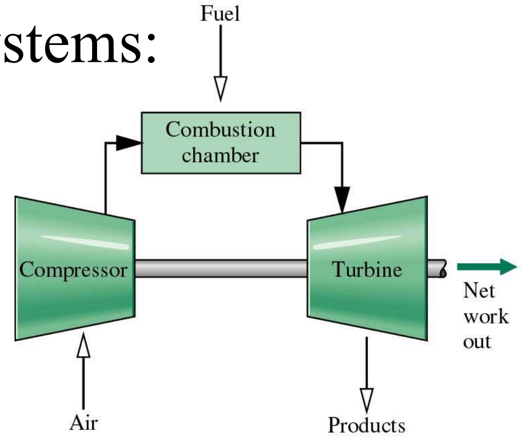
Compression ratio: $r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$

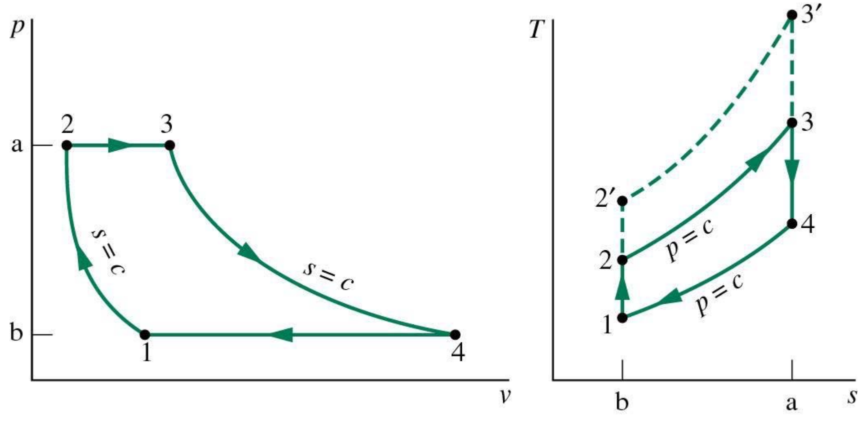
Cut-off ratio: $r_c = \frac{V_3}{V_2}$



Gas turbine power plants

- Gas turbine systems:





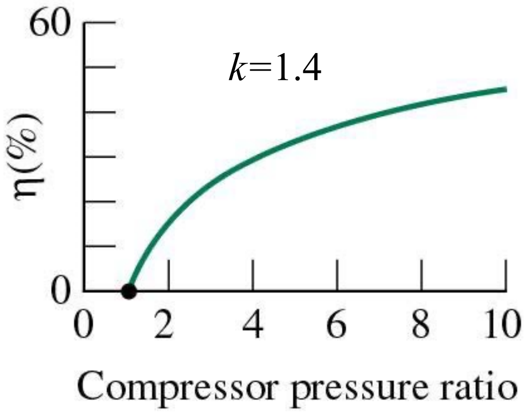
- Air-standard Brayton cycle (ideal):
  - 1-2: Isentropic compression $\frac{\dot{W}_{12}}{\dot{m}} = h_1 - h_2$
  - 2-3: Isobaric heat transfer $\frac{Q_{23}}{m} = h_3 - h_2$
  - 3-4: Isentropic expansion $\frac{\dot{W}_{34}}{\dot{m}} = h_3 - h_4$
  - 4-1: Isobaric heat transfer $\frac{Q_{41}}{m} = h_1 - h_4$

Cycle efficiency:

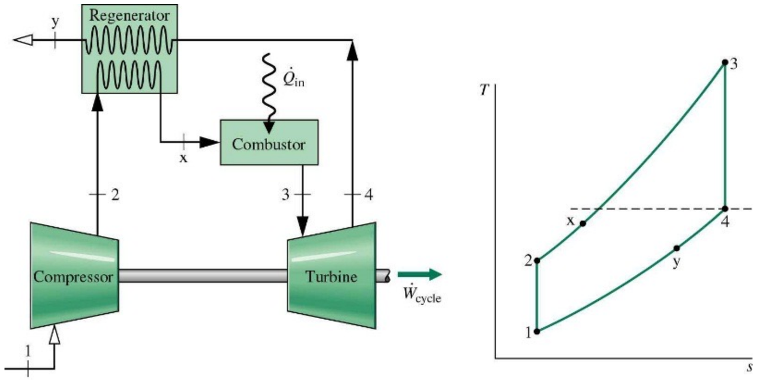
$$\eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{h_3 - h_4 + h_1 - h_2}{h_3 - h_2}$$

Gas turbine power plants

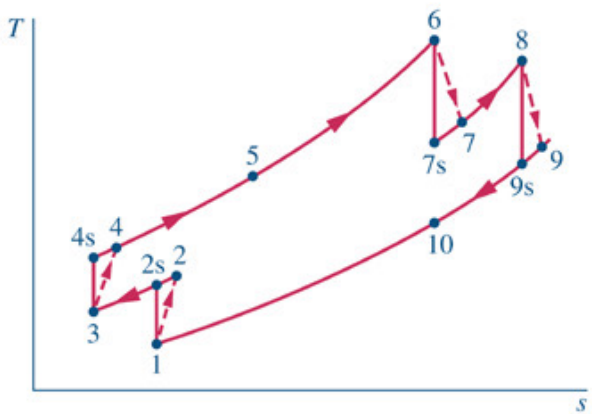
- Air-standard Brayton cycle: pressure ratio effect on performance
  - Efficiency increases with increasing pressure ratio



  - Regeneration:



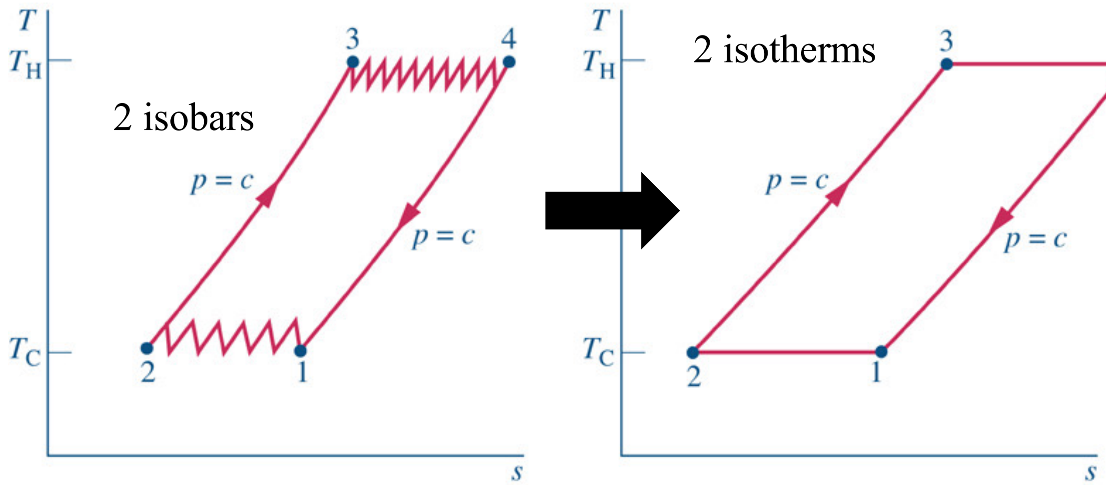
  - Reheating and intercooling:



External combustion engines

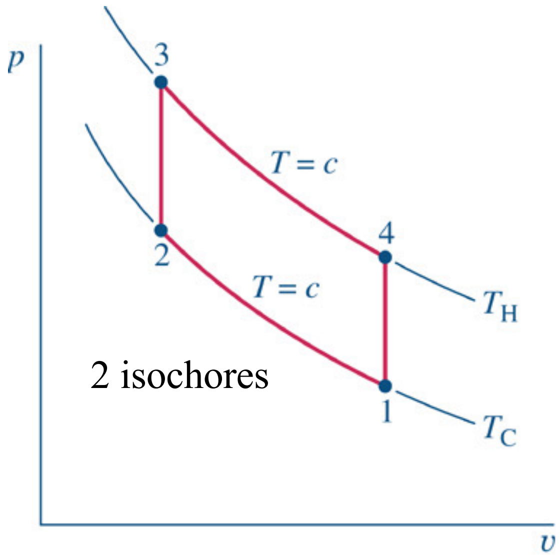
- Ericsson and Stirling cycle (both with same features as Carnot):
  - In the limit of large number of multi-stage compression with inter-cooling, and multi-stage expansion with re-heating, with ideal regeneration

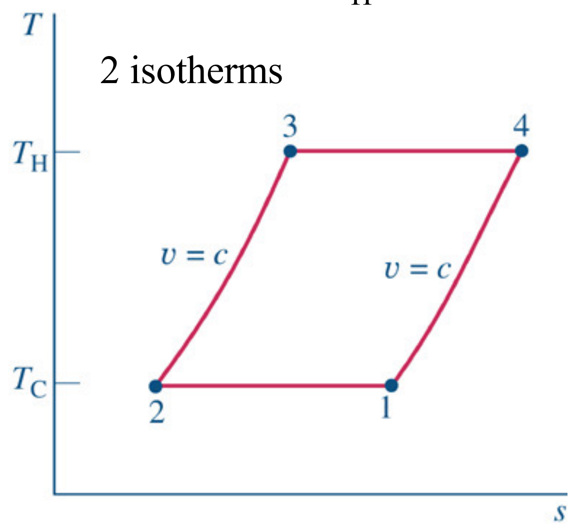
Ericsson cycle



$$\eta_{th} = 1 - \frac{T_C}{T_H}$$

  - Cycle with regeneration, internally reversible, internal heat transfer processes → Stirling cycle





Combined cycle (CC)

- Gas cycle + steam cycle
- Fuels: oil, natural gas, gasified coal fuels
- GT on top of ST ('*topping cycle*') **reduces exergy heat transfer loss** between fuel combustion gases and steam
- ST below the GT ('*bottoming cycle*') **reduces heat exergy loss** of the hot GT exhaust gas (450-650°C)

