ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Renewable Energy

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Content

- Thermodynamic basics
  - Definitions
  - 1st law (energy conservation)
  - 2nd law (entropy)
  - 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

Learning outcomes

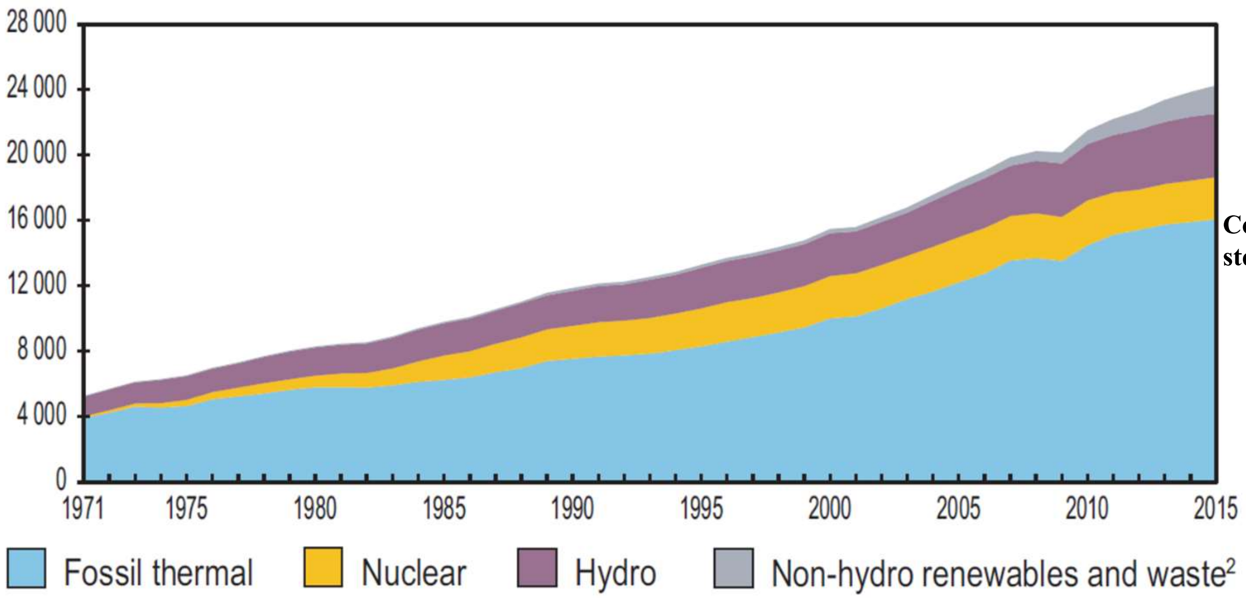
- Understand and apply 1st and 2nd law of thermodynamics, and exergy concept to various relevant systems and thermodynamics cycles

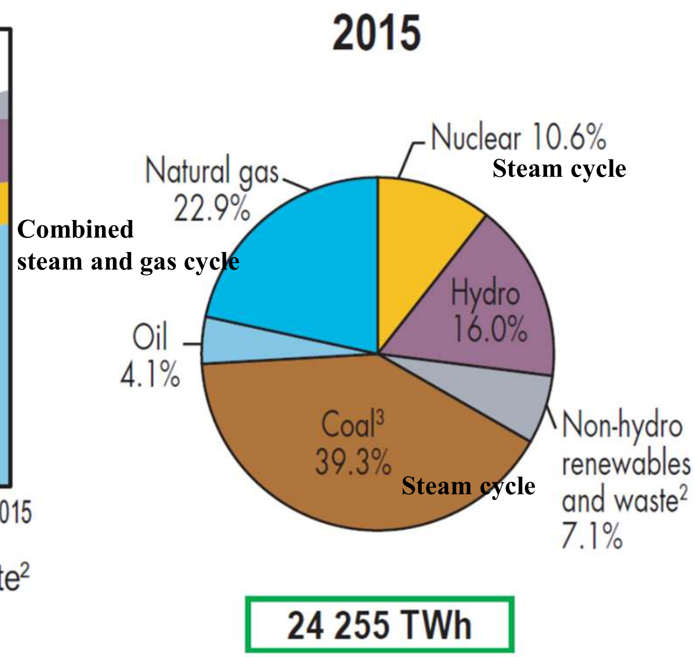
- Apply theory to thermodynamic cycles relevant for renewable energy sources

Motivation

- Current global power production

IEA, World key energy statistics, 2017.





[1] excl. electricity generation from pumped hydro
[2] incl. geothermal, solar, wind, heat, etc.
[3] incl. peat and oil shales

Motivation

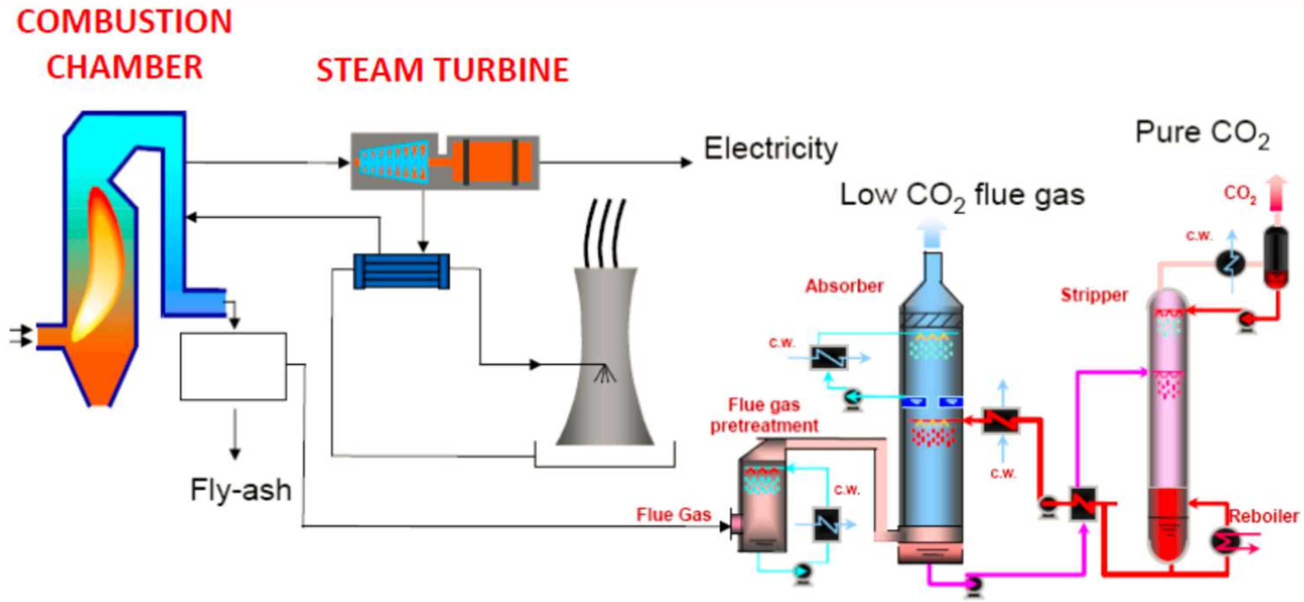
- Energy conversion systems overview

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**

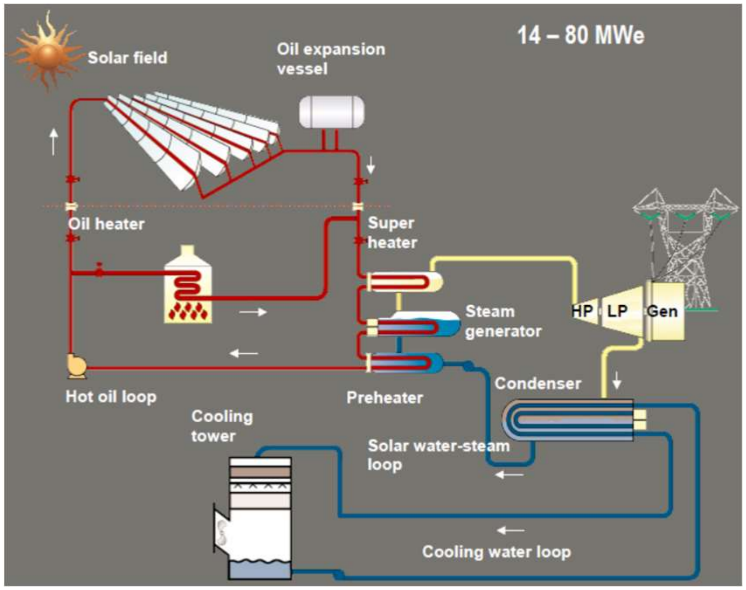
- Traditional and advanced rely on power cycles, traditional turbomachinery: heat → mechanical energy → electricity
- Advanced heating applications reply on heat pumping cycles

Motivation

- Examples:
  - Coal plant with CO_2 capture

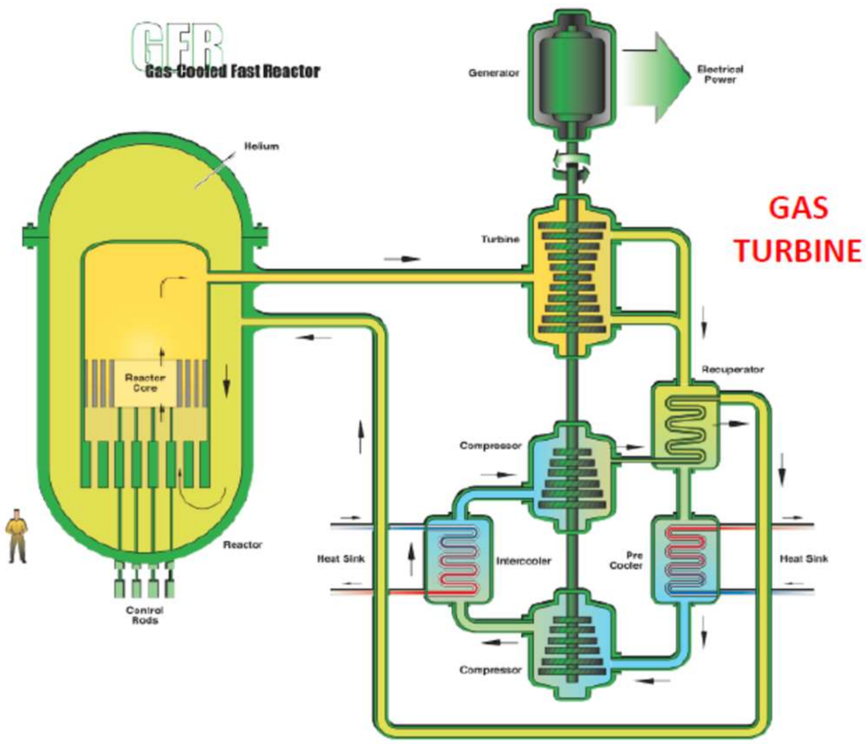


  - Concentrated solar power

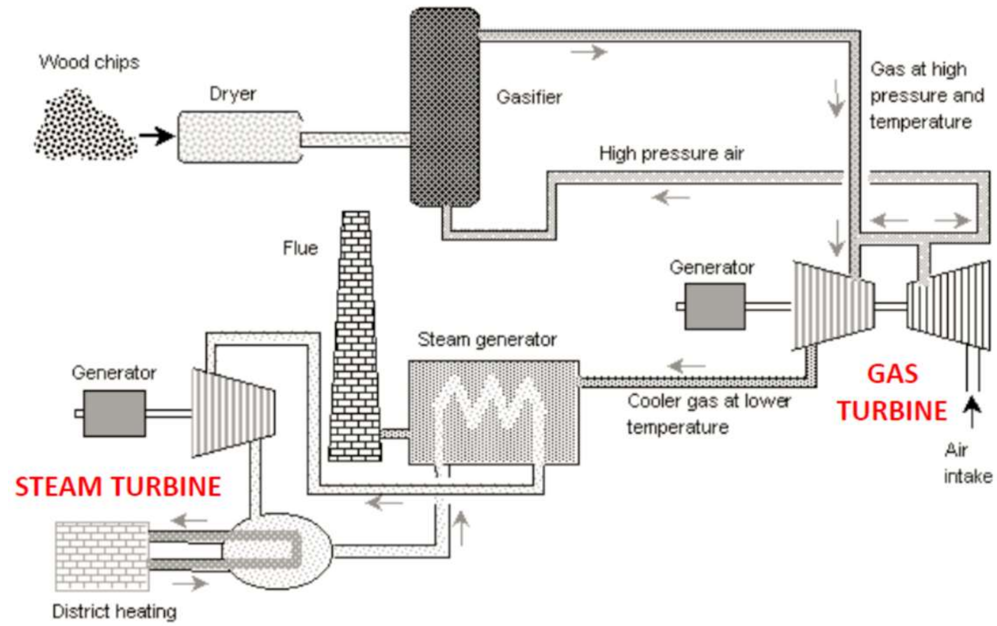


Motivation

- Examples:
  - Nuclear

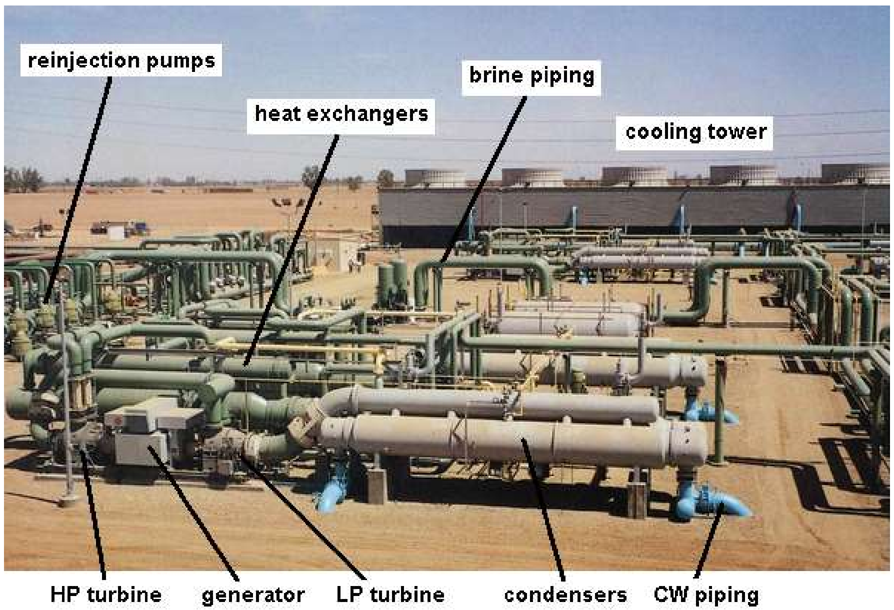


Biomass-fired combined cycle:



Motivation

- Examples:
  - Enhanced geothermal system



Energy and first law for closed systems

- Conservation of energy, first law of thermodynamics for **closed** systems:

$$\Delta E = \Delta U + \Delta PE + \Delta KE = Q_{12} - W_{12}$$

$$\begin{bmatrix} \text{change in the} \\ \text{amount of energy} \\ \text{contained within system} \\ \text{during time interval} \end{bmatrix} = \begin{bmatrix} \text{net amount of energy} \\ \text{transferred in across} \\ \text{system boundary by heat transfer} \\ \text{during time interval} \end{bmatrix} - \begin{bmatrix} \text{net amount of energy} \\ \text{transferred out across} \\ \text{system boundary by work transfer} \\ \text{during time interval} \end{bmatrix}$$

Work: $W > 0$ if work is done *by* the system
$W < 0$ if work is done *on* the system
Heat: $Q > 0$ if heat is transferred *to* the system
$Q < 0$ if heat is transferred *from* the system at

- Differential form: $dE = \delta Q - \delta W$

- Time rate form: $\frac{dE}{dt} = \dot{Q} - \dot{W}$

1st law for closed and open systems

- Energy conservation for **open** systems:

$$\Delta E = \Delta U + \Delta PE + \Delta KE = Q_{12} - W_{12} + E_{\text{in}} - E_{\text{out}}$$

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

$$+ \begin{bmatrix} \text{net rate of energy} \\ \text{transfered into the} \\ \text{control volume} \\ \text{accompanying mass flow} \end{bmatrix}$$

1st law for open systems

- Energy conservation for open systems:
  - Requires mass conservation:

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

  - Energy conservation:

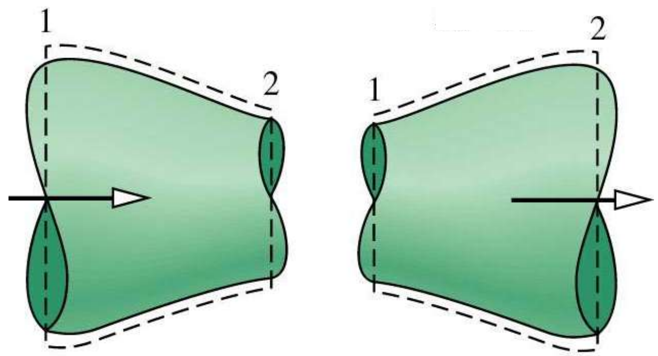
$$\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W} + \sum_i \dot{m}_i \left(u_i + \frac{w_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(u_e + \frac{w_e^2}{2} + gz_e \right)$$

$$\frac{dE_{CV}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{w_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{w_e^2}{2} + gz_e \right)$$

1st law for closed and open systems

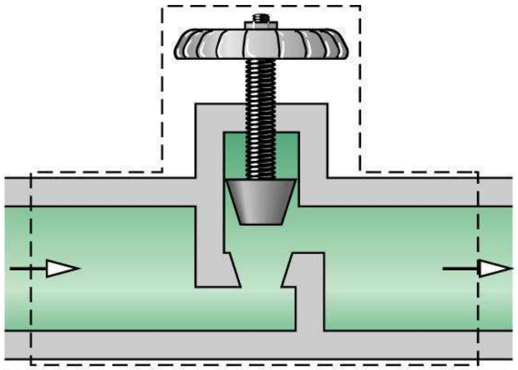
- Energy conservation for open systems, applications:
  - Nozzle, diffusor

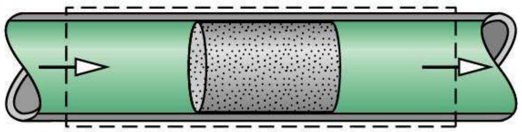
$$h_i + \frac{w_i^2}{2} = h_e + \frac{w_e^2}{2}$$