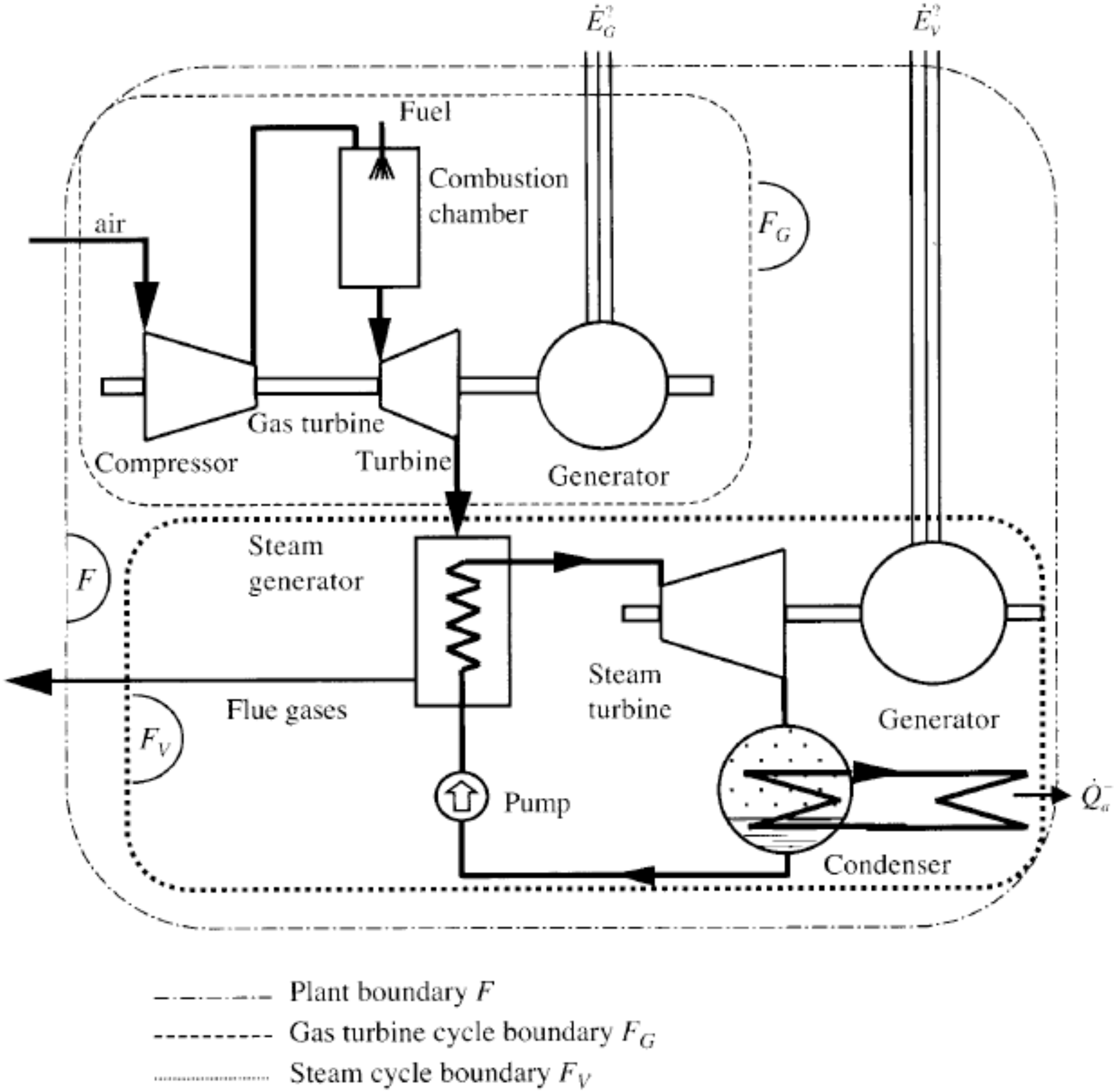
→ ***'win'–'win'*** combination between both cycles

→ the individual cycles in a CC configuration find themselves simplified with respect to their stand-alone configurations:

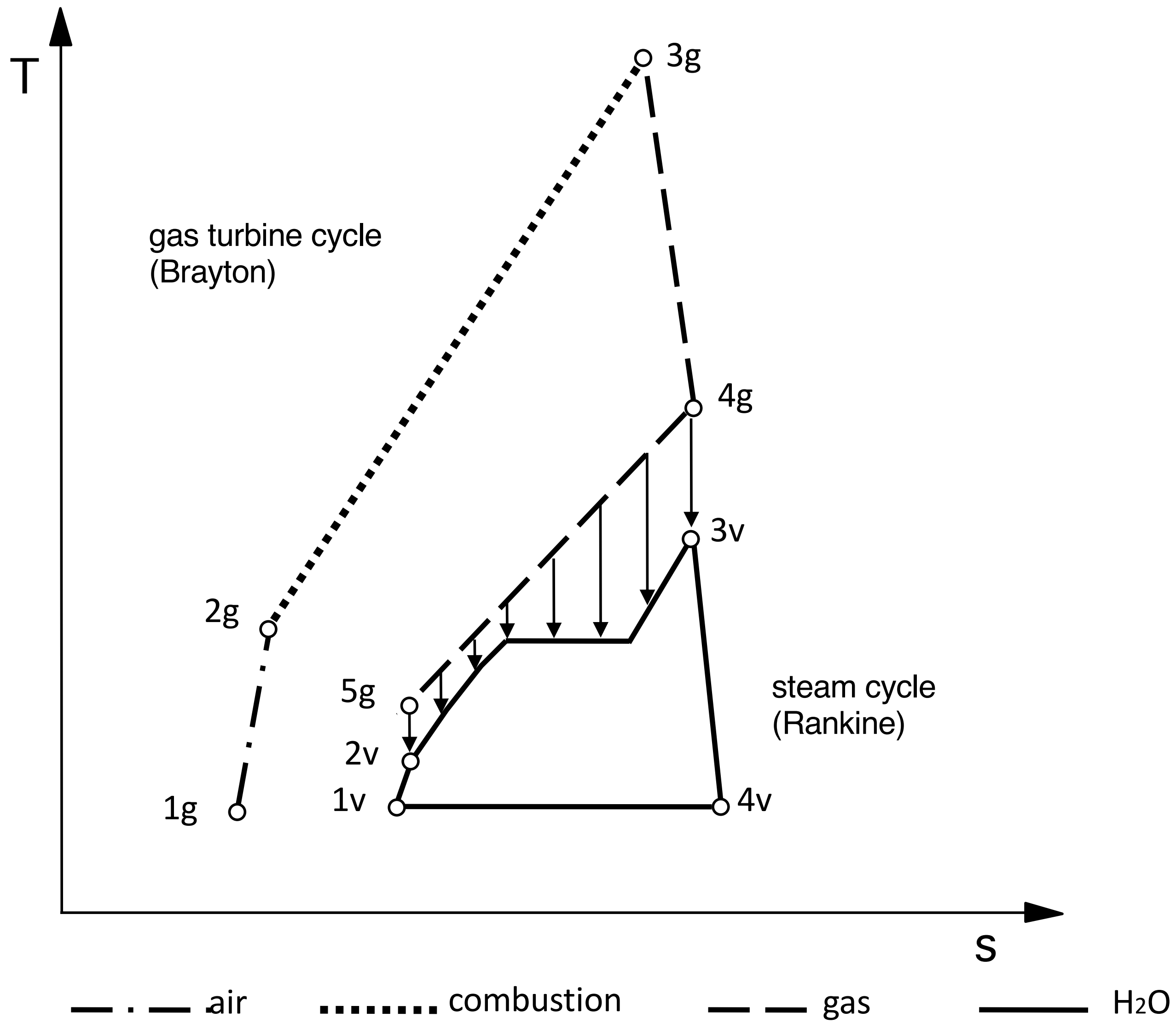
  - for the GT: no regenerator (it becomes the steam heater)
  - for the ST: almost no steam extraction

Layout

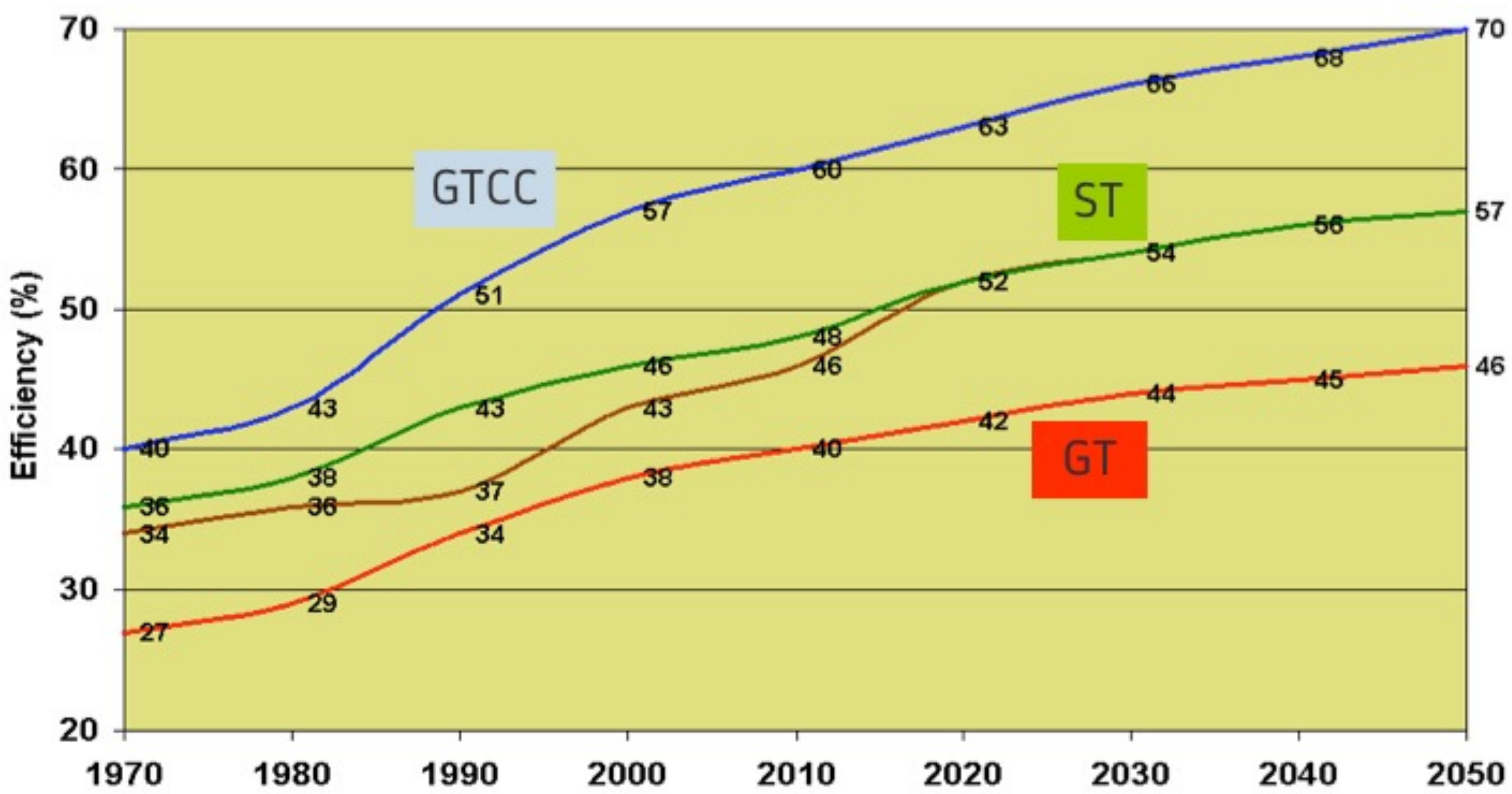
(no cogen.)



Combined gas-steam cycle in *T-s* diagram



Efficiency evolution and perspectives



(T. Kaiser, Alstom)

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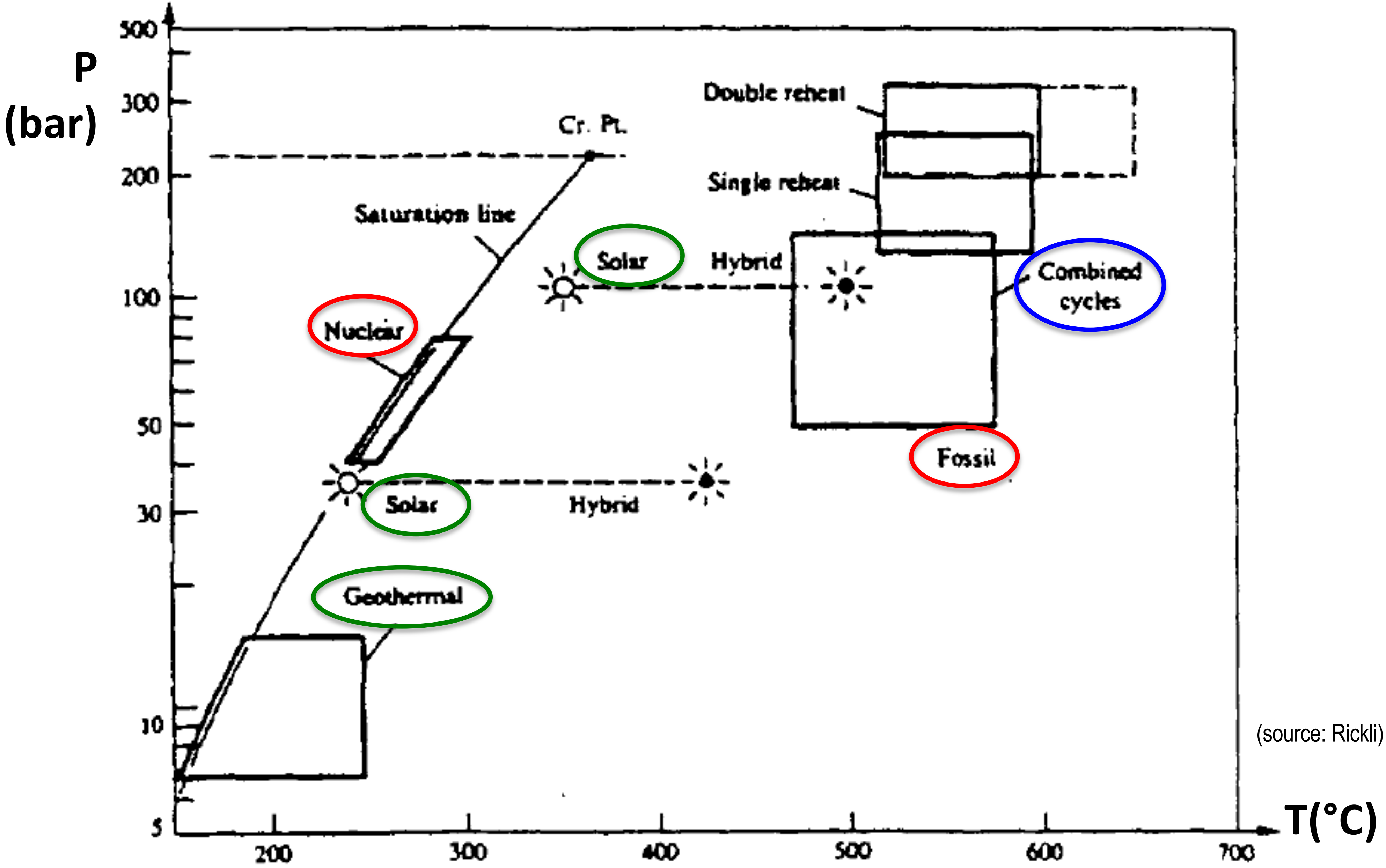
Steam *P-T* diagram for various cycle applications



(source: Rickli)

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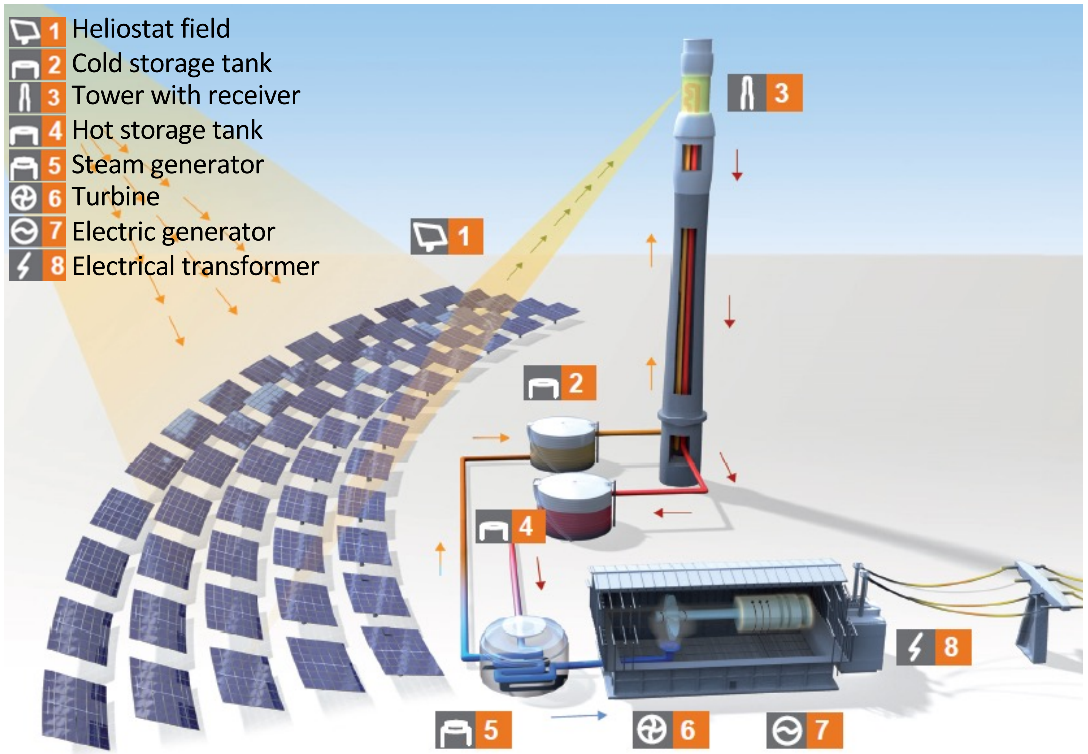
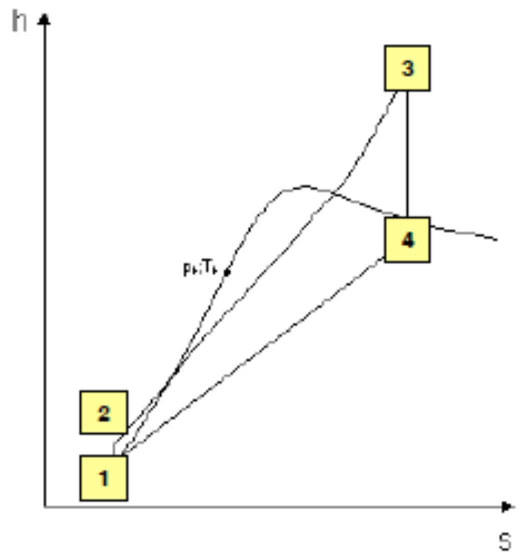
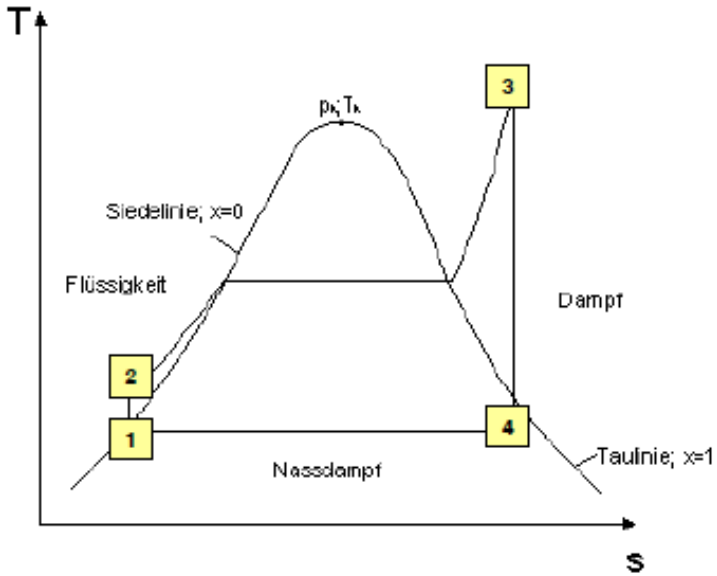
Concentrated Solar Power - Centralized

- Traditional Rankine cycle:





h-s-Diagramm

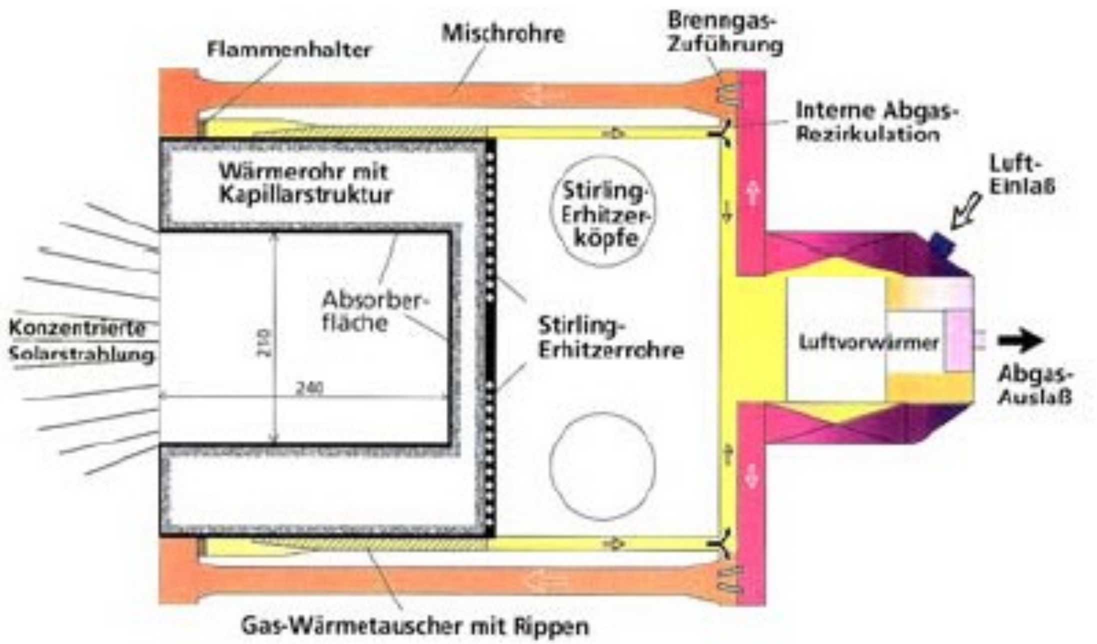


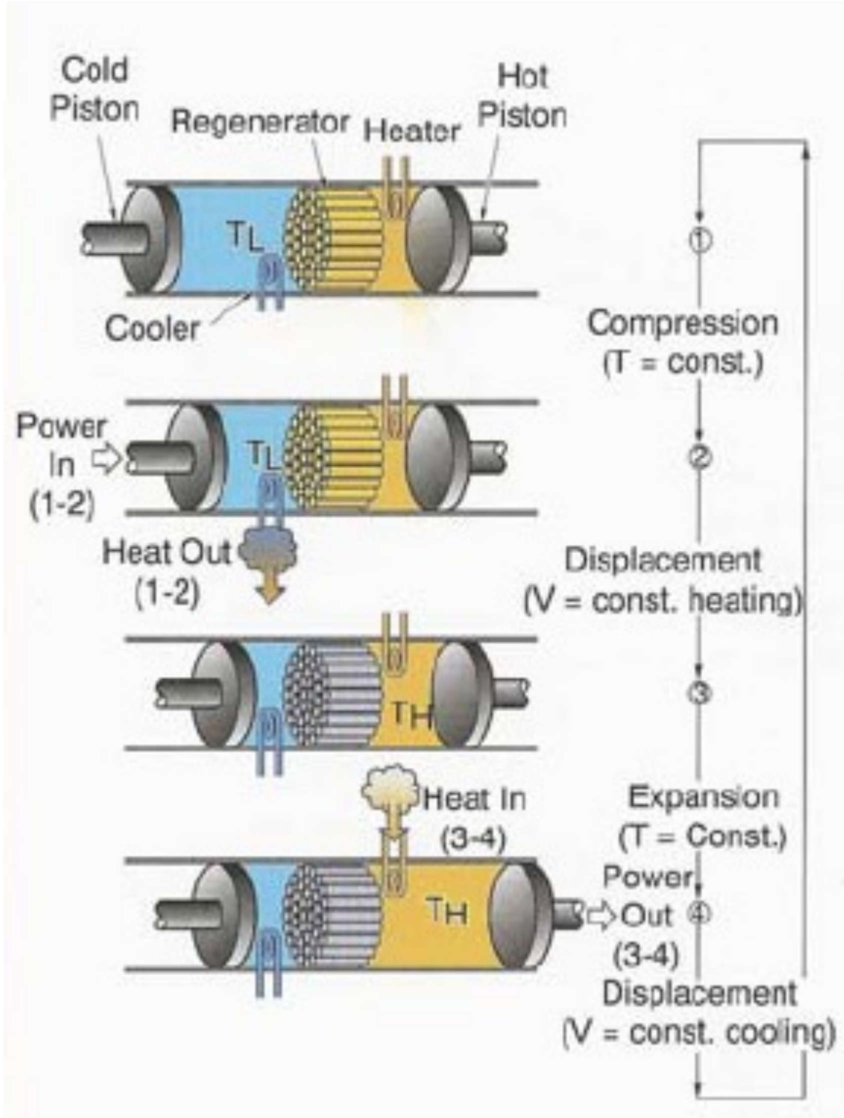
T-s-Diagramm

→ see lecture Solar

Concentrated Solar Power - Decentralized

- Stirling cycle:



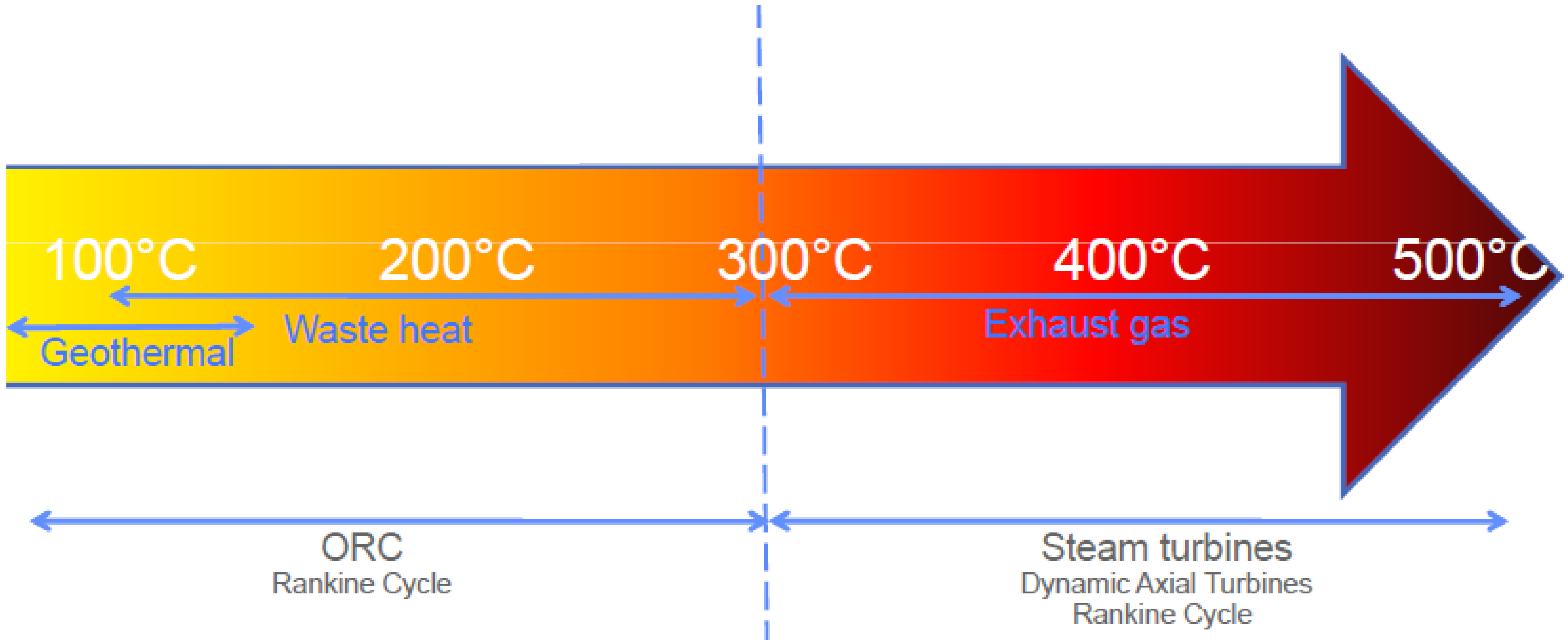


EPFL

→ see lecture Solar

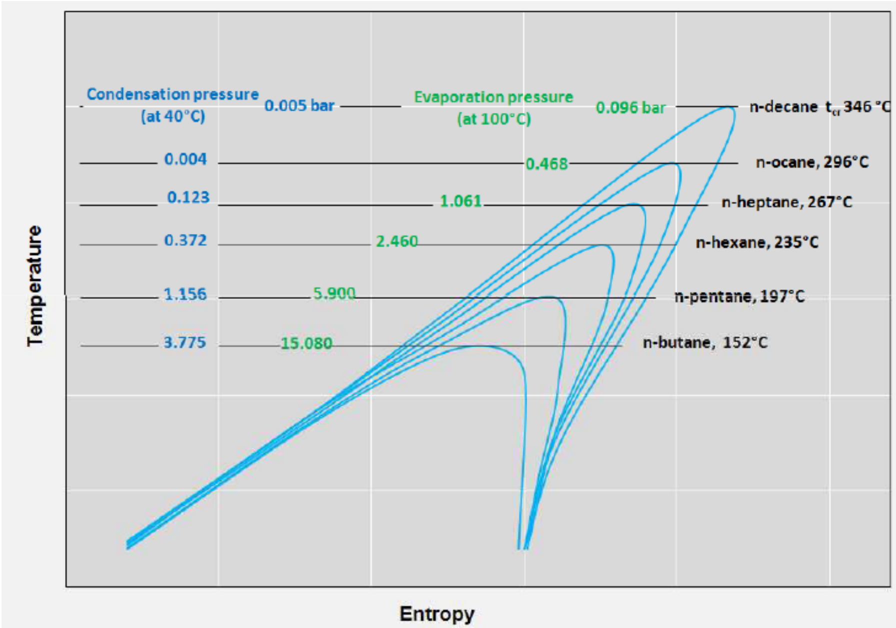
Low temperature heat sources

- For **geothermal, waste heat**, non- / low-concentrated solar:
  - temperatures too low for water as HTF (heat transfer fluid)
  - instead using (organic) fluid with different critical parameters



HTF for ORC

- Choice depends on:
  - Flammability and toxicity depending on security of the site
  - ODP for the environment
  - Stability
  - Authorization for the fluid

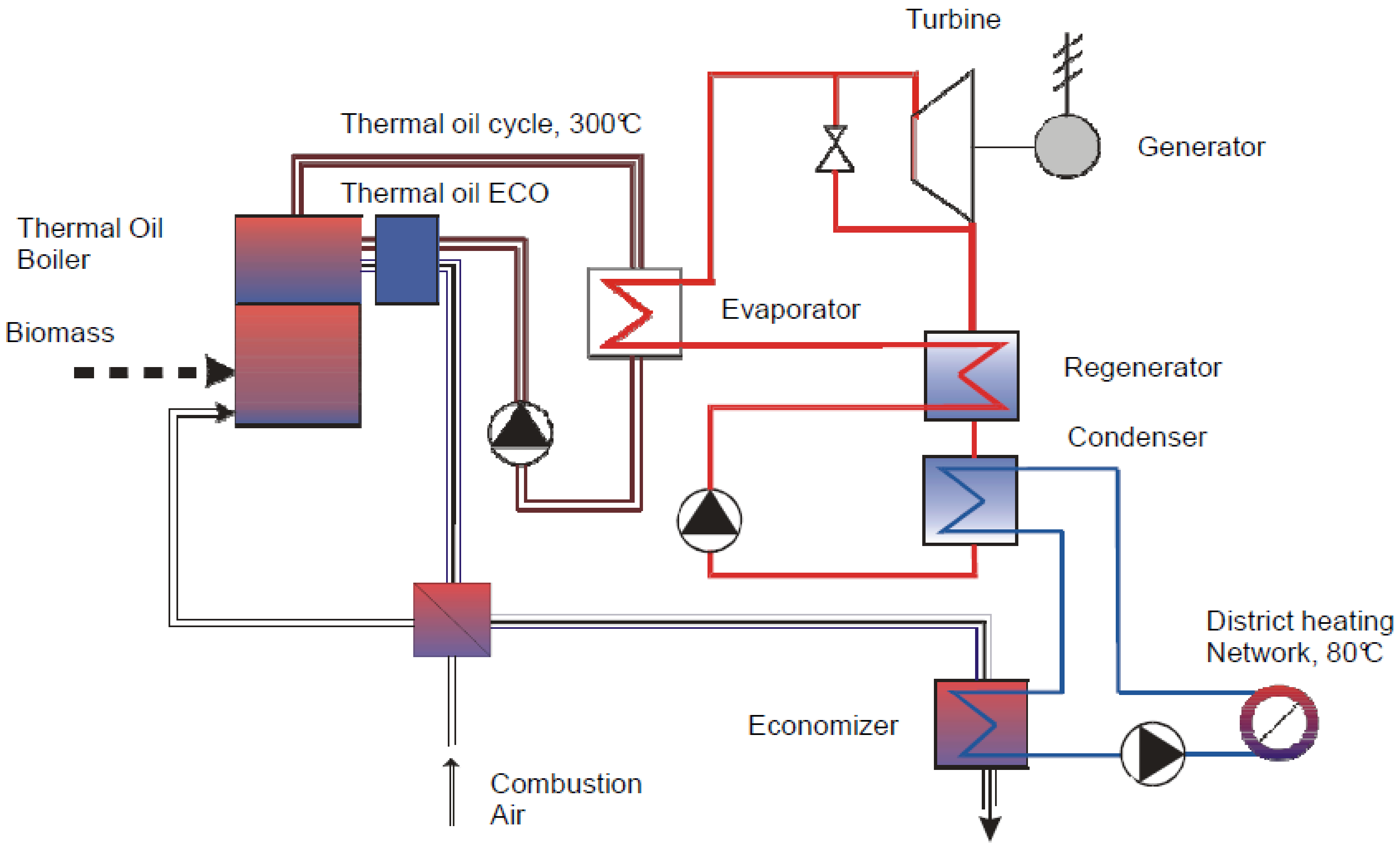


(ODP ozone depletion potential)