  - Throttling valves

$$h_i = h_e$$



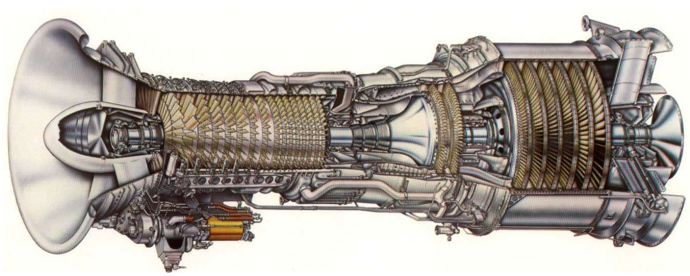


1st law for closed and open systems

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

GE, Roots* API 617 OIB

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



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 measure can be introduced for single components or complete systems
  - Always need a proper definition!
  - Indicates how well a energy conversion or transfer process is accomplished

- General:

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

Efficiency

- Example - Efficiency of *combustion devices*:

Efficiency of combustion is the 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:

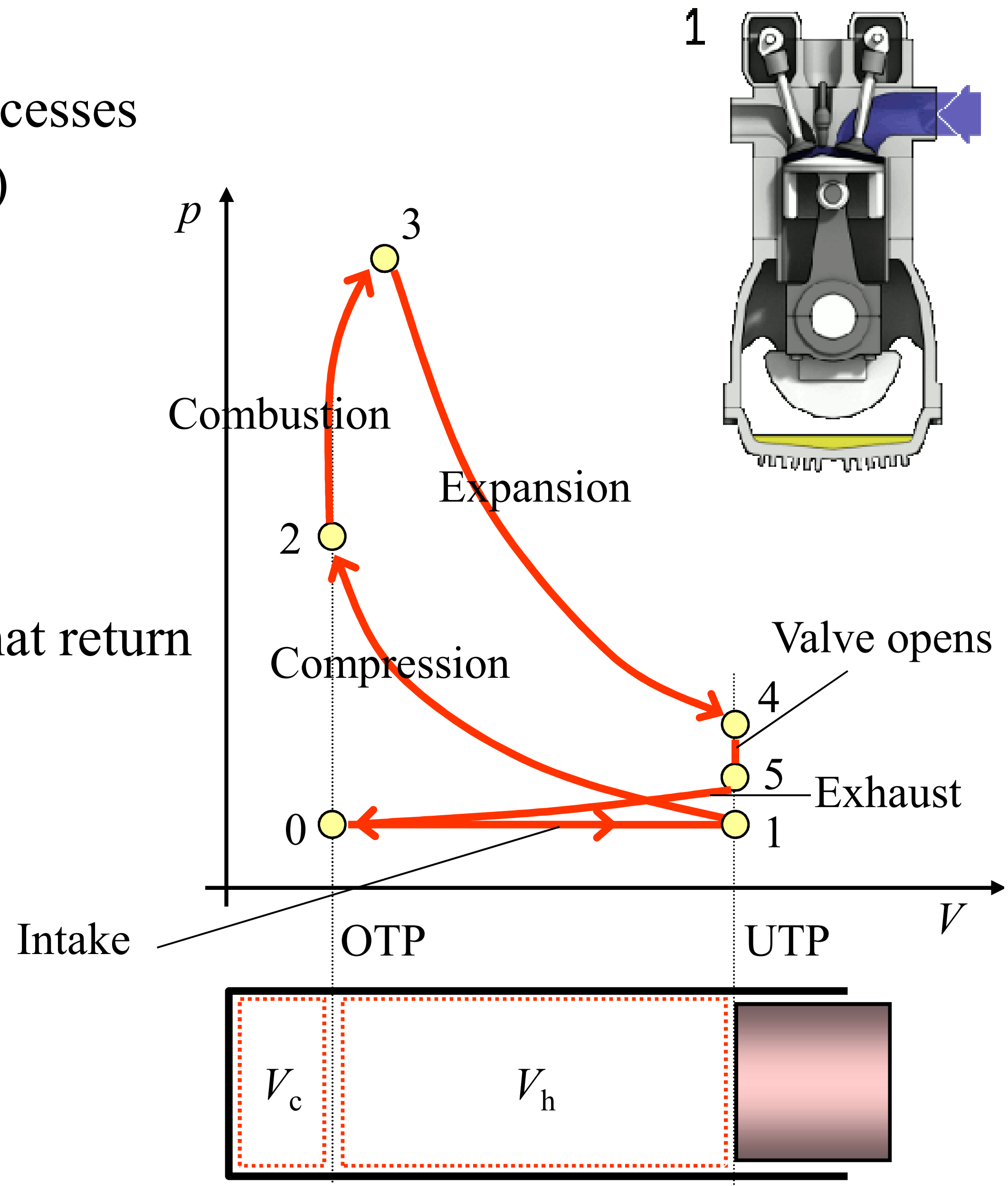
$$\eta_{\text{combustion}} = \frac{\text{amount of heat released during combustion}}{\text{heating value of the fuel burned}} = \frac{\dot{Q}}{\dot{m}\text{HV}}$$

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	

- Heating values (HV):
  - High heating values (HHV):
    water is condensed (furnaces etc.)
  - Low heating values (LHV):
    water is vapor (cars, jet engines, etc.)

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 system to initial state
    E.g. 4-stroke engine



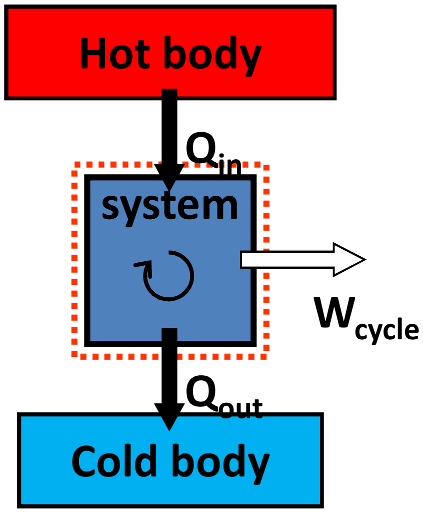
Energy for closed systems

- Cycle analysis:

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

  – Power cycles:

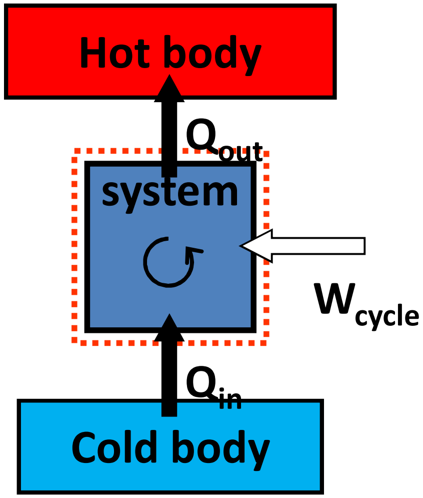
$$\eta_{\text{th}} = \frac{W_{\text{cycle}}}{Q_{\text{in}}} = 1 - \frac{|Q_{\text{out}}|}{Q_{\text{in}}}$$



  – Refrigeration and heat pump cycles:

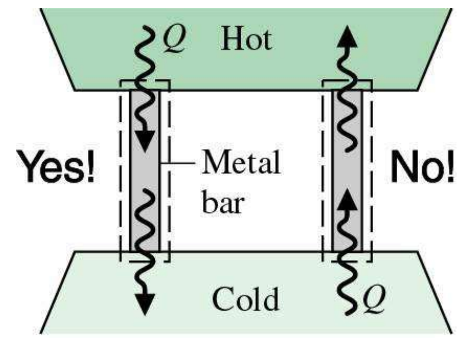
$$\text{COP}_{\text{cm}} = \frac{Q_{\text{in}}}{|W_{\text{cycle}}|} = \frac{Q_{\text{in}}}{|Q_{\text{out}}| - Q_{\text{in}}}$$

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

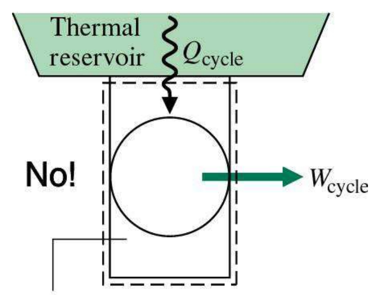


2^{nd} law of thermodynamics

- It is impossible for a system to operate in such a way that the sole 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 entropy is destroyed.

$$S_2 - S_1 = \sum_j \frac{Q_j}{T_j} + \sigma \quad \begin{cases} >0 \text{ irreversibilities} \\ =0 \text{ no irreversibilities} \\ <0 \text{ impossible} \end{cases}$$

Entropy balance – closed systems

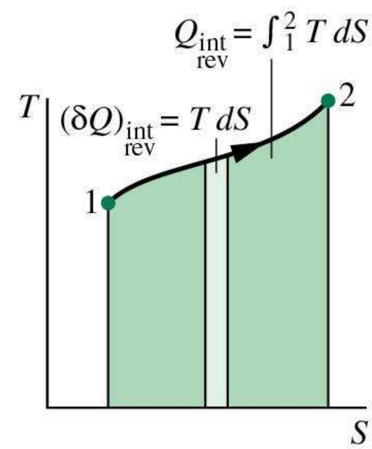
$$\begin{bmatrix}\text{change in the}\\ \text{amount of entropy}\\ \text{contained within system}\\ \text{during time interval}\end{bmatrix} = \begin{bmatrix}\text{net amount of entropy}\\ \text{transferred in across}\\ \text{system boundary}\\ \text{during time interval}\end{bmatrix} + \begin{bmatrix}\text{amount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

- 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:

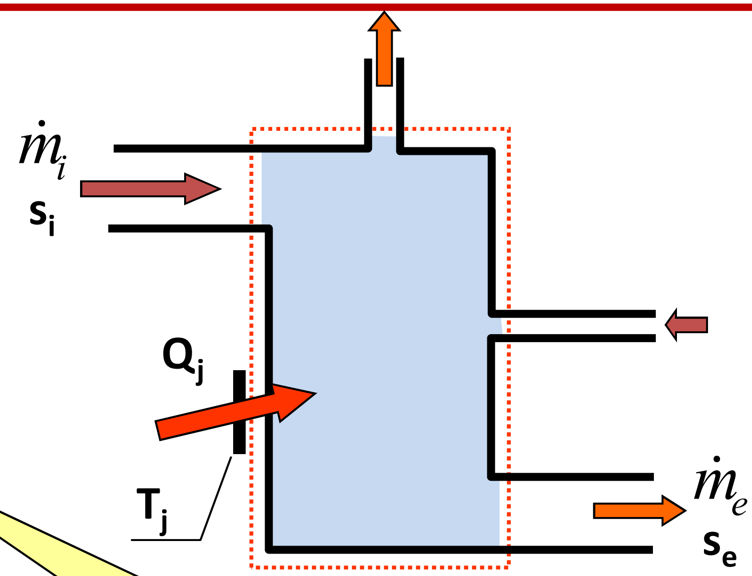
$$S_2 - S_1 = \left(\int_1^2 \frac{\delta Q}{T}\right)_{\substack{\text{int}\\ \text{rev}}} \qquad \frac{dS}{dt} = \left(\sum_j \frac{\dot{Q}_j}{T_j}\right)_{\substack{\text{int}\\ \text{rev}}}$$



Entropy balance – open systems

- Entropy balance for an open system:

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



Rate of entropy change in control volume

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

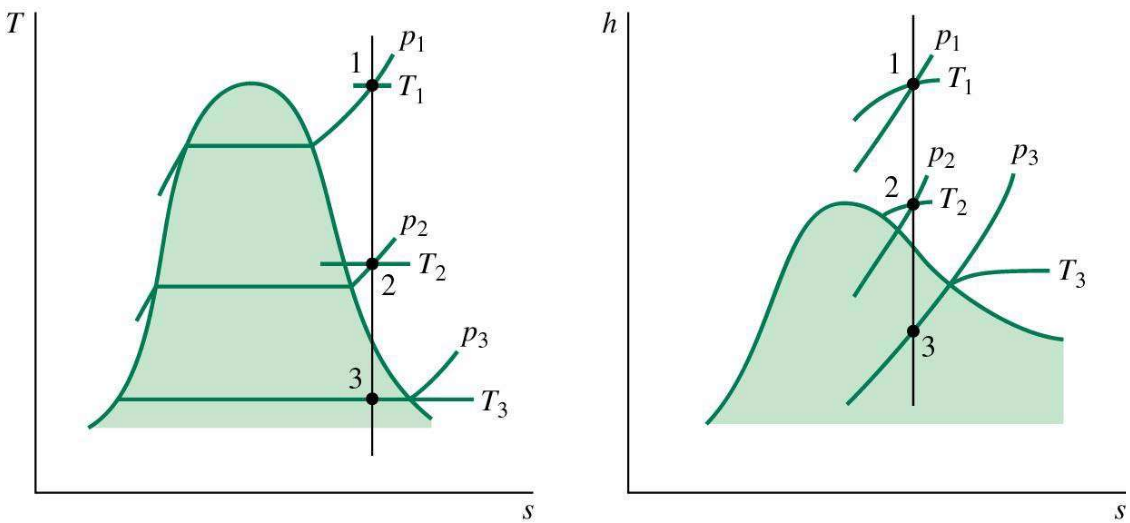
Convective entropy transport

Entropy production within the control volume

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

Isentropic processes

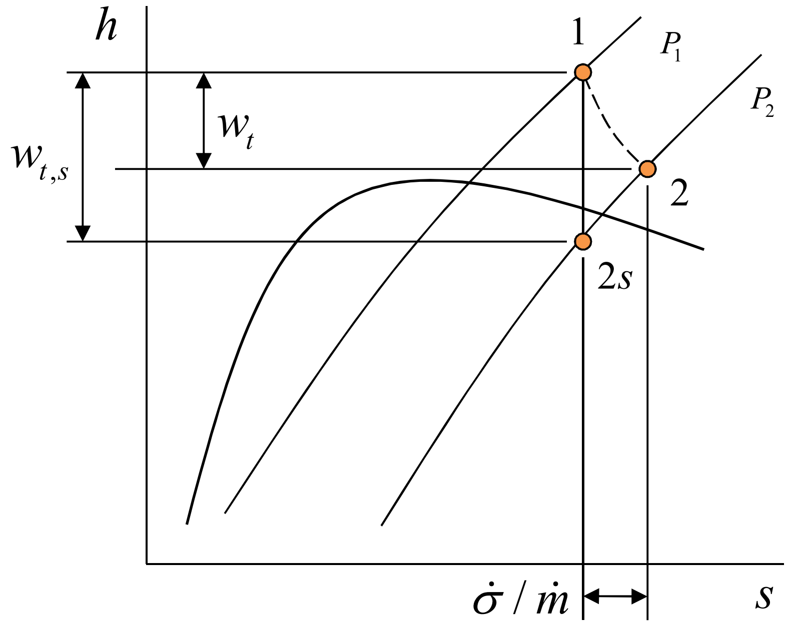
- Isentropic means constant entropy.
- Isentropic processes are processes where the entropy at the initial and final state are equal.
- Isentropic processes, e.g.: closed system, reversible and adiabatic process



Isentropic efficiencies

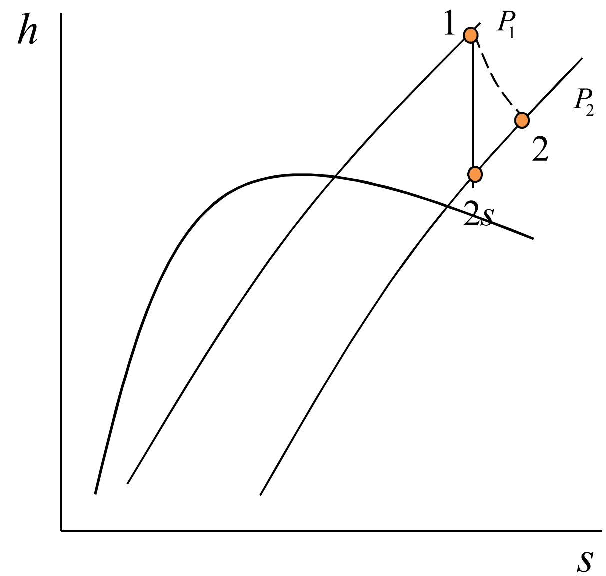
- Turbine:

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



- Compressor/pump:

$$\eta_{\mathrm{c/p,s}} = \frac{\left(-\dot{W}/\dot{m}\right)_{\mathrm{s}}}{-\dot{W}/\dot{m}} = \frac{h_{2,\mathrm{s}} - h_1}{h_2 - h_1}$$



- Nozzle:

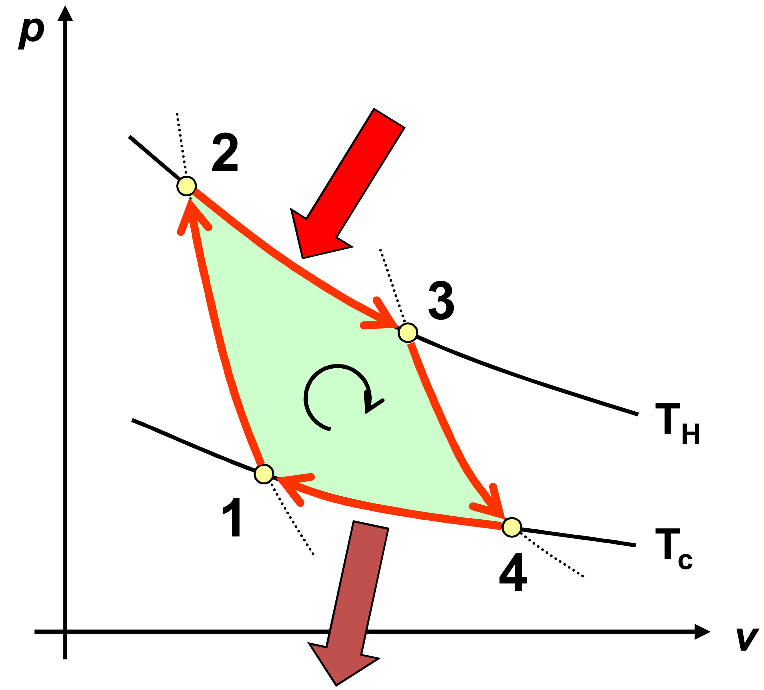
$$\eta_{\mathrm{n,s}} = \frac{h_1 - h_2}{h_1 - h_{2,\mathrm{s}}} = \frac{w_2^2/2 - w_1^2/2}{\left(w_2^2/2 - w_1^2/2\right)_{\mathrm{s}}}$$