	R245 fa	R152A	R32	Pen-tane	Iso-Butane	Toluene
Saturated pressure at 120℃ (bar)	19.2	42	58	9	28	1.3
Service temperature (℃)	140	140	140	140	140	140
Saturated pressure at 50℃ (bar)	3.5	11	31	1.6	6.8	0.1
Expander pressure ratio	5.6	3.6	1.8	5.7	4.1	10.7
Ozone Depletion Potential	0	0	0	0	0	0
Global Warming Potential	950	140	675	7	3	3
ASHRAE Safety group	B1	A2	A2L	A3	A3	A3
Power density [kW/Exp]	16	26	16	8	21	1.4

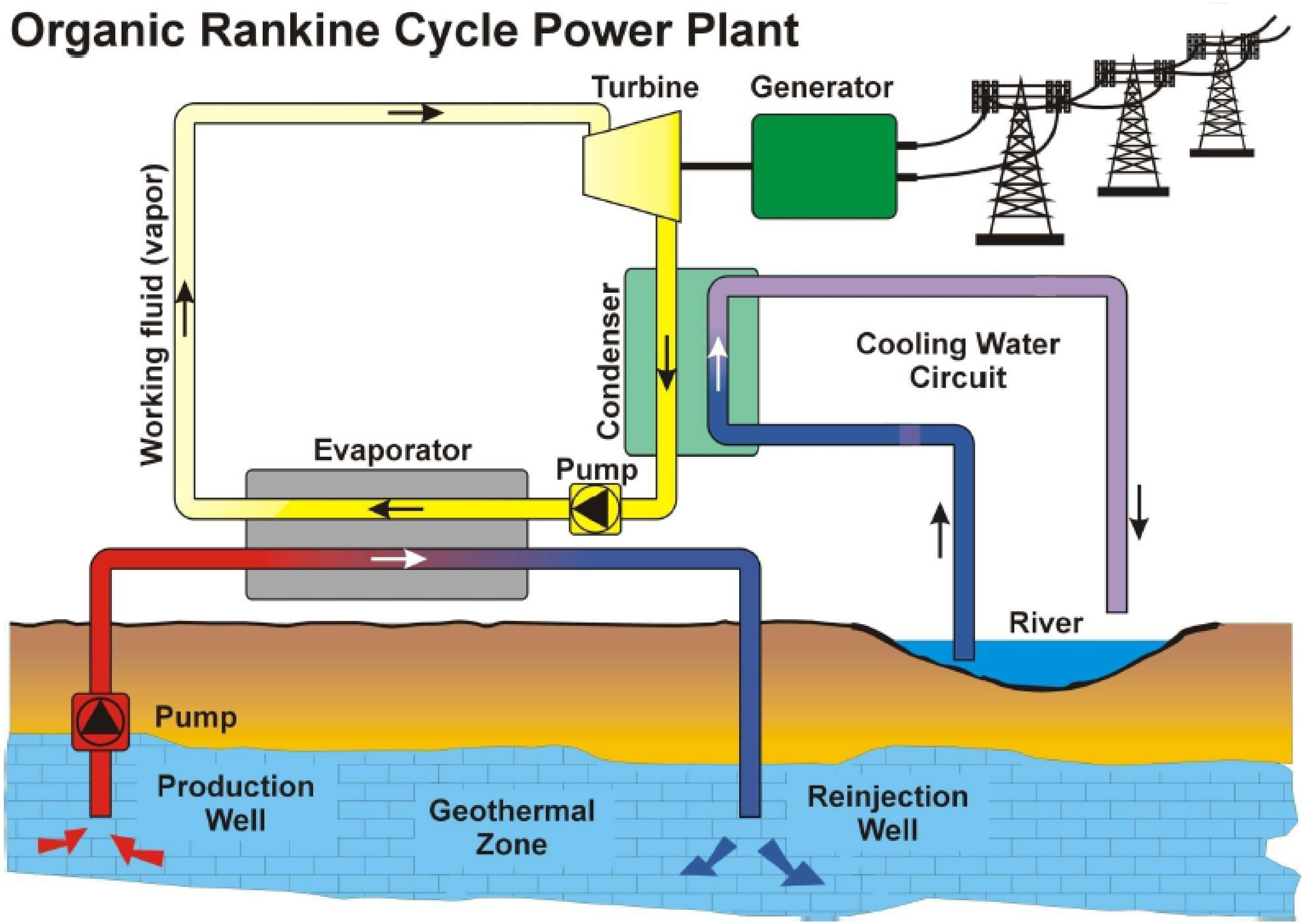
ORC example

- Biomass: working fluid silicone oil



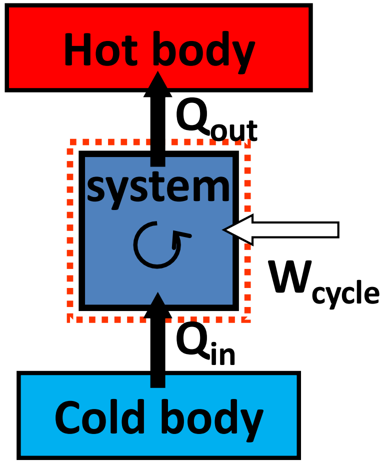
ORC example

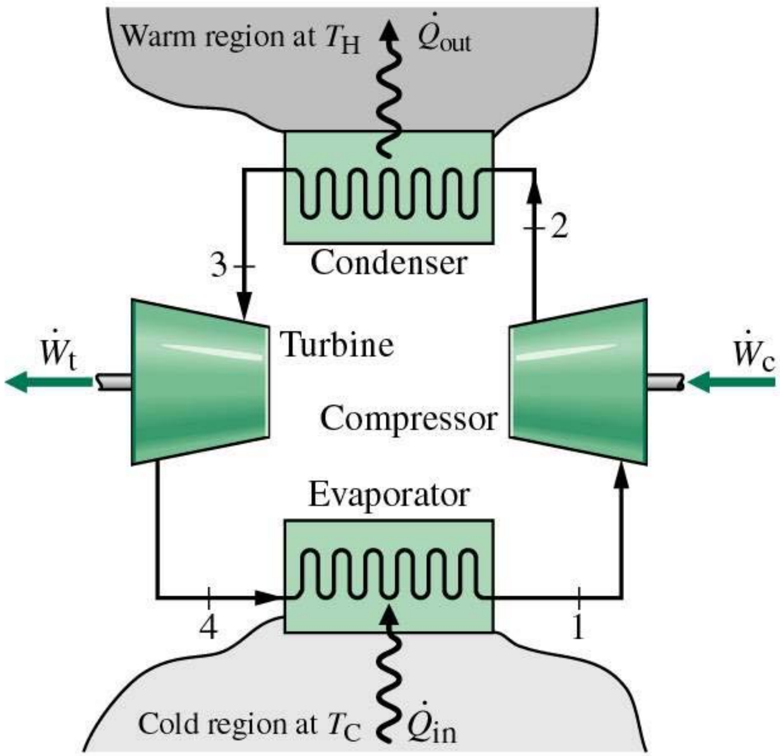
- Geothermal



Refrigeration and heat pump systems

- Refrigeration and heat pump
  - Maintain colder temperature below temperature of surrounding
  - Maintain higher temperature above temperature of surrounding





Vapor-compression refrigeration system

- Practical refrigeration/heat pump cycle, ideal:
  - 1-2: Isentropic compression

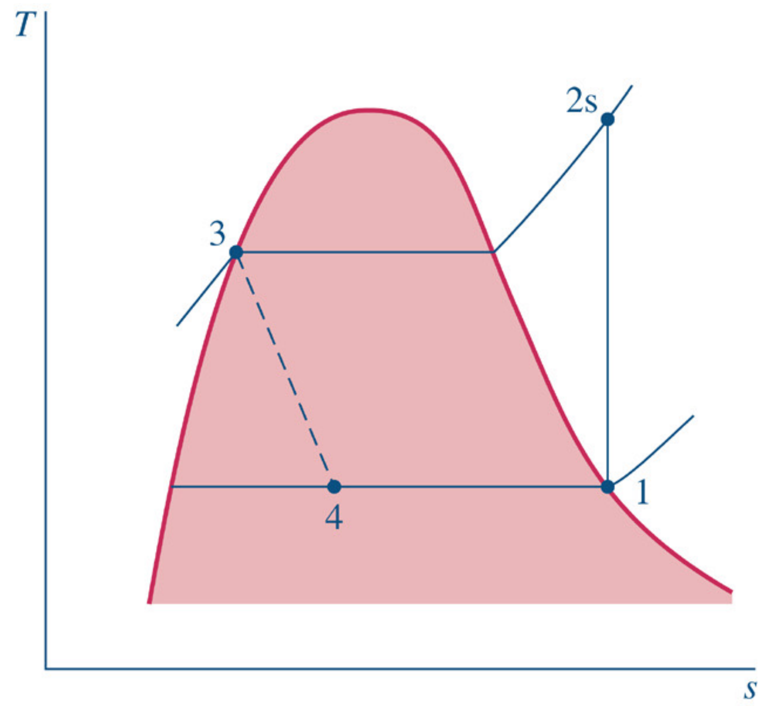
$$\frac{\dot{W}_c}{\dot{m}} = h_1 - h_2$$

  - 2-3: Isobaric heat rejection (incl. condensing step)

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$$

  - 3-4: throttling process

$$h_3 = h_4$$



  - 4-1: Isobaric heat addition (evaporation step)

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

  - Coefficient of performance:

$$\mathrm{COP}_{cm} = \frac{h_1 - h_4}{h_2 - h_1} < \mathrm{COP}_{cm,max}$$

$$\mathrm{COP}_{hm} = \frac{h_2 - h_3}{h_2 - h_1} < \mathrm{COP}_{hm,max}$$

Gas refrigeration systems

- Gas refrigeration systems, Brayton refrigeration cycle
  - 1-2(s): (Isentropic) compression

$$\frac{\dot{W}_c}{\dot{m}} = h_1 - h_2$$

  - 2-3: Isobaric cooling

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$$

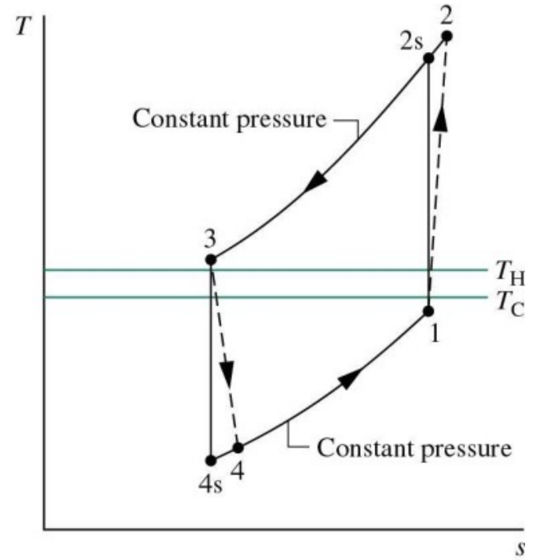
  - 3-4(s): (Isentropic) expansion

$$\frac{\dot{W}_t}{\dot{m}} = h_3 - h_4$$

  - 4-1: Isobaric evaporation/heating

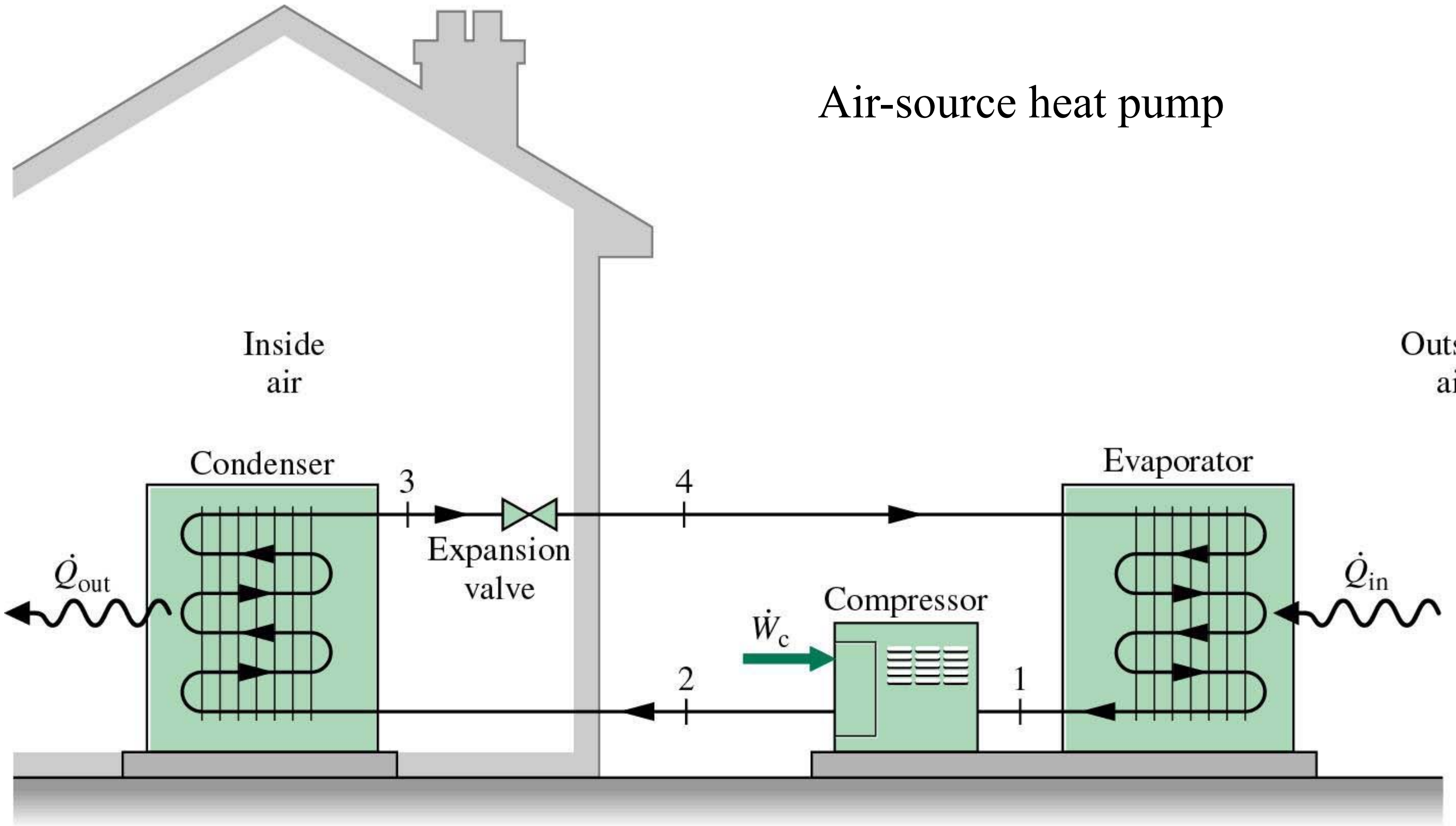
$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

  - Coefficient of performance: $\mathrm{COP}_{cm} = \dfrac{h_1 - h_4}{\left| h_1 - h_2 - (h_3 - h_4) \right|}$



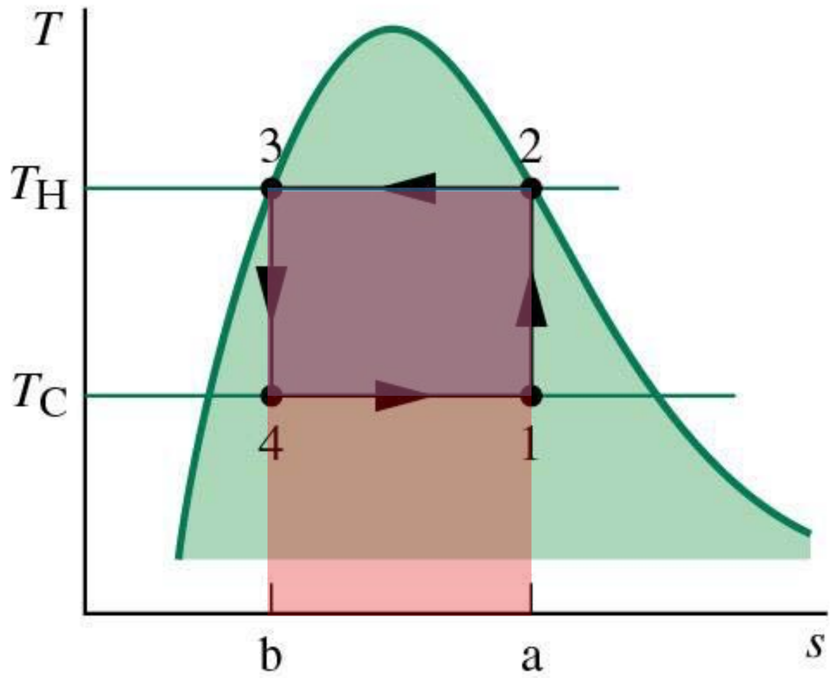
Heat pump systems

- Heat pump system:
  - Common application: space heating
  - Vapor-compression as well as absorption heat pumps



Heat pump systems

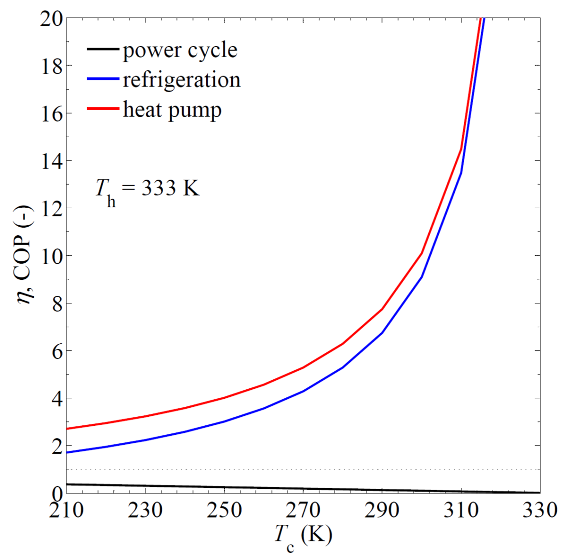
- Carnot heat pump cycle:



  - Performance:

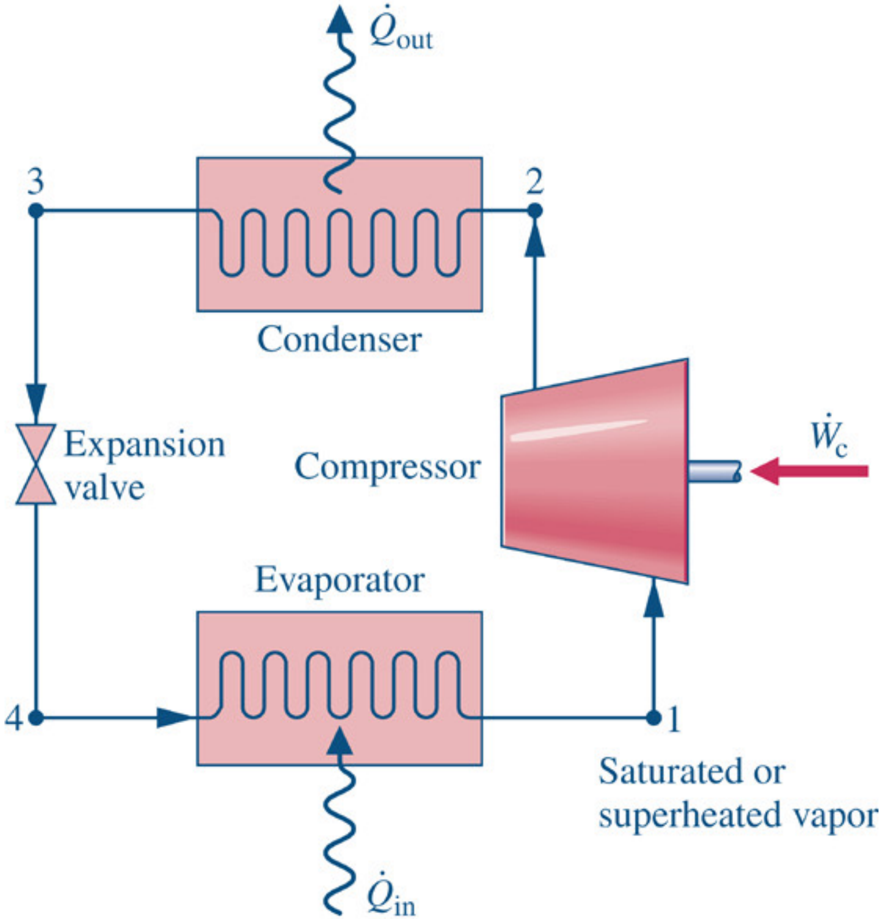
$$\text{COP}_{\text{hm,max}} = \frac{\dot{Q}_{\text{out}} / \dot{m}}{\left| \underbrace{\dot{W}_{\text{c}} / \dot{m}}_{\text{compressor}} - \underbrace{\dot{W}_{\text{t}} / \dot{m}}_{\text{turbine}} \right|} = \frac{T_{\text{H}}(s_a - s_b)}{(T_{\text{H}} - T_{\text{C}})(s_a - s_b)}$$

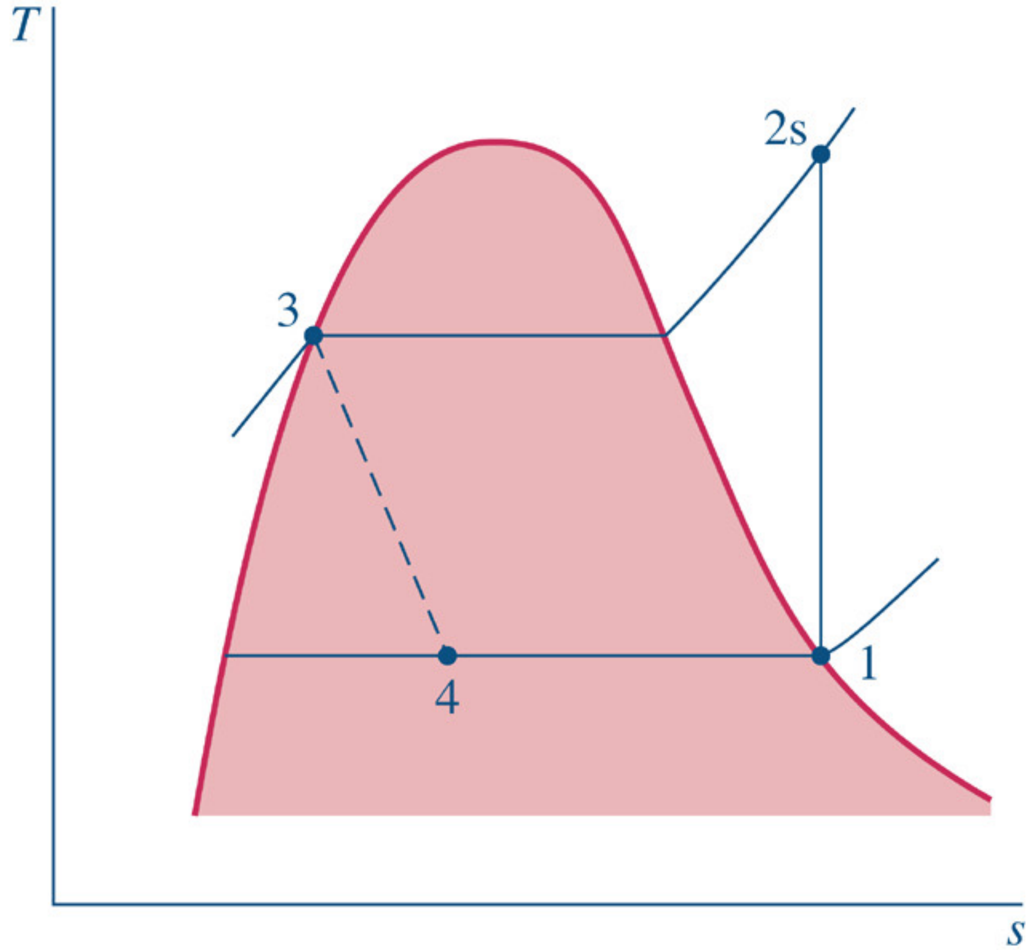
$$= \frac{T_{\text{H}}}{T_{\text{H}} - T_{\text{C}}}$$