Carnot cycle

- Carnot cycle:
  Famous cycle that undergoes four reversible processes

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

- Two adiabatic processes

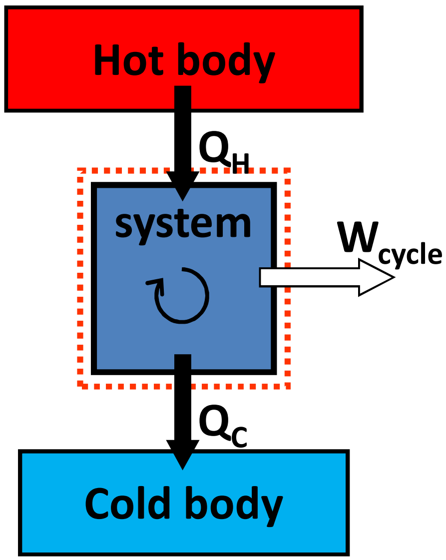


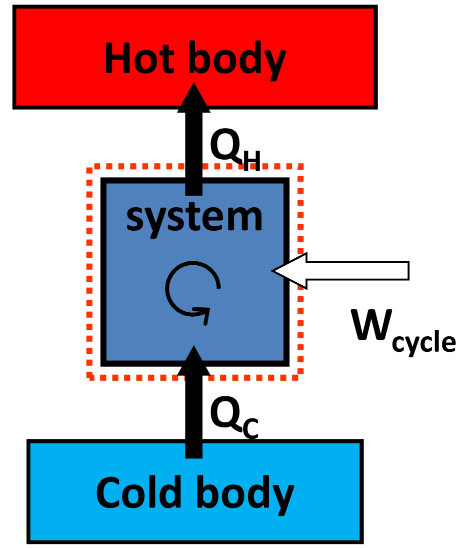
- Reverse direction: refrigeration or heat pump cycle

- Efficiency given by Carnot efficiency or COP

Carnot efficiency

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



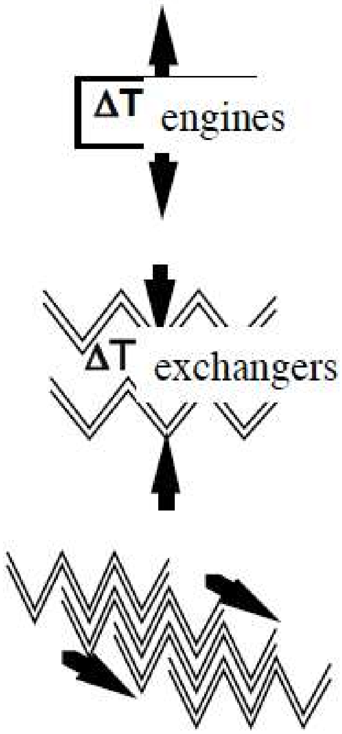


Efficiency	$\eta_{th} = \frac{W_{cycle}}{Q_H} = 1 - \frac{Q_C}{Q_H}$	$COP_{cm} = \frac{Q_C}{W_{cycle}} = \frac{Q_C}{Q_H - Q_C}$	$COP_{hm} = \frac{Q_H}{W_{cycle}} = \frac{Q_H}{Q_H - Q_C}$
Max. efficiency (Carnot)	$\eta_{th,max} = 1 - \left(\frac{Q_C}{Q_H}\right)_{\substack{rev\\cycle}} = 1 - \frac{T_C}{T_H}$	$COP_{cm,max} = \frac{T_C}{T_H - T_C}$	$COP_{hm,max} = \frac{T_H}{T_H - T_C}$

Consequences of the 2nd Law

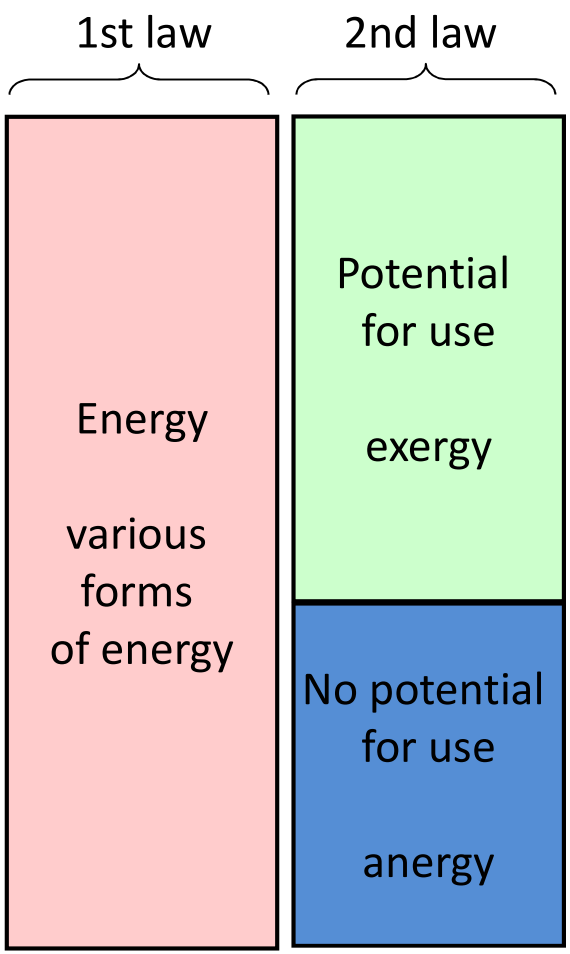
Practical implications from the second law:

- **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 - closed systems

- Closed systems:

$$Ex_2 - Ex_1 = \underbrace{\int_1^2 \left(1 - \frac{T_0}{T}\right)\delta Q}_{\text{Exergy transfer by heat transfer}} - \underbrace{\left(W_{12} - p_0\left(V_2 - V_1\right)\right)}_{\text{Exergy transfer by work}} - \underbrace{T_0 \sigma}_{\text{Exergy destruction by irreversibilities}}$$

Exergy transfer by heat transfer - **Exergy transfer by work** - **Exergy destruction** by irreversibilities

- Rate:

$$\frac{dEx}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \left(\dot{W}_{12} - p_0 \frac{dV}{dt}\right) - T_0 \dot{\sigma}$$

- Expressed alternatively:

$$Ex_2 - Ex_1 = Ex_q - Ex_w - Ex_d$$

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 outlest** - **Exergy destruction due to irreversibilities**

- With flow exergy:

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

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

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

Exergetic efficiency

- Exergy efficiency describes the effectiveness of energy resource utilization

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

energy efficiency (η)

- Components:
  - Turbine:

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

  - Compressor/pump:

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

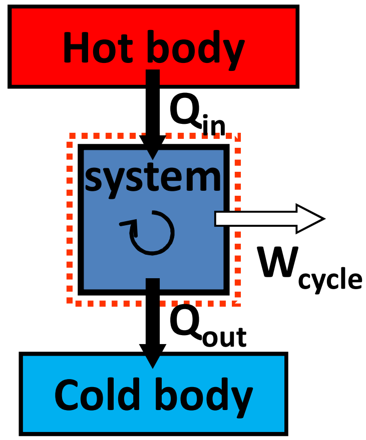
  - Heat exchanger: (non/mixing)

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

Example thermodynamic power cycles

Power systems

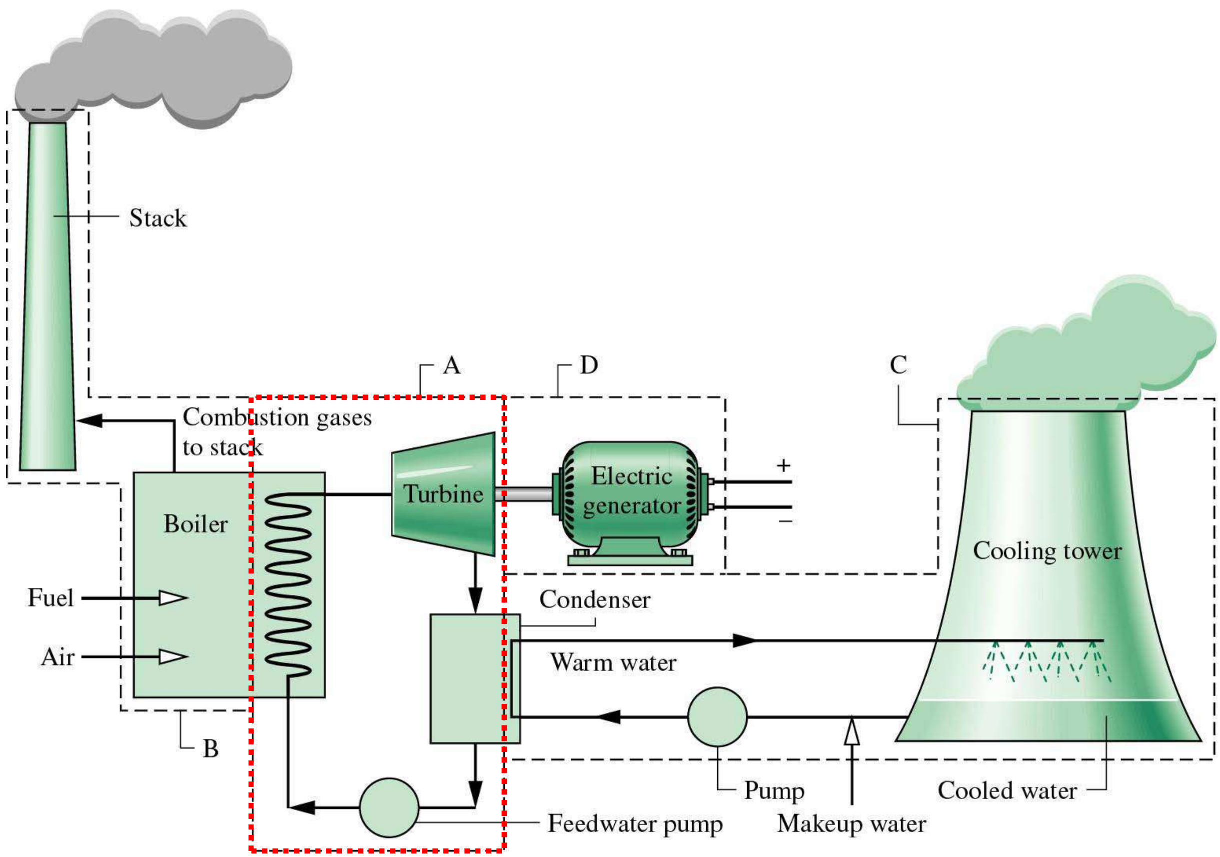
- Produce net power output from a energy source, such as fossil fuel, nuclear, or solar power



- 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 simplified systems are:
    - Boiler
    - Turbine
    - Condenser
    - Pump



Vapor power systems

- Idealized *Rankine* cycle:
  - Turbine: *isentropic* expansion

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

  - Condenser: *isobaric* heat transfer

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

  - Pump: *isentropic* compression

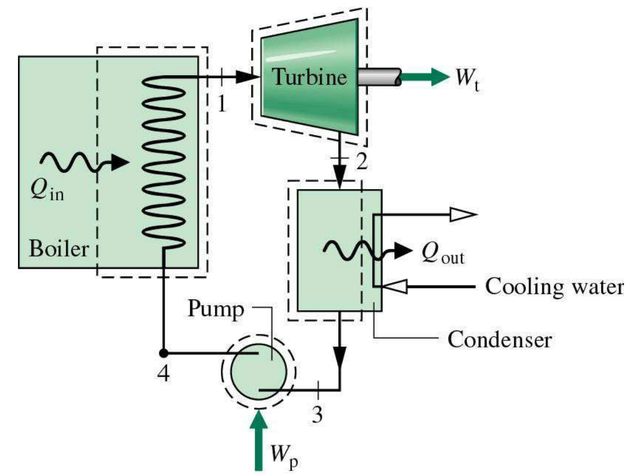
    $$\dot{W}_p / \dot{m} = (h_3 - h_4)$$

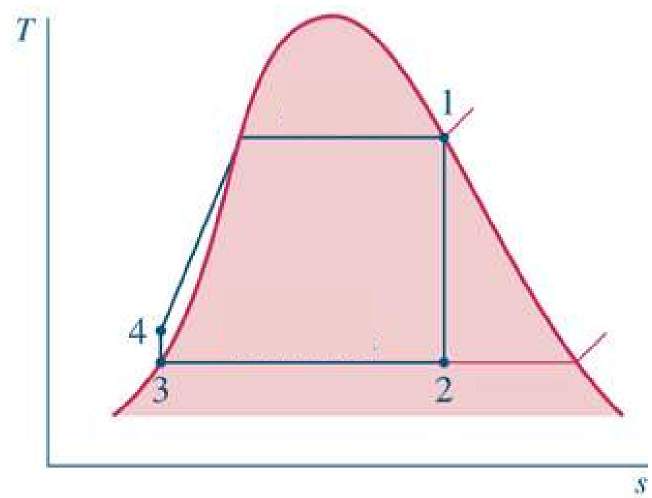
  - Boiler: *isobaric* heat transfer

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

  - Efficiency:

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



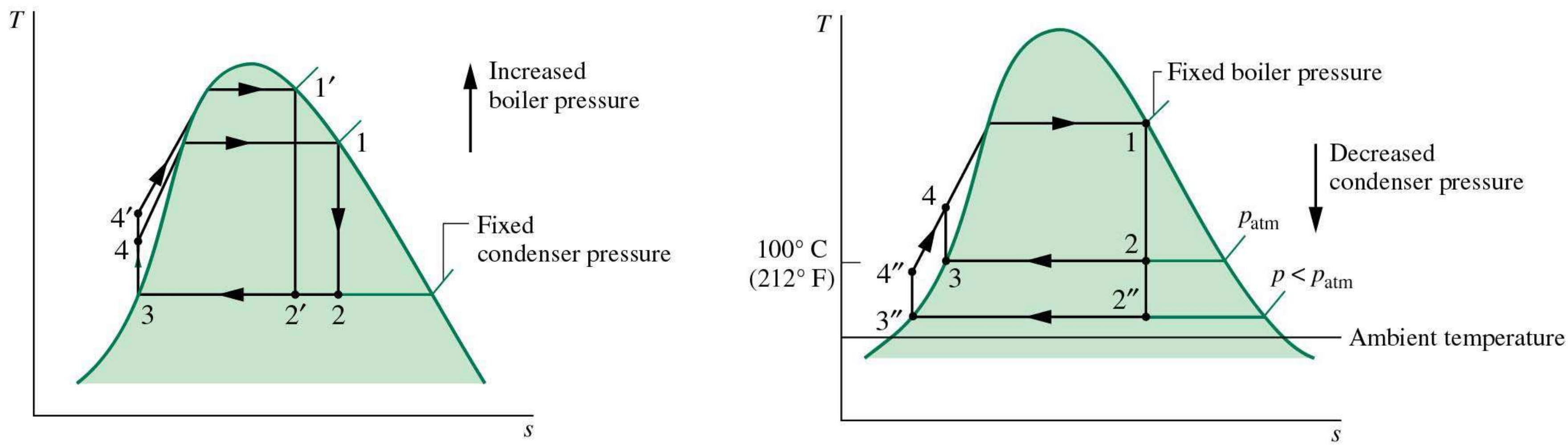


Vapor power systems

- 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):

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

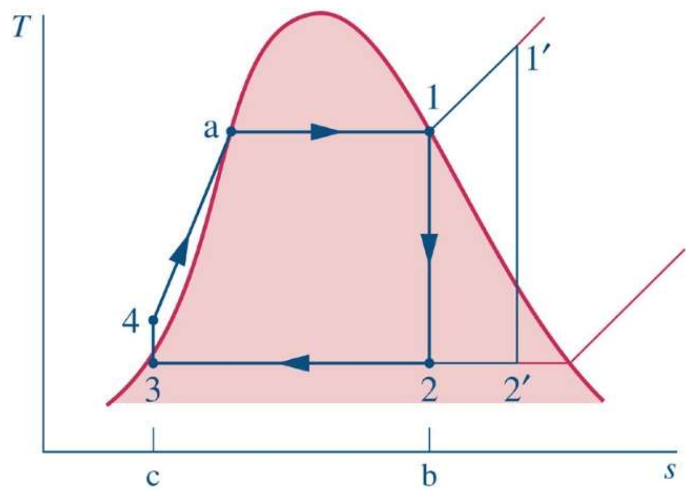
  - Increase in boiler pressure and decrease in condenser pressures:



(a) (b)

Vapor power systems

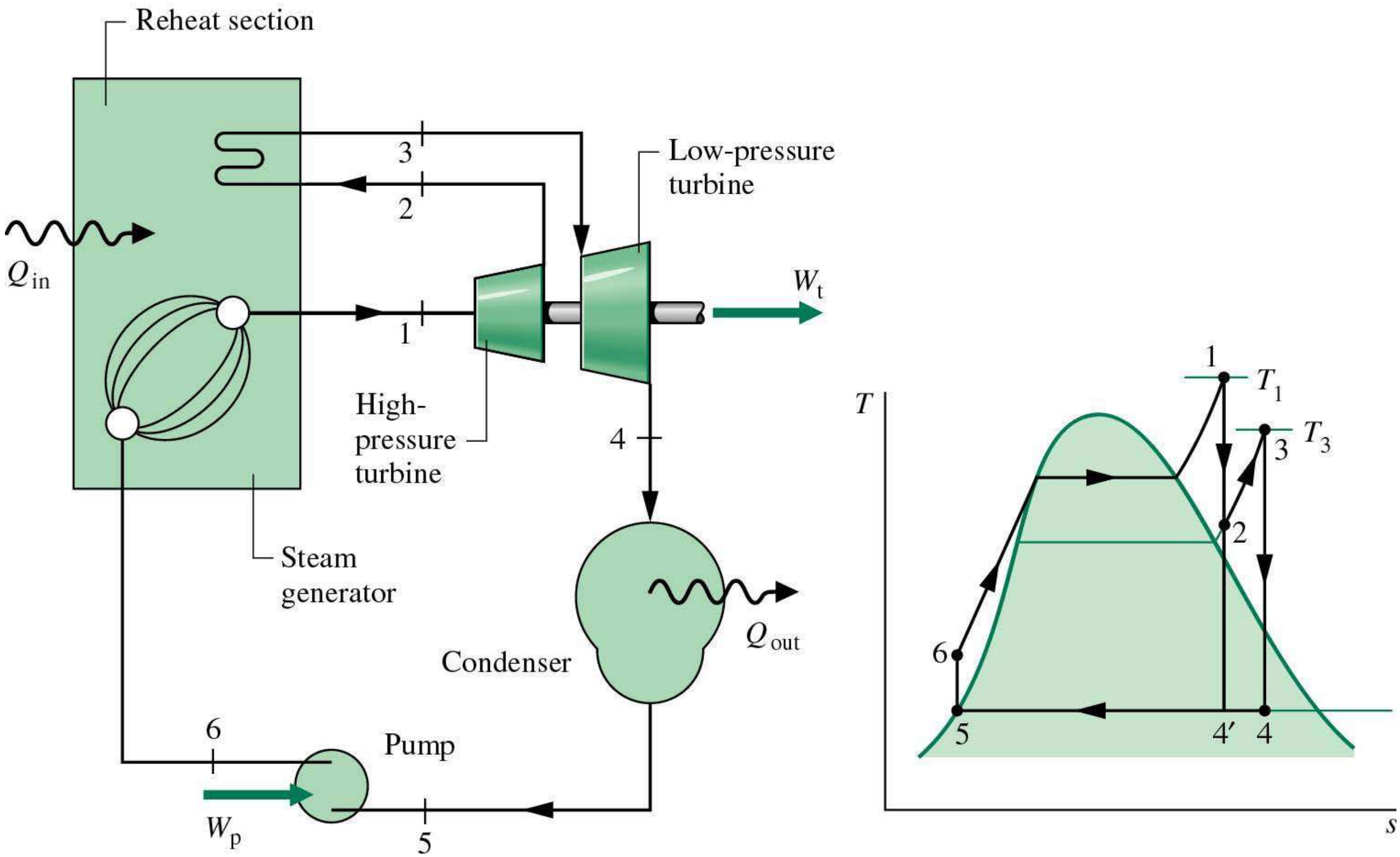
- Rankine cycle: improving performance:
  - Superheating (using additional heat exchanger, combination of boiler and heat exchanger is called steam generator)



Protect turbine (higher x) and increase efficiency (higher T)

Vapor power systems

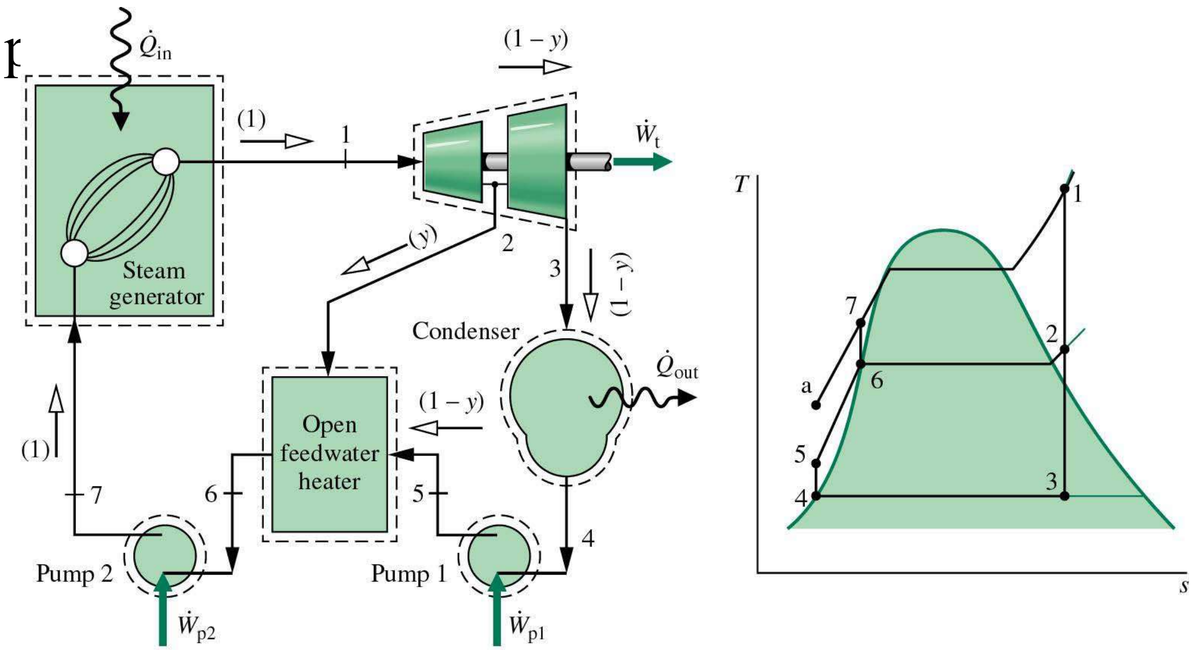
- Rankine cycle: improving performance:
  - Reheating



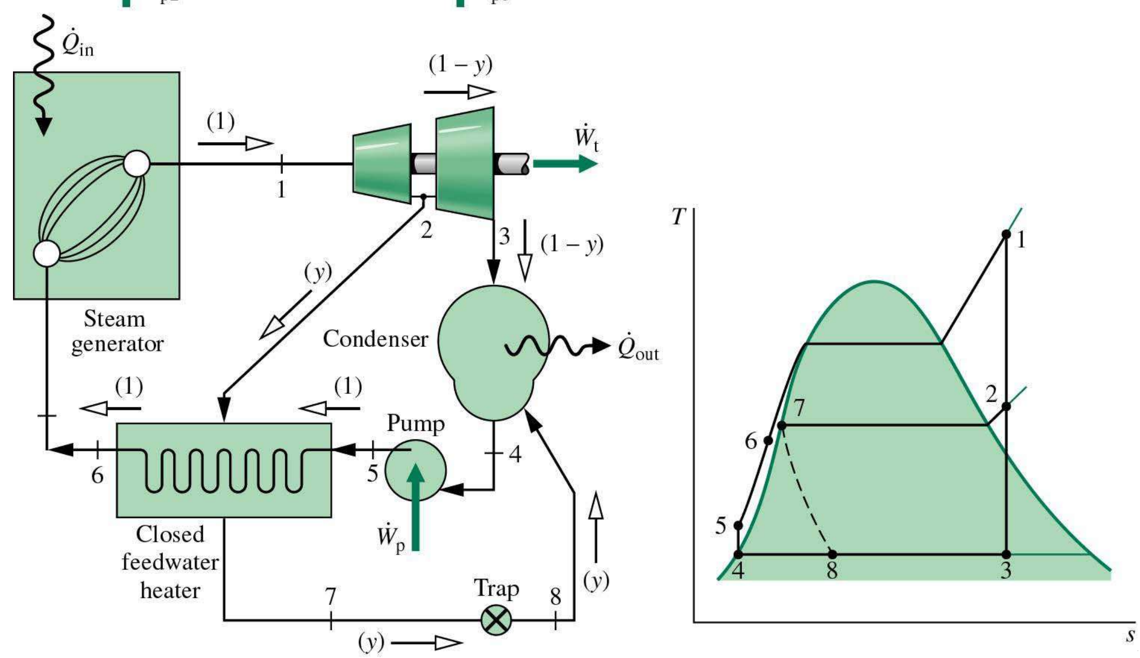
Vapor power systems

- Rankine cycle: improving p
  - Regeneration via

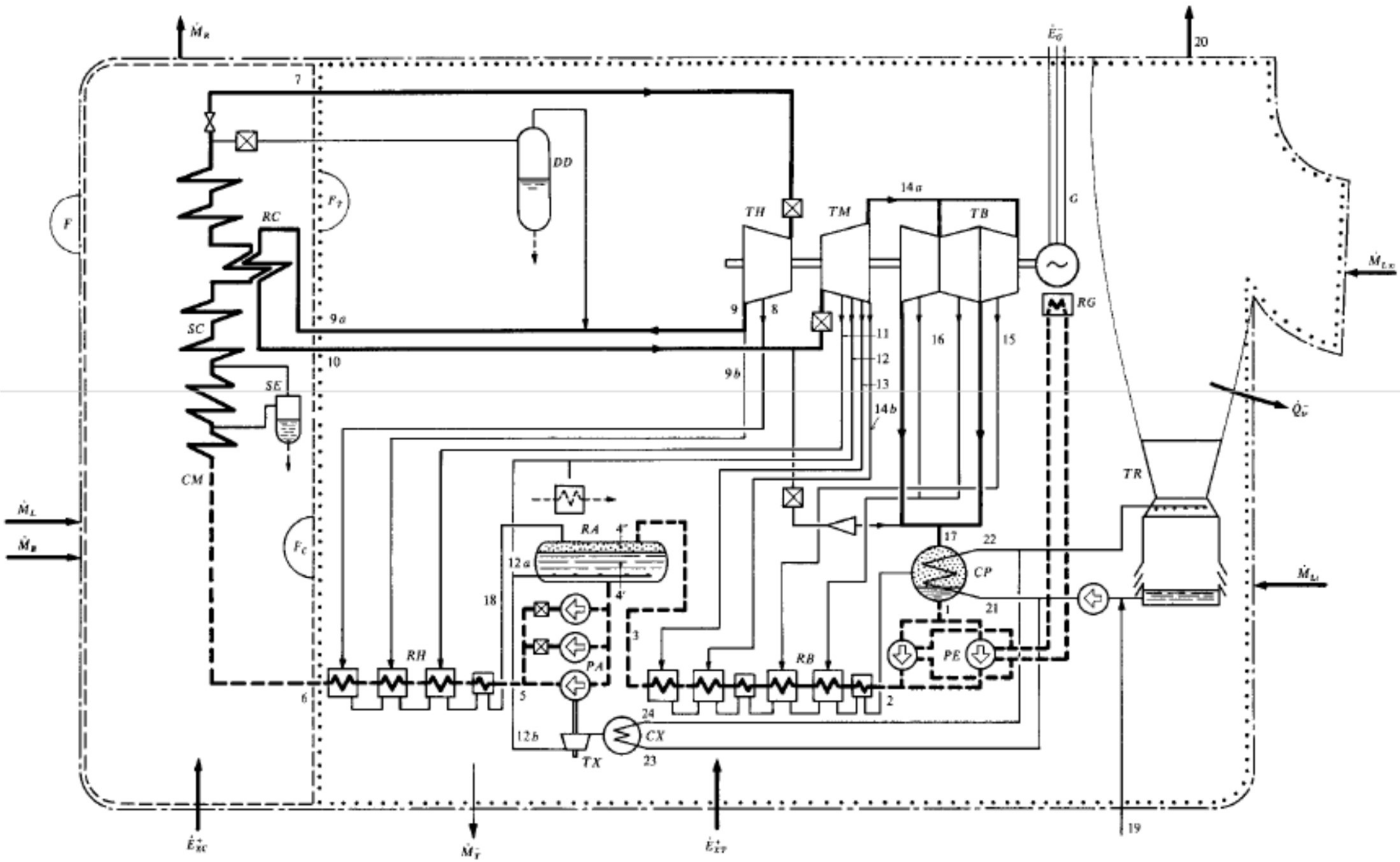
    open feedwater heaer



    closed feedwater heater



Real steam plant example:



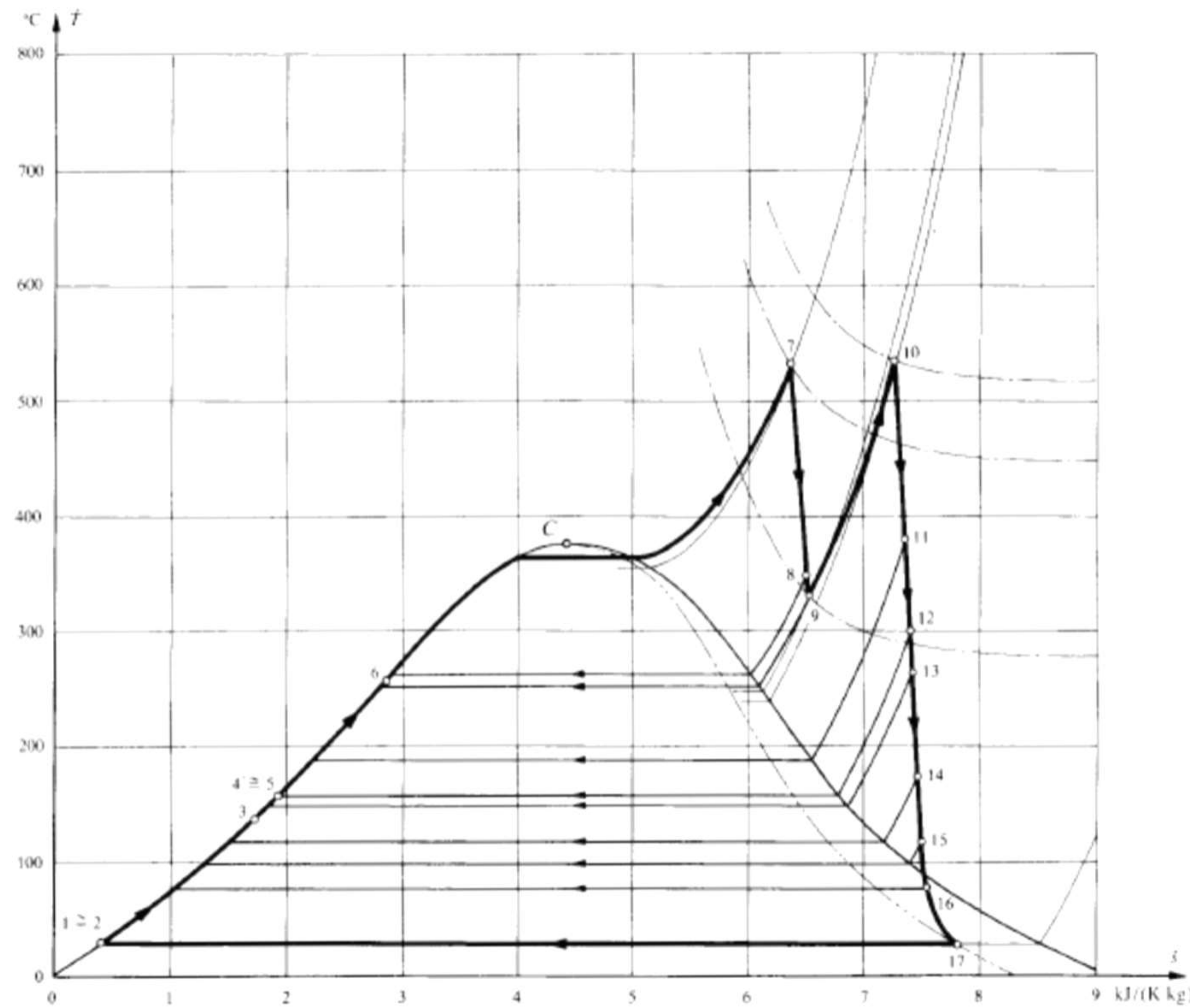
Real steam plant example:

- 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

$\varepsilon_{Turbogroup} = 75\%$

$\varepsilon_{Boiler} = 52\%$

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

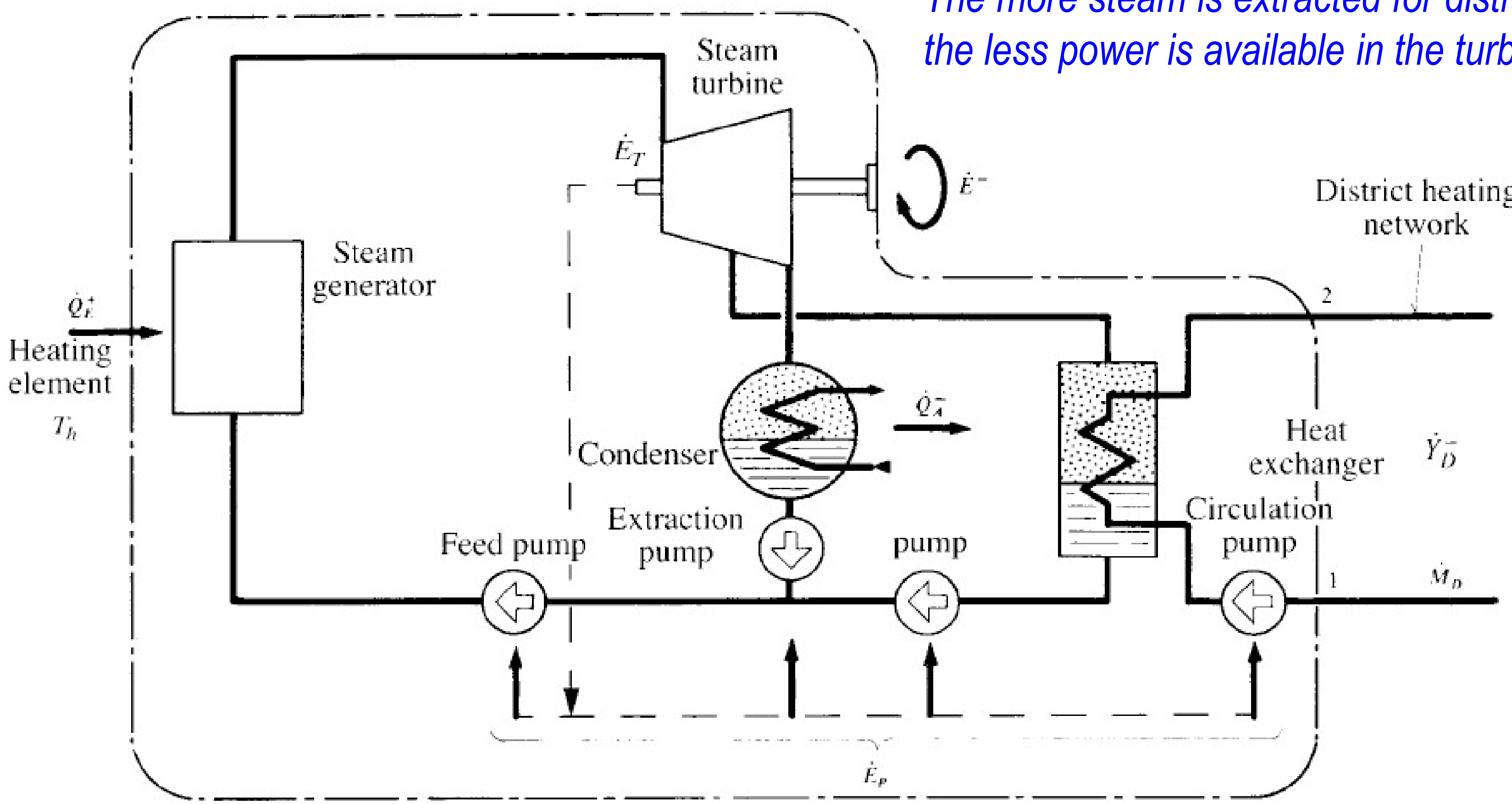


= still the main exergy loss (large T drop) ←→ 1st law : 94%

Co-generation

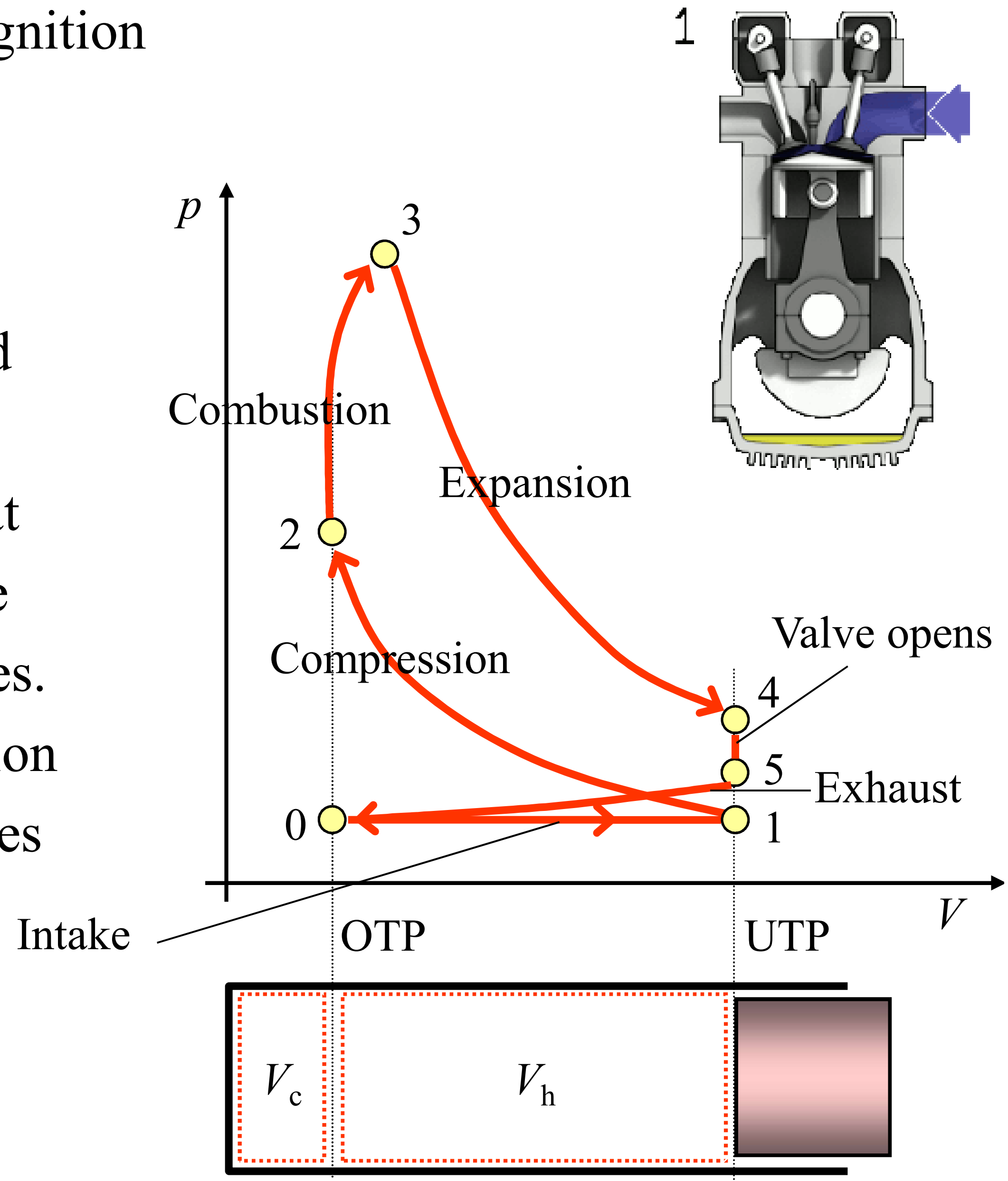
- Power and heat:
  - steam extraction to HEX for district heating (70°C)
  - output service: power E^- and transformation Y_D^-

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

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

  - 2-3: Constant-volume heat transfer

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

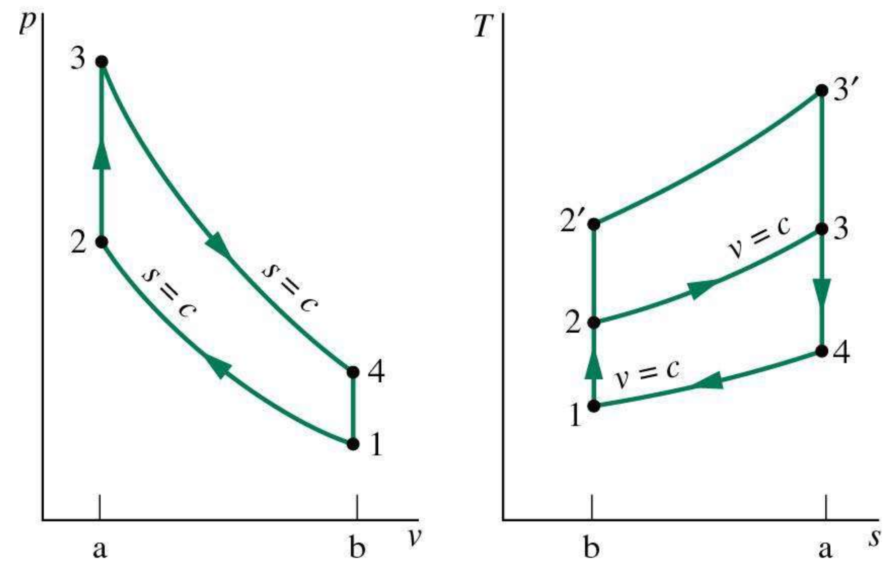
  - 3-4: Isentropic expansion

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

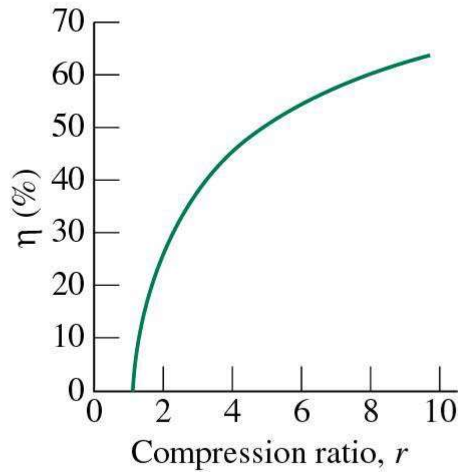
  - 4-1: Constant-volume heat

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

  - 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

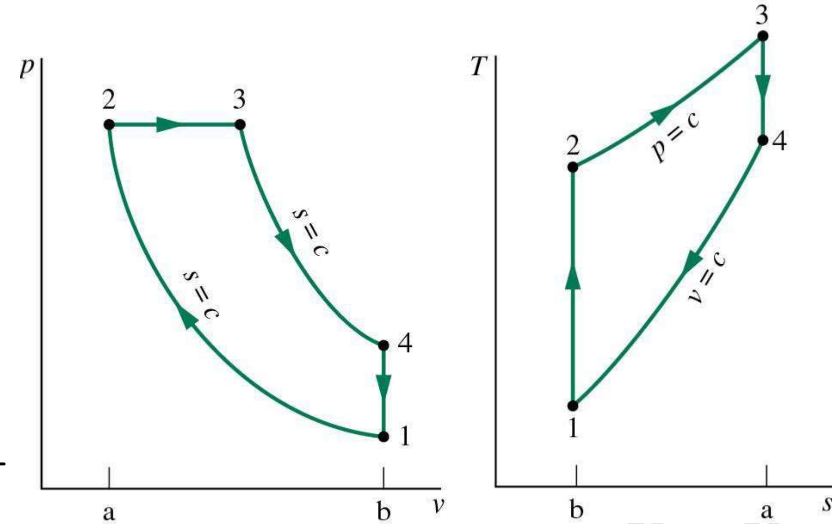
$$\frac{W_{34}}{m} = u_3 - u_4$$

  - 4-1: Constant-volume heat rejection

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

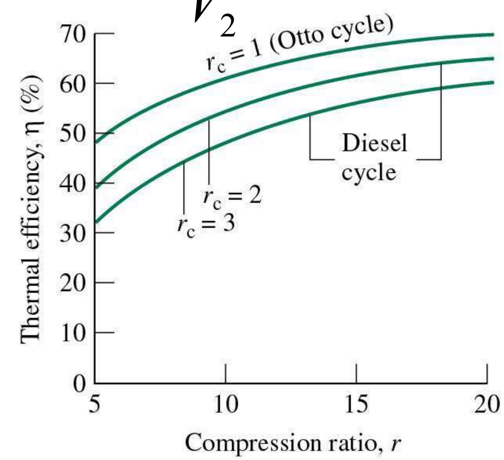
  - Cycle efficiency:

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



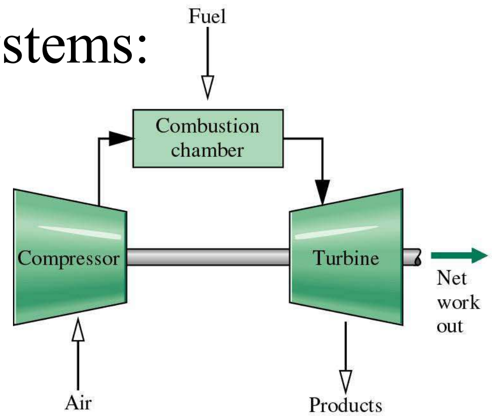
Compression ratio: $r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$

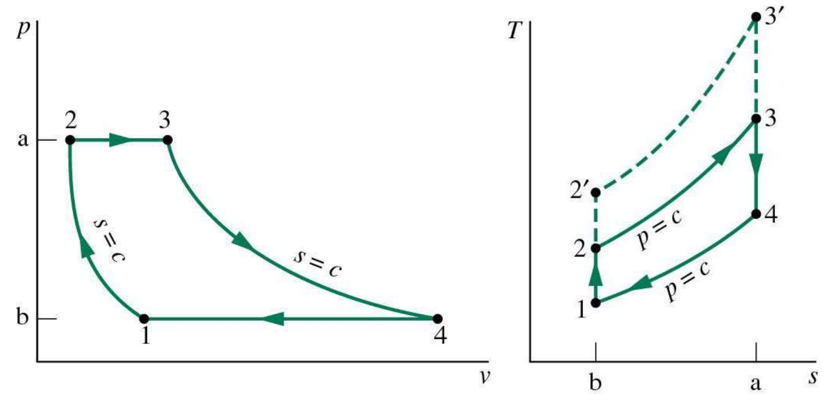
Cut-off ratio: $r_c = \frac{V_3}{V_2}$



Gas turbine power plants

- Gas turbine systems:





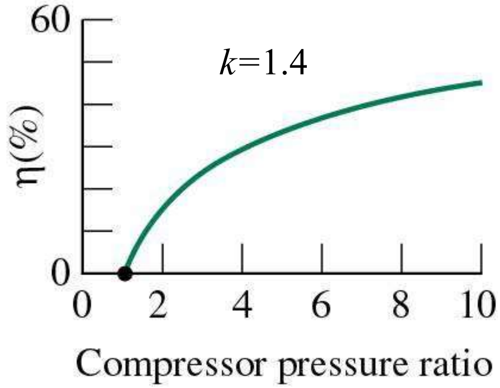
- Air-standard Brayton cycle (ideal):
  - 1-2: Isentropic compression $\frac{\dot{W}_{12}}{\dot{m}} = h_1 - h_2$
  - 2-3: Isobaric heat transfer $\frac{Q_{23}}{m} = h_3 - h_2$
  - 3-4: Isentropic expansion $\frac{\dot{W}_{34}}{\dot{m}} = h_3 - h_4$
  - 4-1: Isobaric heat transfer $\frac{Q_{41}}{m} =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

Cycle efficiency:

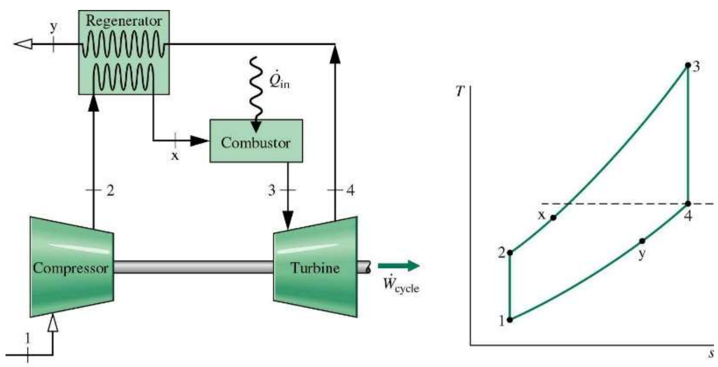
$$\eta = \frac{W_{cycle}}{Q_{23}} = \frac{h_3 - h_4 + h_1 - h_2}{h_3 - h_2}$$

Gas turbine power plants

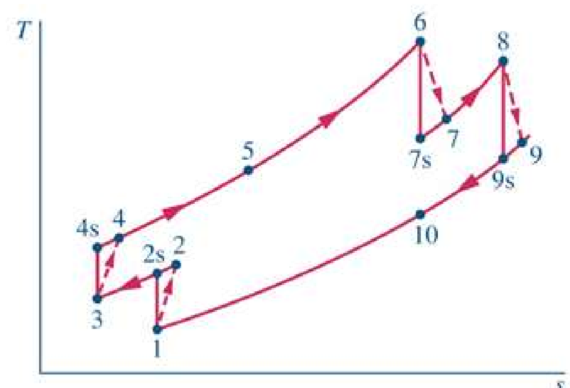
- Air-standard Brayton cycle: pressure ratio effect on performance
  - Efficiency increases with increasing pressure ratio



  - Regeneration:



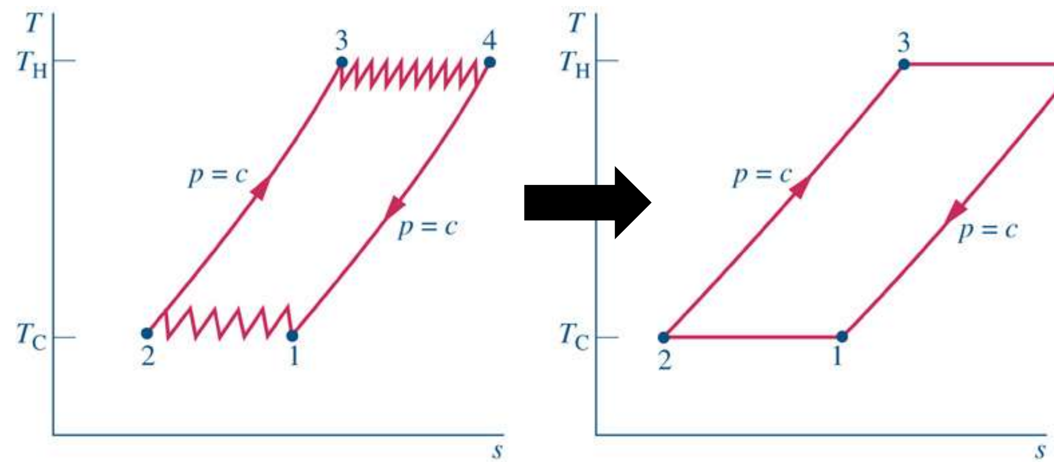
  - Reheating and intercooling:



Internal combustion engines

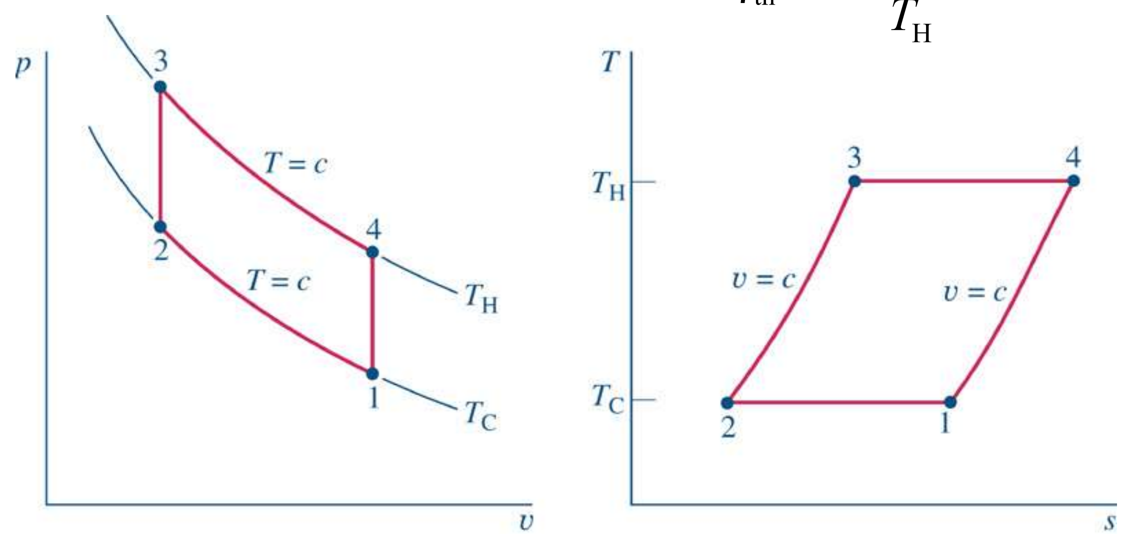
- Ericsson and Stirling cycle (both with same features as Carnot):
  - In the limit of large number of multi-stage compression with inter-cooling, and multi-stage expansion with re-heating, with ideal regeneration

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 the exergy heat transfer loss** between fuel combustion gases and steam
- ST below the GT (‘*bottoming cycle*’) **reduces transformation exergy loss** of the hot GT exhaust gas (450-650°C)