Heat pump systems

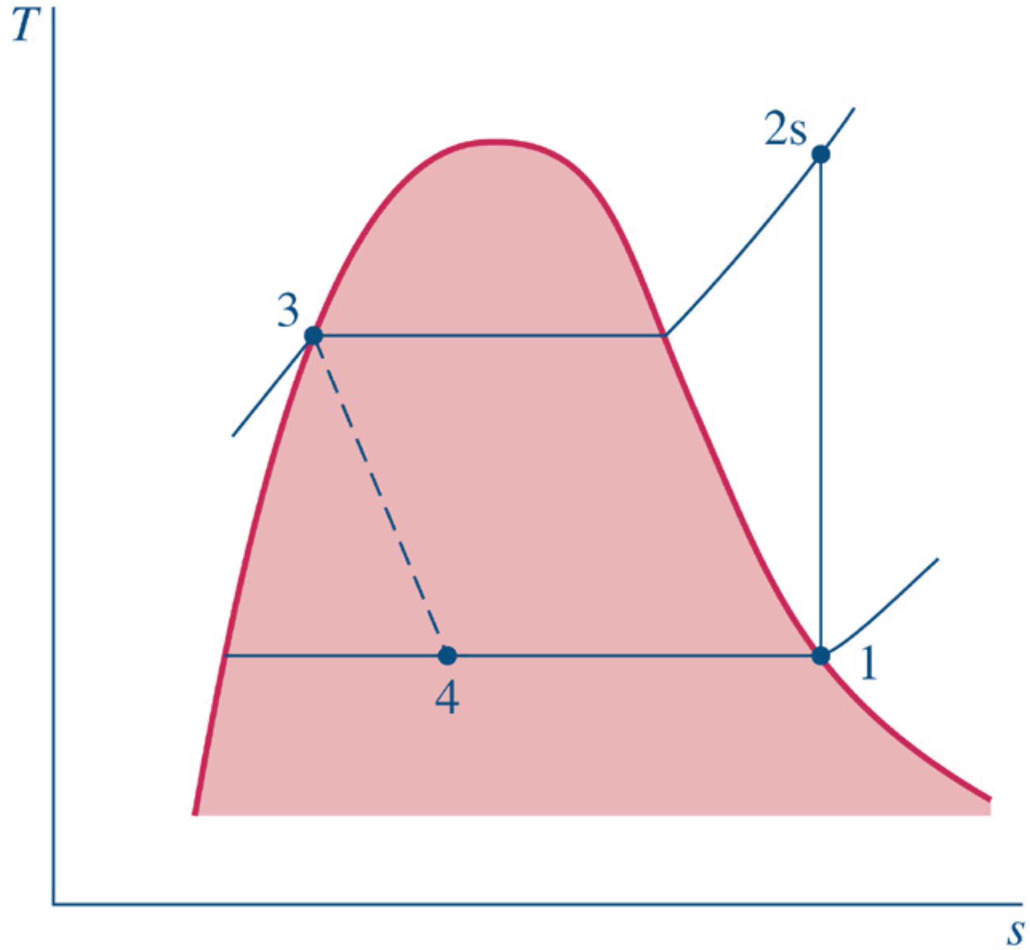
- Vapor-compression heat pumps:





Heat pump systems

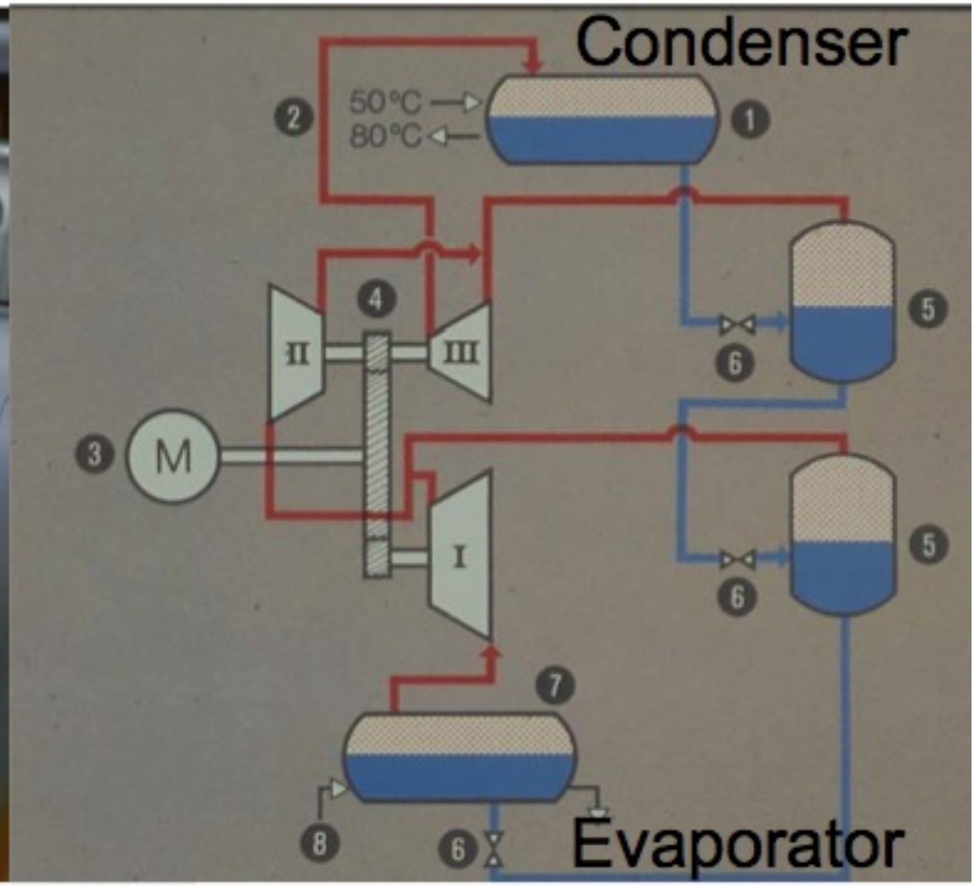
- Vapor-compression heat pumps:
  - 1-2: $$\frac{\dot{W}_c}{\dot{m}} = h_1 - h_2$$
  - 2-3: $$\frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$$
  - 3-4: $$h_3 = h_4$$
  - 4-1: $$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$
  - Performance: $$COP_{hm} = \frac{\dot{Q}_{out} / \dot{m}}{\dot{W}_c / \dot{m}} = \frac{h_2 - h_3}{h_2 - h_1}$$



EPFL

Heat pump

The largest heat pump (for District heating): 3 compression stages



Goteborg: 45 MW_{th}

EPFL

Absorption heat pump

- Principle: achieve the pressure raise from low (BP) → high (HP) not by *mechanical compression*, but by desorption (using a *heat source*) of a working fluid from its solvent, in which this working fluid had previously been absorbed (=rejecting heat during absorption)
  - e.g. working fluid **NH_3** with **water** as solvent
  - e.g. working fluid **water** with **LiBr** as solvent

often low temperature (~100°C), ideal for many renewables

EPFL

Absorption heat pump

replaces a compressor

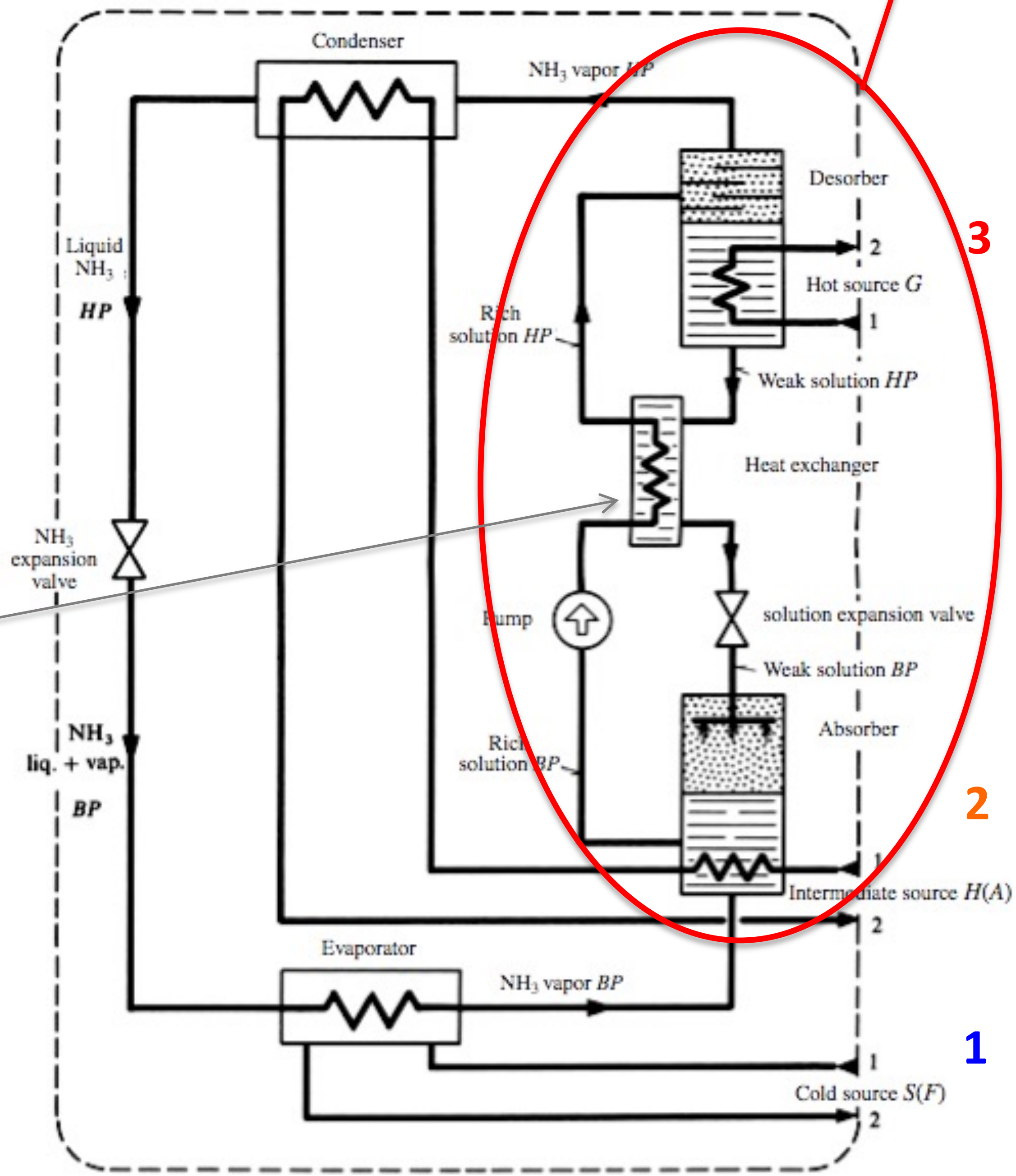
- absorber (water):

  receives low p NH_3 vapor (BP)