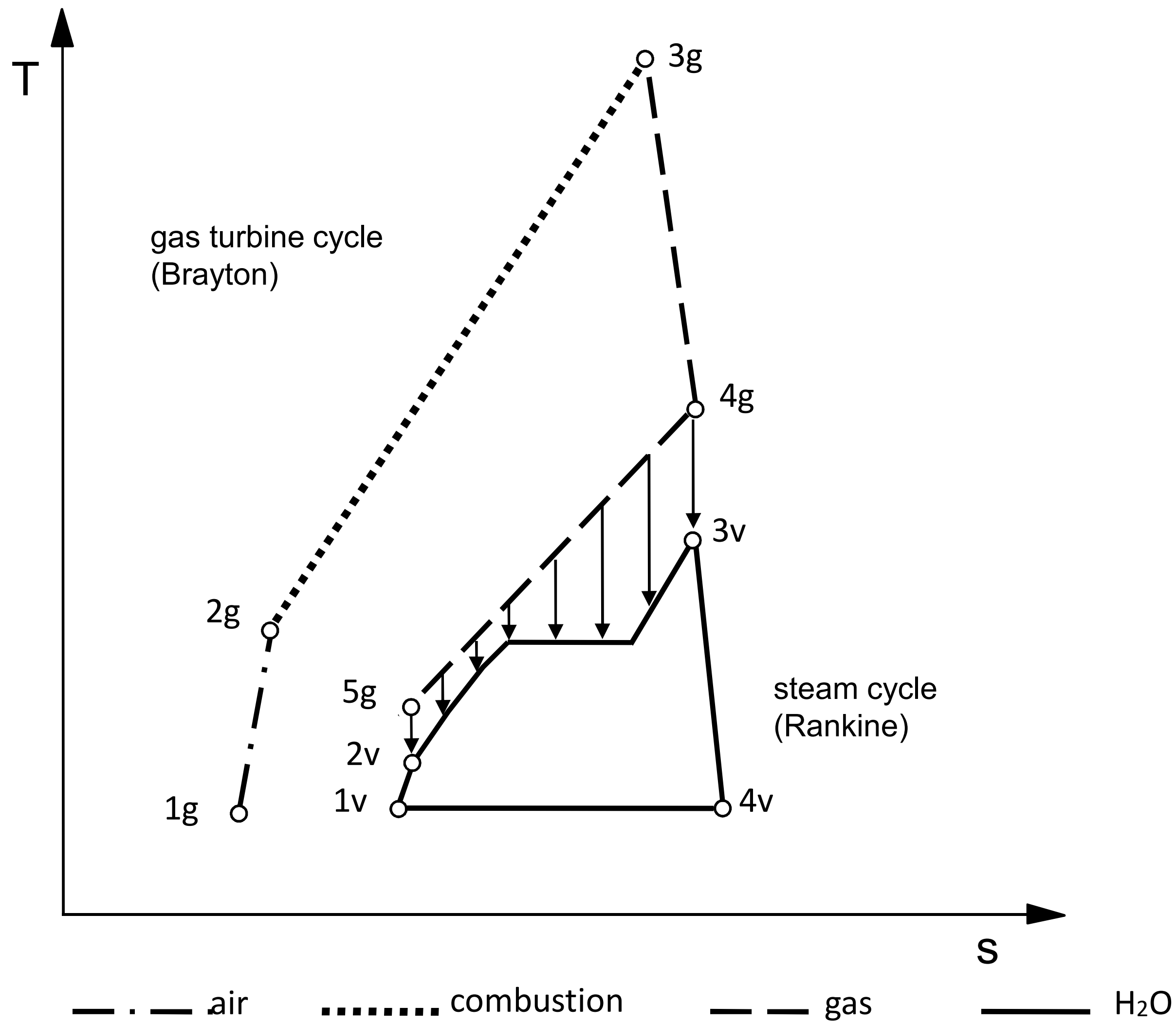
→ ***‘win’–’win’*** combination between both cycles

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

  – for the GT: obviously no regenerator ! (it becomes the steam heater)

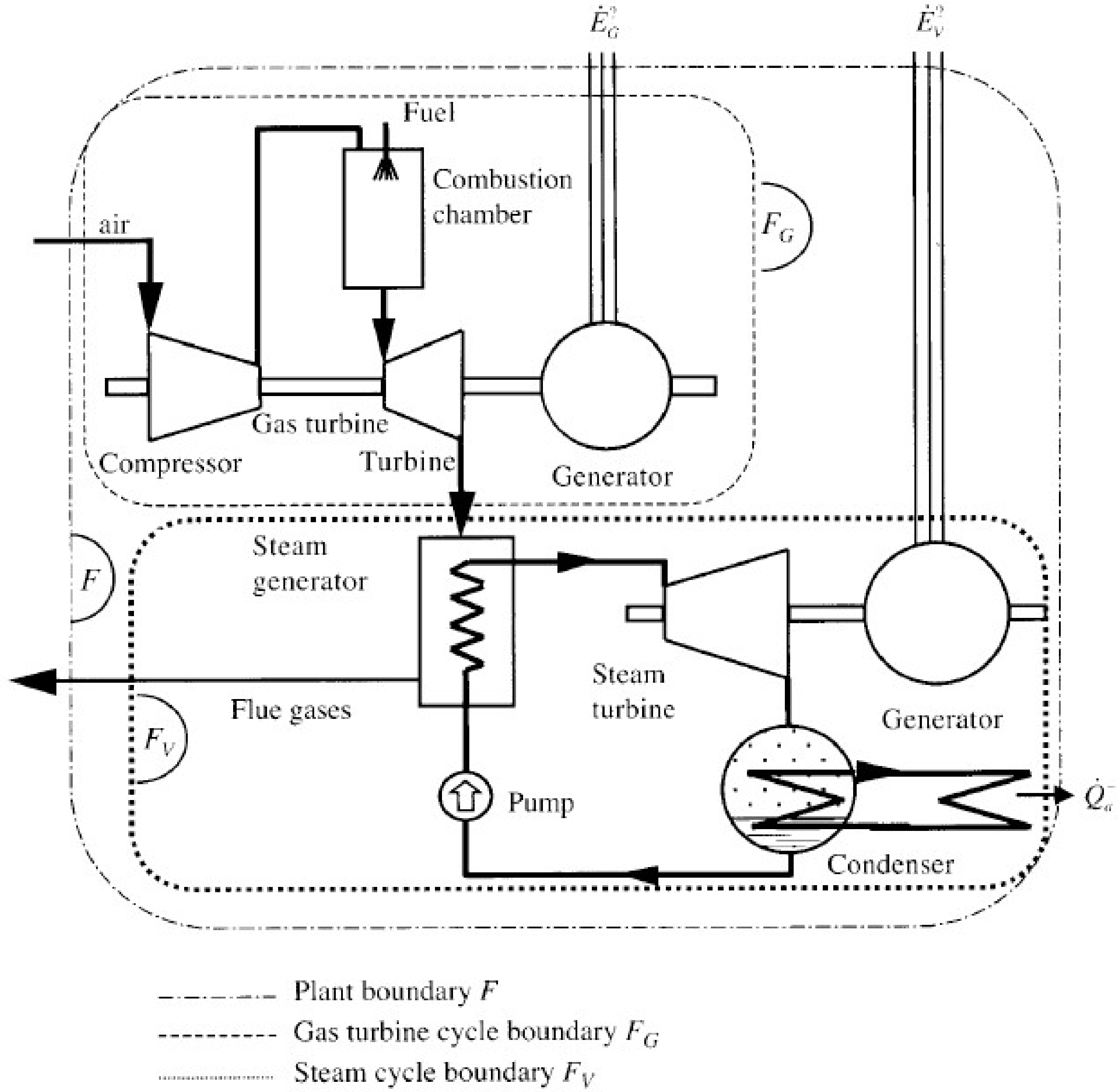
  – for the ST: almost no steam extraction

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

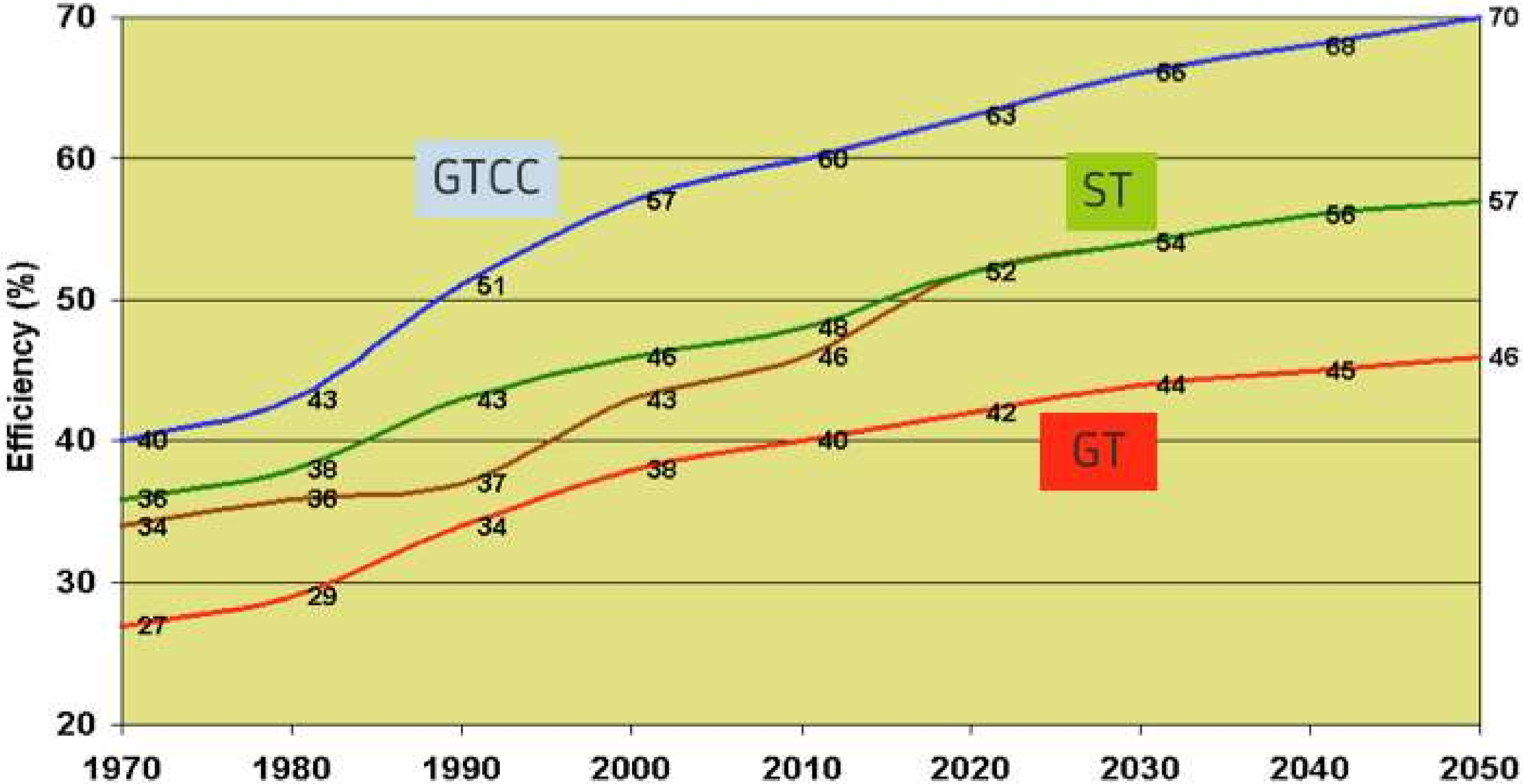


Layout

(no cogen.)



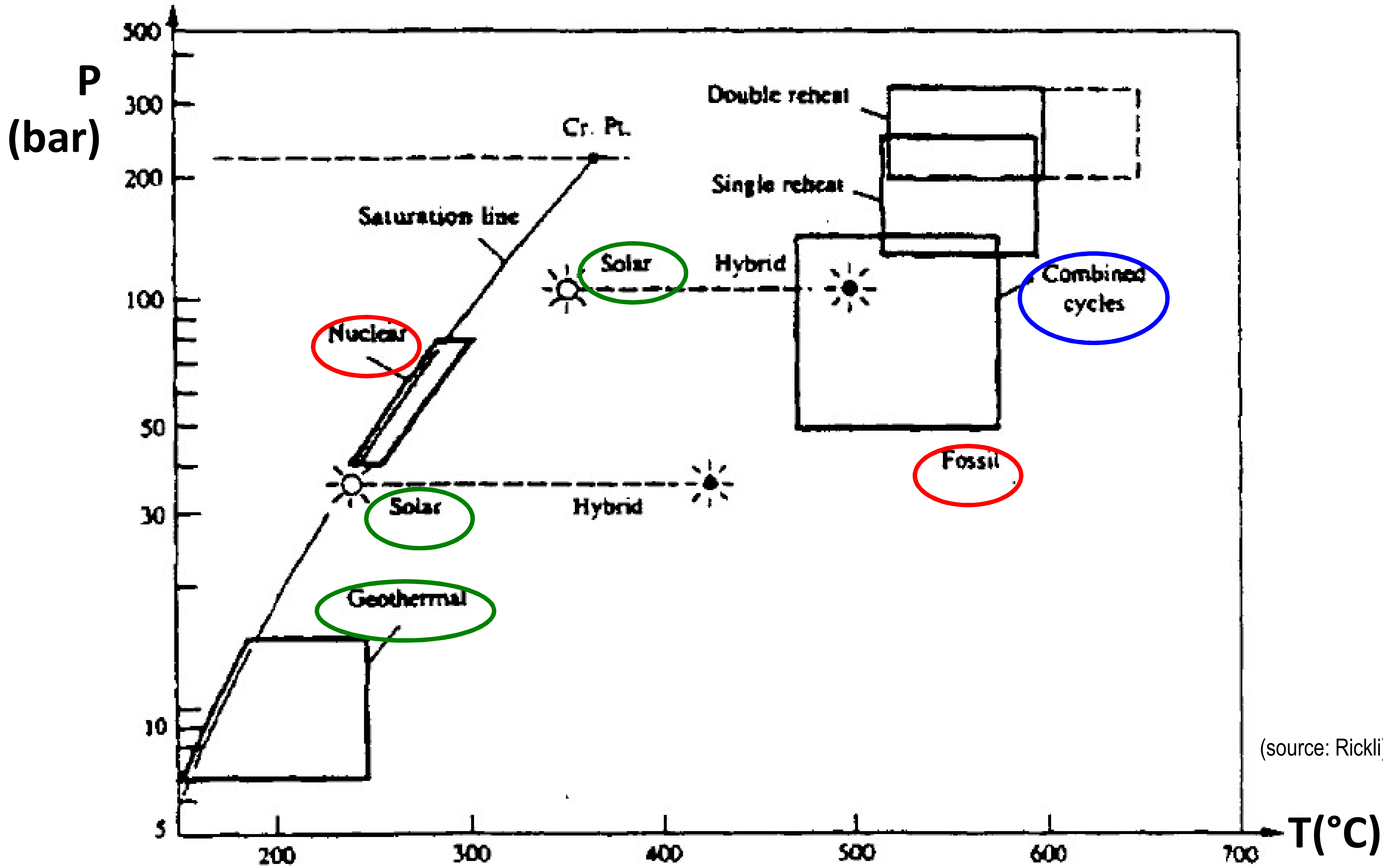
Efficiency evolution and perspectives



(T. Kaiser, Alstom)

Thermodynamic power cycles for renewable sources

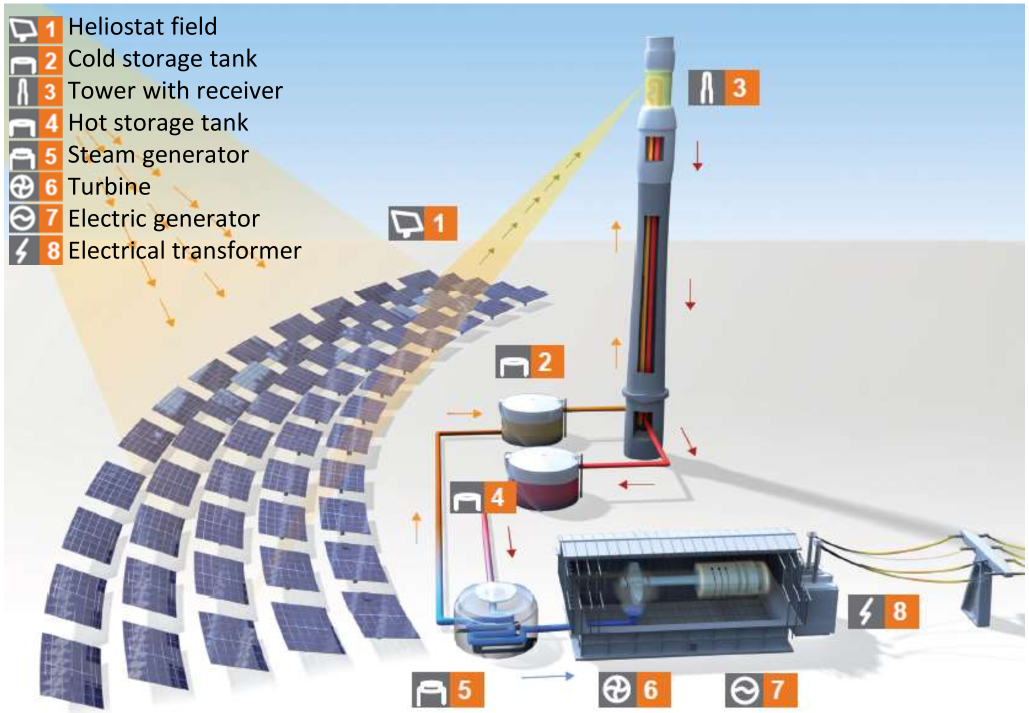
Steam *P-T* diagram for various cycle applications

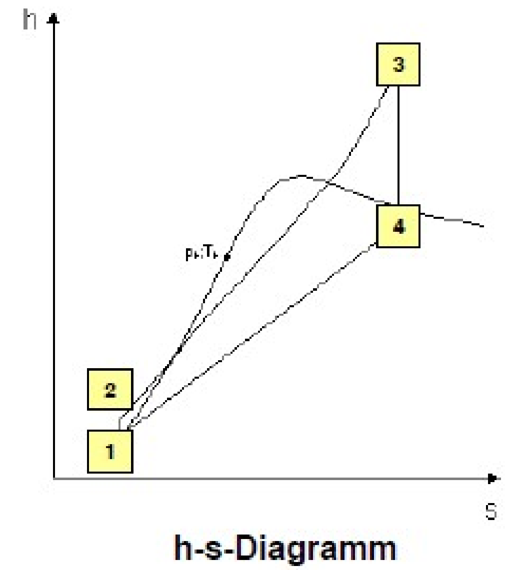


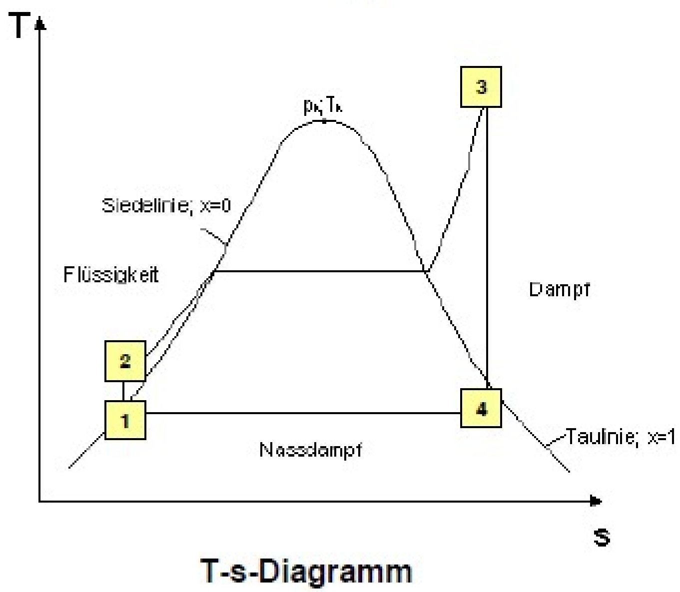
(source: Rickli)

Concentrated Solar Power - Centralized

- Traditional Rankine cycle:



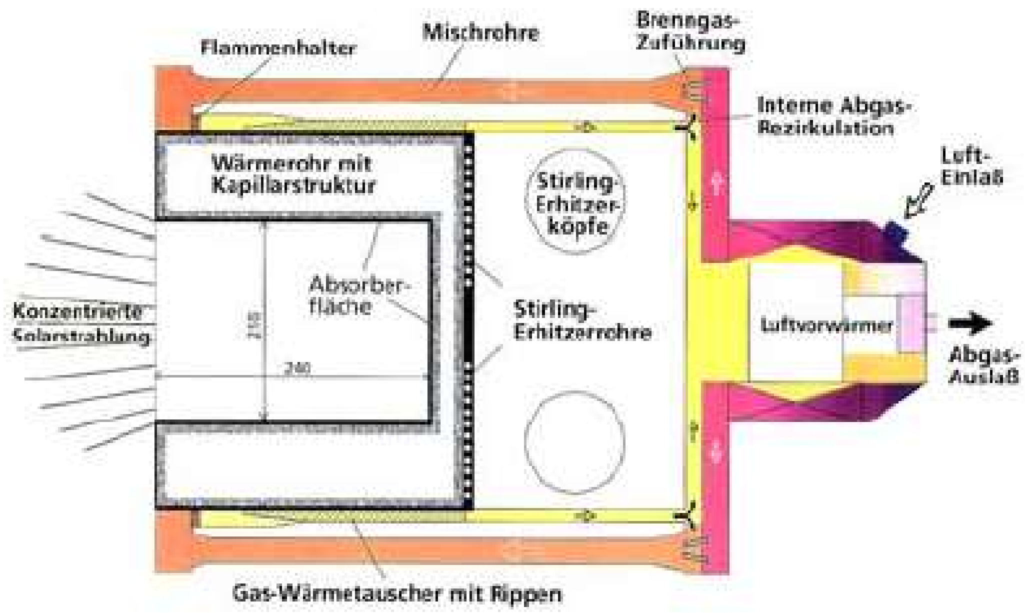


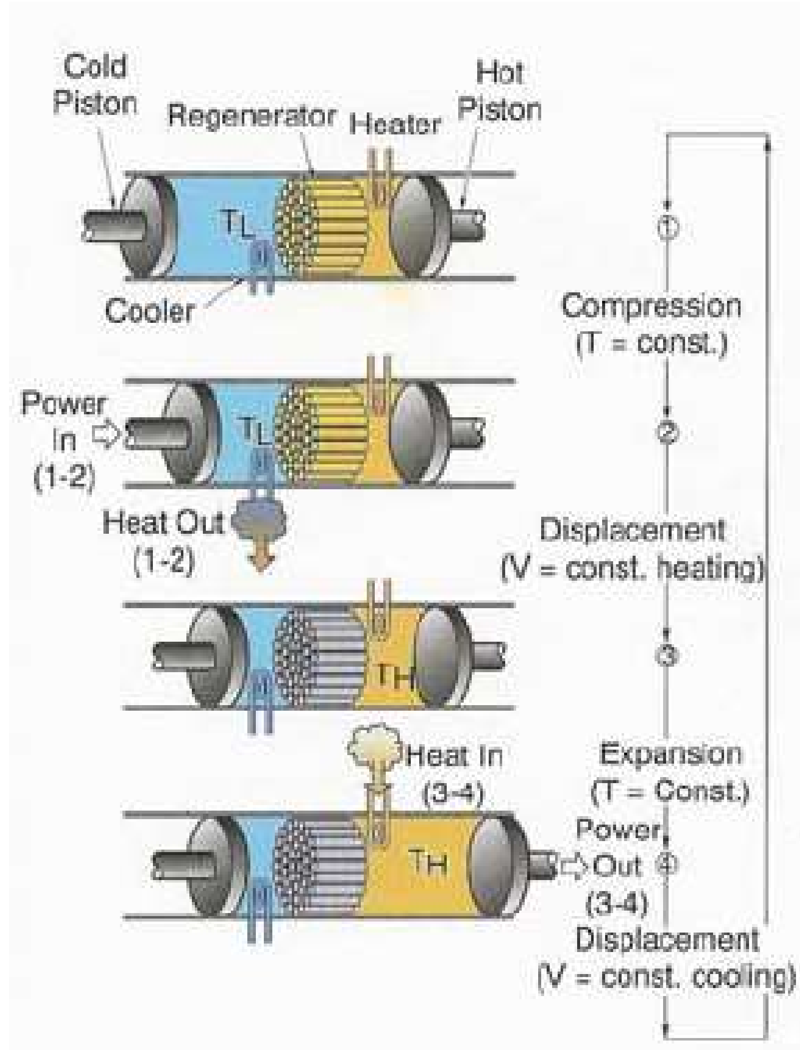


→ see lecture next week

Concentrated Solar Power - Decentralized

- Stirling cycle:

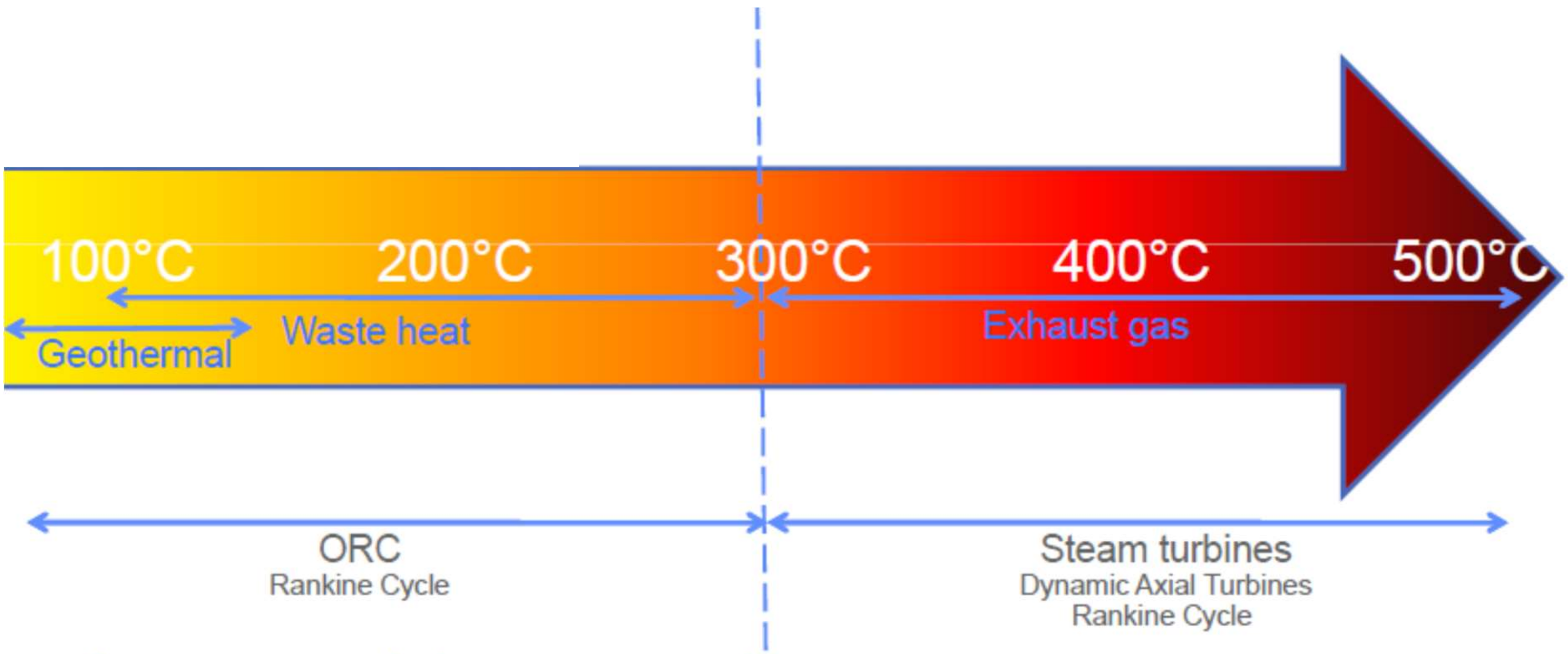




→ see lecture next week

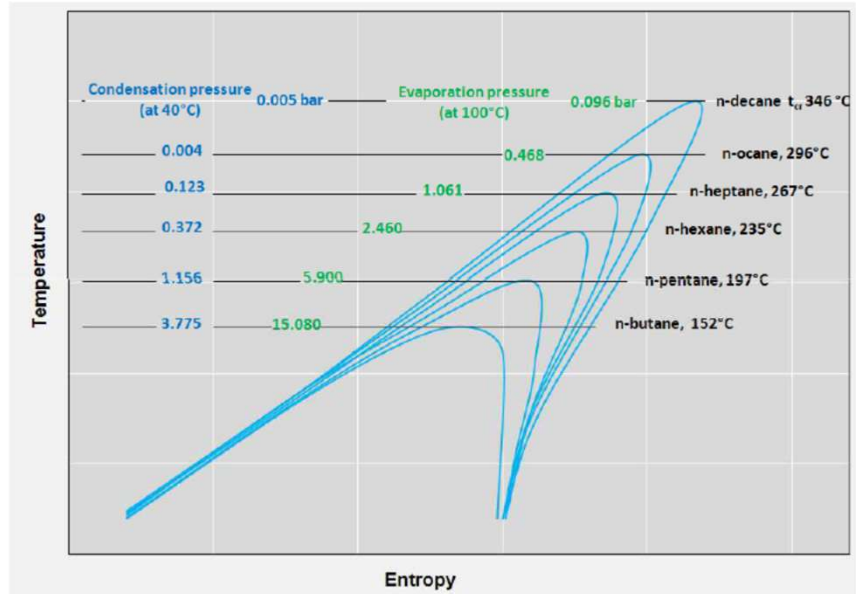
Low temperature sources

- For geothermal, waste heat, non / low-concentrated solar:
  - Temperatures too low for HTF water
  - Instead using fluid with different critical parameters



HTF for ORC

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

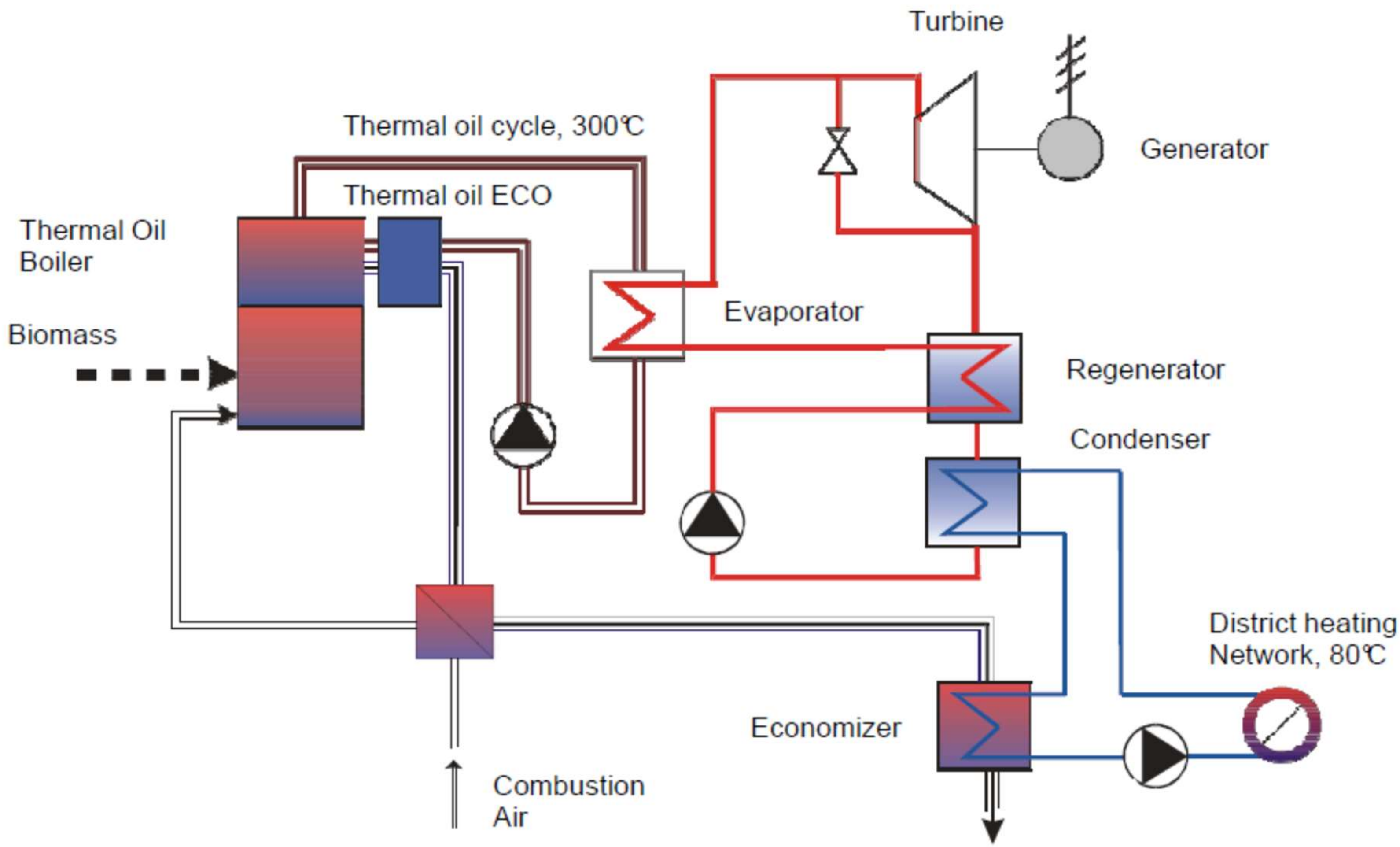


	R245 fa	R152A	R32	Pen-tane	Iso-Butane	Toluene
Saturated pressure at 120℃ (bar)	19.2	42	58	9	28	1.3
Service temperature (℃)	140	140	140	140	140	140
Saturated pressure at 50℃ (bar)	3.5	11	31	1.6	6.8	0.1
Expander pressure ratio	5.6	3.6	1.8	5.7	4.1	10.7
Ozone Depletion Potential	0	0	0	0	0	0
Global Warming 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