$\Rightarrow$ liberates absorption heat (H)

- liquid pump BP→HP
- boiler: delivers the absorption heat (G) to desorb the NH_3 vapor → HP
- expander (liq.) HP→BP
- internal heat exchanger between the rich and poor solutions (in NH_3)
- tubing

$\dot{E}_P^+$



TRITHERMAL CYCLE 1, 2, 3

Learning outcomes

- Introduction into thermodynamics:
  - 1st law for closed and open systems
  - 2nd law for closed and open systems, entropy definition
  - Exergy
  - State functions
- Exemplary thermodynamic power systems:
  - Power systems:
    - Vapor power systems
    - Gas power systems:
      - Internal combustion engines
      - Gas turbine power plants
- Examples of relevant power cycles for renewable sources
- Examples thermodynamic cooling and heating systems:
  - Refrigeration and heat pump systems

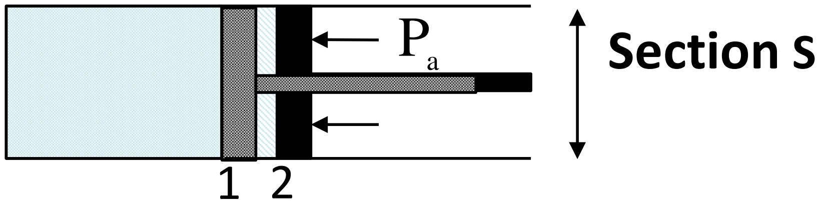
Addendum :
derivation of exergy balance from 1st + 2nd Laws

1st Law

Mechanical work transfer + **Heat transfer** + **Enthalpy flow balance (linked to mass flow)** = **Rate of variation of internal energy (accumulation or diminution)**

$$\sum_k \left(\dot{E}_k^+\right) + \dot{E}_a^+ \quad + \quad \sum_i \left(\dot{Q}_i^+\right) + \dot{Q}_a^+ \quad + \quad \sum_j \left(h_{cz_j} \dot{M}_j^+\right) = dU_{cz} / dt$$

Effective work (via crankshaft or connecting rod)



$$\dot{E}_a^+ = -P_a dV / dt =$$ mechanical work related to the atmosphere

1^{st} Law
(separating atmosphere terms)

$$\sum_k \left[\dot{E}_k^+\right] - P_a \frac{dV}{dt} + \sum_i \left[\dot{Q}_i^+\right] + \dot{Q}_a^+ + \sum_j \left[h_{czj} \dot{M}_j^+\right] = \frac{dU_{cz}}{dt}$$

$$\sum_k \left[\dot{E}_k^+\right] + \sum_i \left[\dot{Q}_i^+\right] + \dot{Q}_a^+ + \sum_j \left[h_{czj} \dot{M}_j^+\right] = \frac{d(U_{cz} + P_a dV)}{dt}$$

For 1 network:

$$\sum_k \left[\dot{E}_k^+\right] + \sum_i \left[\dot{Q}_i^+\right] + \dot{Q}_a^+ + \sum_j \left[h_{czj} \dot{M}_j^+\right] - \frac{d(U_{cz} + P_a V)}{dt} = 0$$

For n networks:

$$\sum_k \left[\dot{E}_k^+\right] + \sum_i \left[\dot{Q}_i^+\right] + \dot{Q}_a^+ + \sum_n \left(\sum_j \left[h_{czj} \dot{M}_j^+\right] - \frac{d(U_{cz} + P_a V)}{dt} \right)_n = 0$$

2nd Law (separating heat transfer with atmosphere)

Entropy transferred by heat transfer	+	Entropy flow balance (linked to mass flow)	+	Internal entropy creation rate	=	Rate of variation of system entropy
$\sum_i \dot{Q}_i^+ / T_i + \dot{Q}_a^+ / T_a$	+	$\sum_j \left(s_j \dot{M}_j^+ \right)$	+	$\delta S^i / dt \geq 0$	=	dS / dt

1st law:

$$\sum_k \left(\dot{E}_k^+ \right) + \sum_i \dot{Q}_i^+ + \dot{Q}_a^+ + \sum_j \left(h_{cz_j} \dot{M}_j^+ \right) = d\left(U_{cz} + P_a V \right) / dt$$

$$\sum_i \dot{Q}_i^+ / T_i + \dot{Q}_a^+ / T_a + \sum_j \left(s_j \dot{M}_j^+ \right) - dS/dt + \delta S^i / dt = 0$$

$$T_a \sum_i \dot{Q}_i^+ / T_i + \dot{Q}_a^+ + T_a \sum_j \left(s_j \dot{M}_j^+ \right) - T_a dS/dt = -T_a \delta S^i / dt$$

EXERGY BALANCE (1st Law *minus* 2nd Law):

1st Law

$$\sum_k \left(\dot{E}_k^+\right) + \sum_i \dot{Q}_i^+ + \dot{Q}_a^+ + \sum_j \left(h_{cz_j} \dot{M}_j^+\right) - d\left(U_{cz} + P_a V\right)/dt = 0$$

minus the 2nd Law

$$-T_a \sum_i \dot{Q}_i^+ / T_i - \dot{Q}_a^+ - T_a \sum_j \left(s_j \dot{M}_j^+\right) + T_a dS/dt = T_a \delta S^i / dt$$

$$\sum_k \left(\dot{E}_k^+\right) + \sum_i \left(1 - \frac{T_a}{T_i}\right) \dot{Q}_i^+ + \sum_j \left(h_{cz_j} - T_a s_j\right) \dot{M}_j^+ - d\left(U_{cz} + P_a V - T_a S\right)/dt = T_a \delta S^i / dt$$

Carnot Factor θ

Total Coenthalpy k_{cz}

Total Coenergy J_{cz}

(grouped as 'transformation-exergy' on next slide)

EXERGY BALANCE

1st Law

$$\sum_k \left(\dot{E}_k^+\right) + \sum_i \dot{Q}_i^+ + \dot{Q}_a^+ + \sum_j \left(h_{cz_j} \dot{M}_j^+\right) - d\left(U_{cz} + P_a V\right)/dt = 0$$

minus the 2nd Law

$$-T_a \sum_i \dot{Q}_i^+ / T_i - \dot{Q}_a^+ - T_a \sum_j \left(s_j \dot{M}_j^+\right) + T_a dS/dt = T_a \delta S^i / dt$$

$$\sum_k \left(\dot{E}_k^+\right) + \sum_i \left(1 - \frac{T_a}{T_i}\right)\dot{Q}_i^+ + \sum_j \left(h_{cz_j} - T_a s_j\right)\dot{M}_j^+ - d\left(U_{cz} + P_a V - T_a S\right)/dt = T_a \delta S^i / dt$$

Mech.work-exergy

Heat-exergy

Transformation-exergy (1 per network n)

Exergy loss

$$\sum_k \dot{E}_k^+ + \sum_i \dot{E}_{qi}^+ + \sum_n \dot{E}_{yn}^+ = \dot{L}$$

In this formulation, every term is either positive or negative

Summary of formulations (with + = entering the system)

Energy balance (1st law)

$$\sum_k \left(\dot{E}_k^+\right) + \sum_i \dot{Q}_i^+ + \dot{Q}_a^+ + \sum_j \left(h_{cz_j} \dot{M}_j^+\right) - d\left(U_{cz} + P_a V\right)/dt = 0$$

$$\sum_k \dot{E}_k^+ + \sum_i \dot{Q}_i^+ + \sum_n \dot{Y}_n^+ - \dot{Q}_a^- = 0$$

Every received energy quantity not kept in the system eventually is heat loss to the atmosphere

Exergy balance (1st + 2nd laws)

$$\sum_k \left(\dot{E}_k^+\right) + \sum_i \left(1 - \frac{T_a}{T_i}\right)\dot{Q}_i^+ + \sum_j \left(h_{cz_j} - T_a s_j\right)\dot{M}_j^+ - d\left(U_{cz} + P_a V - T_a S\right)/dt - T_a \delta S^i / dt = 0$$

$$\sum_k \dot{E}_k^+ + \sum_i \dot{E}_{qi}^+ + \sum_n \dot{E}_{yn}^+ - \dot{L} = 0$$

Every received work quantity not exported as work from the system is internal entropy creation

Formulations with only positive terms

Energy balance (1st law)

$$\sum_k \dot{E}_k^+ + \sum_i \dot{Q}_i^+ + \sum_n \dot{Y}_n^+ - \dot{Q}_a^- = \sum_k \dot{E}_k^- + \sum_i \dot{Q}_i^- + \sum_n \dot{Y}_n^-$$

All received energy in a system equals the energy output services plus the heat loss to the atmosphere

Exergy balance (1st + 2nd laws)

$$\sum_k \dot{E}_k^+ + \sum_i \dot{E}_{qi}^+ + \sum_n \dot{E}_{yn}^+ - \dot{L} = \sum_k \dot{E}_k^- + \sum_i \dot{E}_{qi}^- + \sum_n \dot{E}_{yn}^-$$

Real equivalent work output of a system equals the maximal equivalent work received by the system minus the irreversibility losses due to internal entropy creation

Effectiveness and exergy efficiency

Effectiveness (1st law)

$$\varepsilon = \frac{\sum\left[\dot{E}^-\right]+\sum\left[\dot{Q}^-\right]+\sum\left[\dot{Y}^-\right]}{\sum\left[\dot{E}^+\right]+\sum\left[\dot{Q}^+\right]+\sum\left[\dot{Y}^+\right]}$$

Examples:

Heat pump

$$\varepsilon_h = \frac{\dot{Q}^-_{cond}}{\dot{E}^+_{élec}}$$

Refrigeration pump

$$\varepsilon_f = \frac{\dot{Q}^+_{evap}}{\dot{E}^+_{élec}}$$

! not general !

Exergy efficiency (1st and 2nd laws)

$$\eta = \frac{\sum\left[\dot{E}^-\right]+\sum\left[\dot{E}^-_q\right]+\sum\left[\dot{E}^-_y\right]}{\sum\left[\dot{E}^+\right]+\sum\left[\dot{E}^+_q\right]+\sum\left[\dot{E}^+_y\right]}$$

General and always applicable

$$\eta = \frac{\dot{E}^-_q}{\dot{E}^+}$$

$$\eta = \frac{\dot{Q}^-_{cond}\left(1-\frac{T_a}{T_{cond}}\right)}{\dot{E}^+}$$

$$\eta = \frac{\dot{Q}^+_{evap}\left(\frac{T_a}{T_{evap}}-1\right)}{\dot{E}^+}$$