M. Kane

ORC example

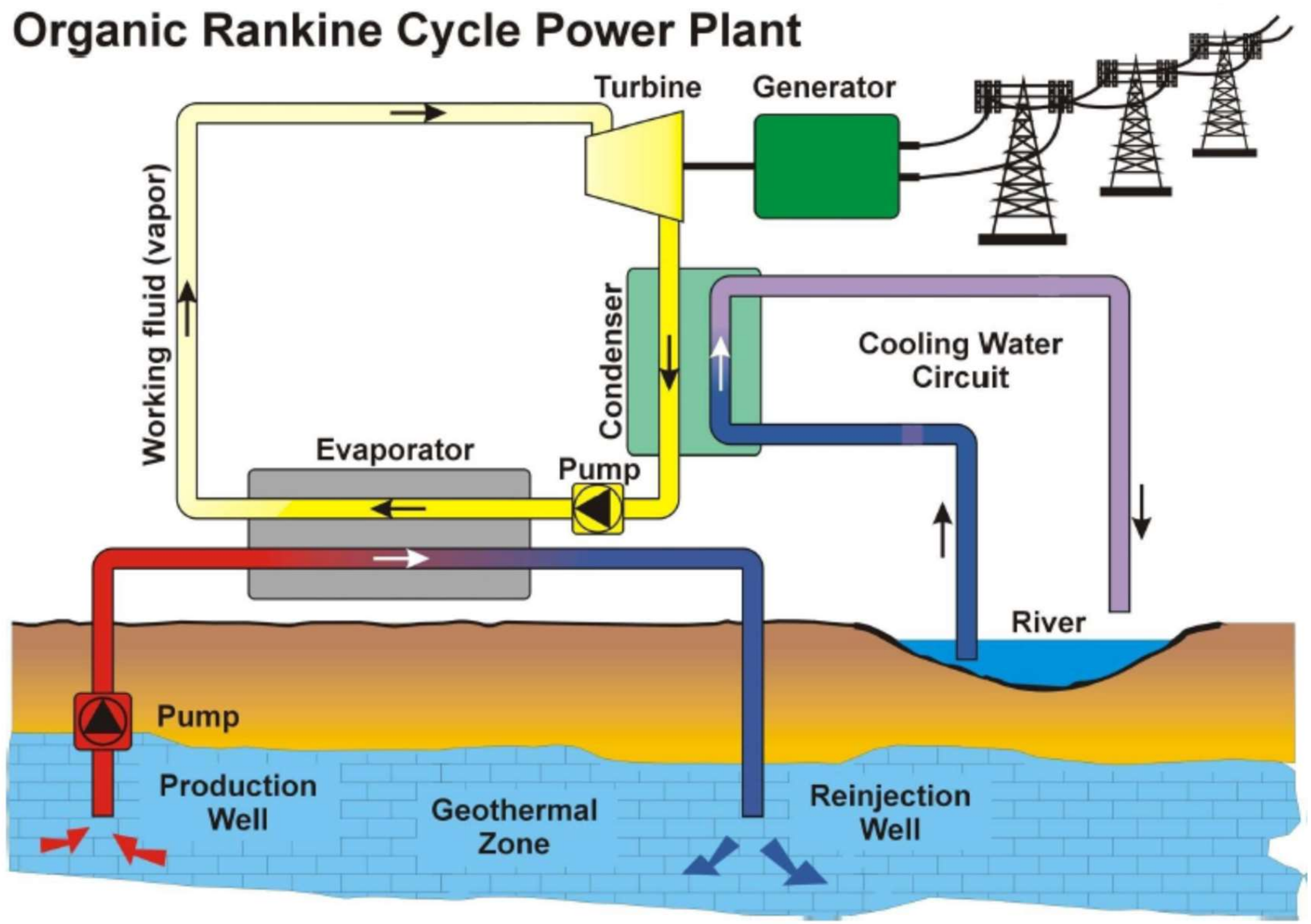
- Biomass: Working fluid silicone oil



M. Kane

ORC example

- Geothermal

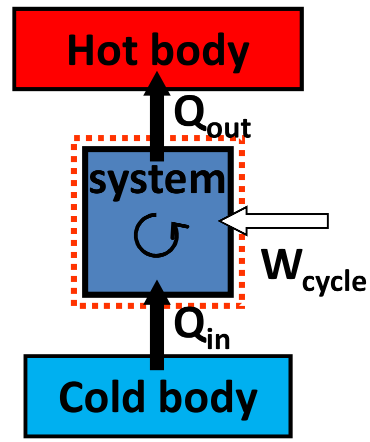


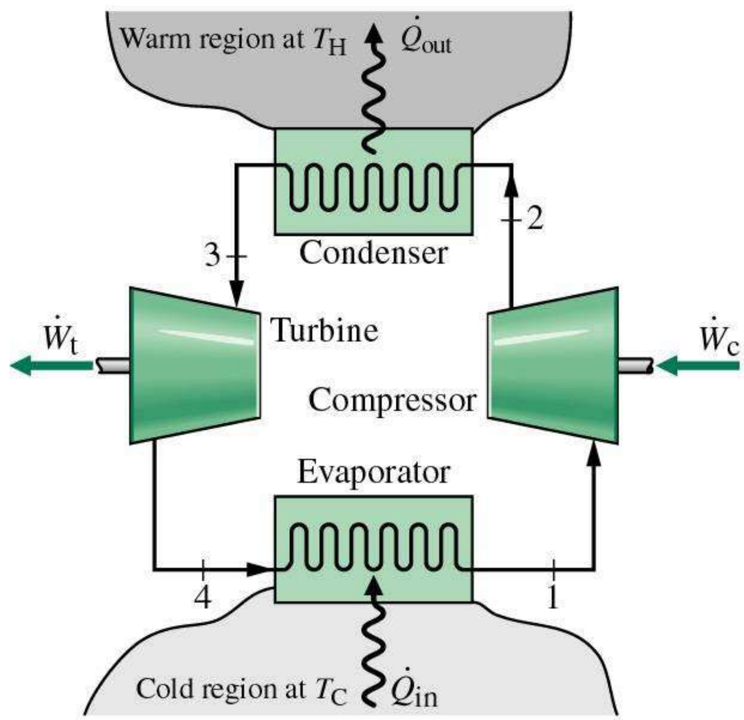
M. Kane

Example thermodynamic cooling and heating cycles

Refrigeration and heat pump systems

- Refrigeration and heat pump
  - Maintain cold temperature below temperature of surrounding
  - Maintain high 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

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

  - 3-4: throttling process

$$h_3 = h_4$$

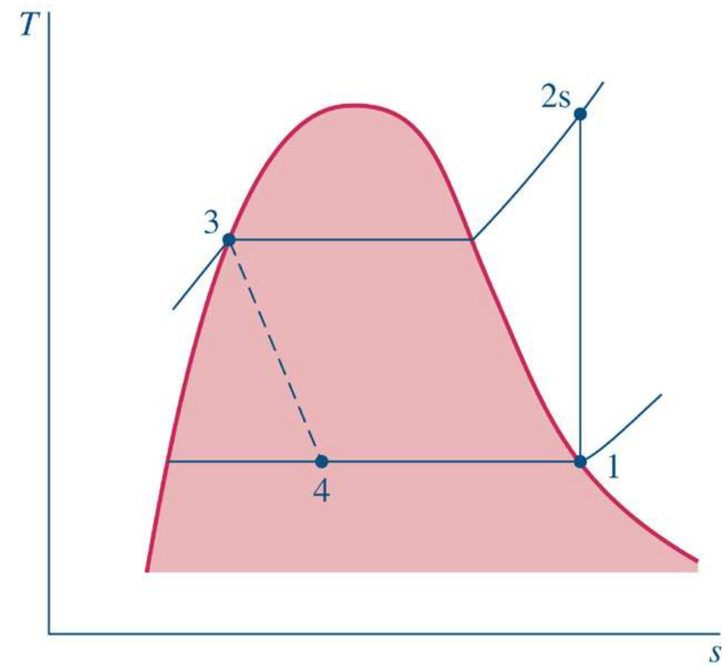
  - 4-1: Isobaric heat addition

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

  - Coefficient of performance:

$$COP_{cm} = \frac{h_1 - h_4}{h_2 - h_1} < COP_{cm,max}$$

$$COP_{hm} = \frac{h_2 - h_3}{h_2 - h_1} < COP_{hm,max}$$



Gas refrigeration systems

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

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

  - 2-3: Isobaric cooling

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

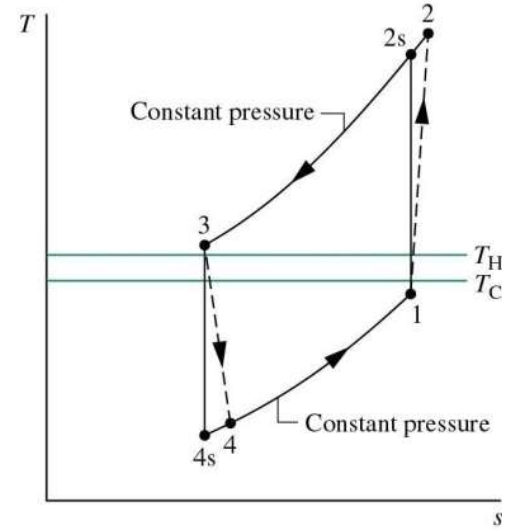
  - 3-4: (Isentropic) expansion

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

  - 4-1: Isobaric evaporation

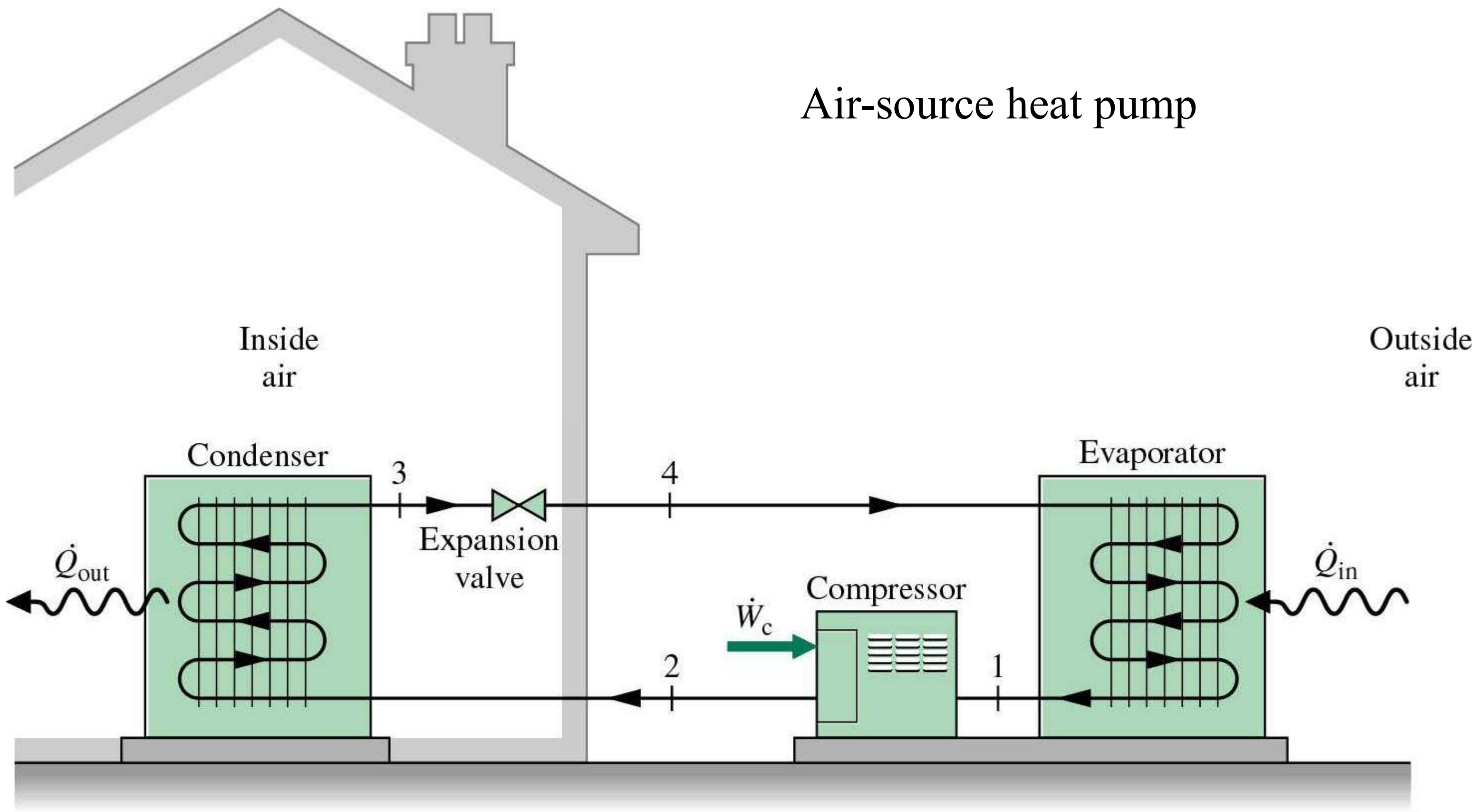
$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

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



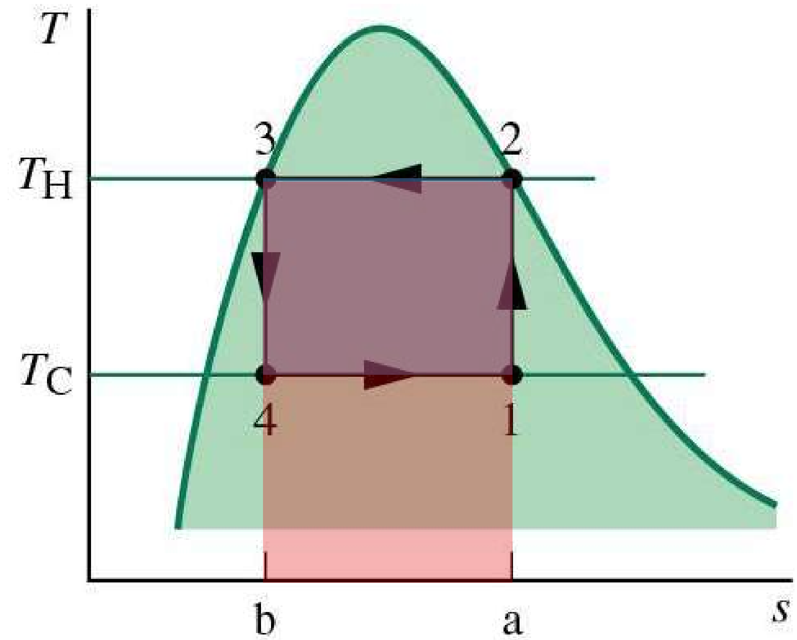
Heat pump systems

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



Heat pump systems

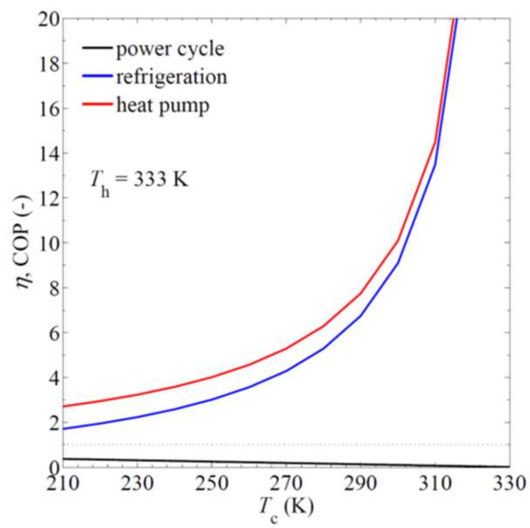
- Carnot heat pump cycle:
  - Same processes
  - Different purpose



  - Performance:

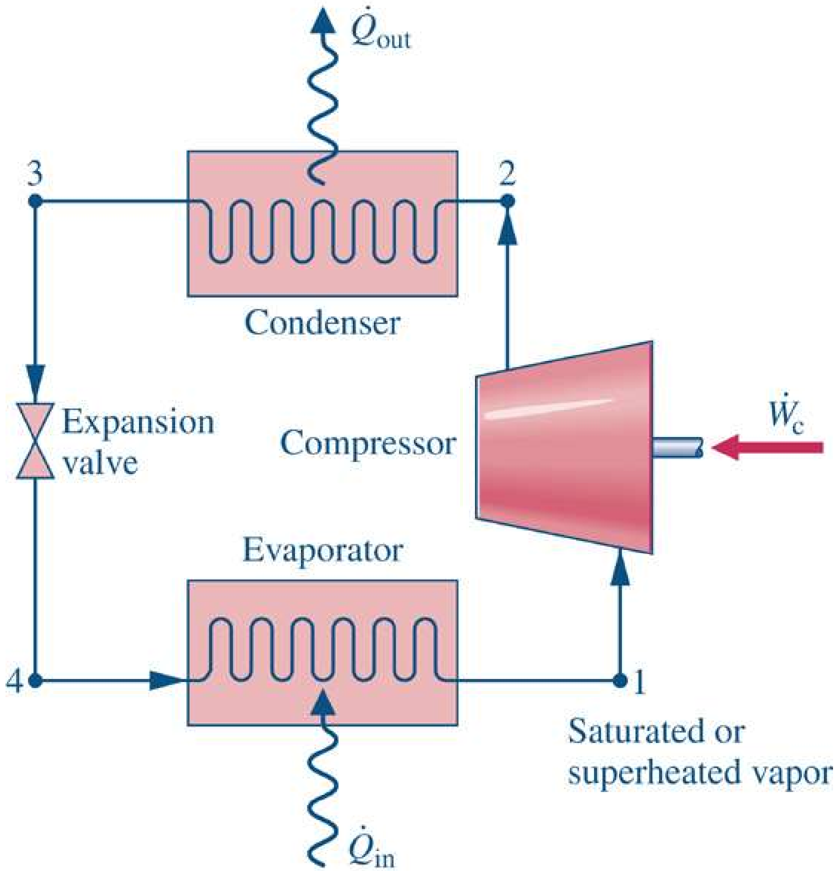
$$\mathrm{COP}_{\mathrm{hm,max}} = \frac{\dot{Q}_{\mathrm{out}} / \dot{m}}{\left| \dot{W}_{\mathrm{c}} / \dot{m} - \dot{W}_{\mathrm{t}} / \dot{m} \right|} = \frac{T_{\mathrm{H}}(s_a - s_b)}{(T_{\mathrm{H}} - T_{\mathrm{C}})(s_a - s_b)}$$

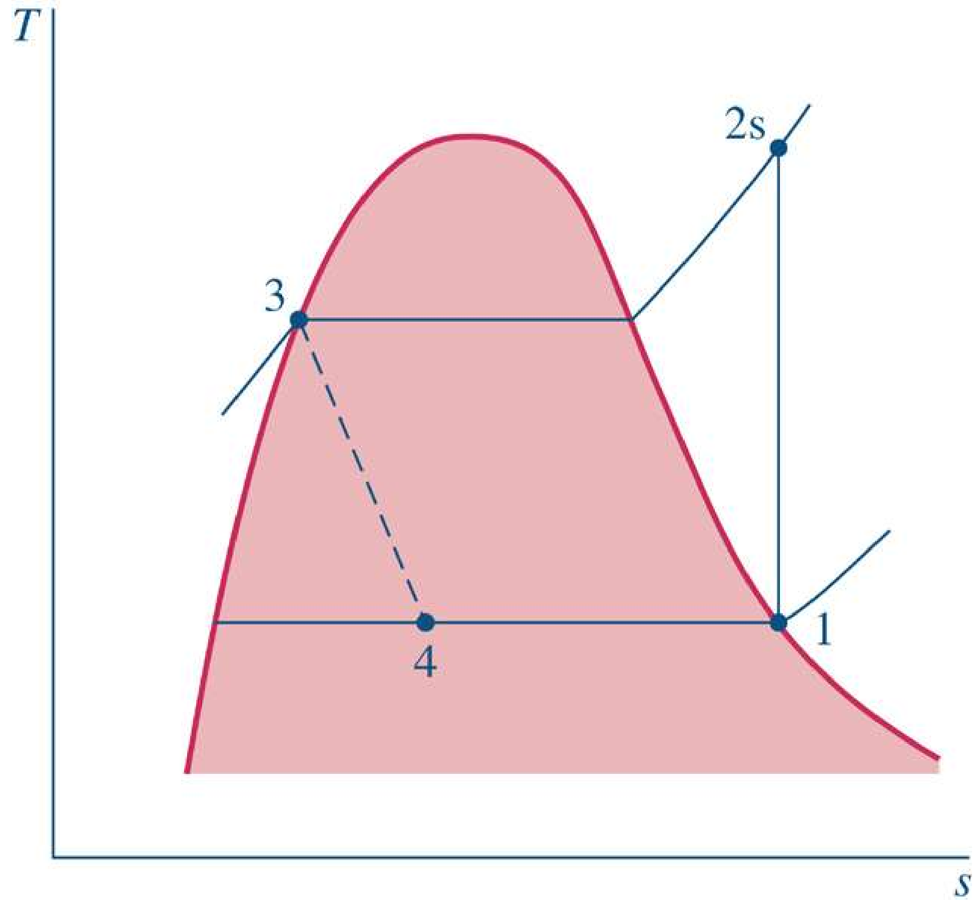
$$= \frac{T_{\mathrm{H}}}{T_{\mathrm{H}} - T_{\mathrm{C}}}$$



Heat pump systems

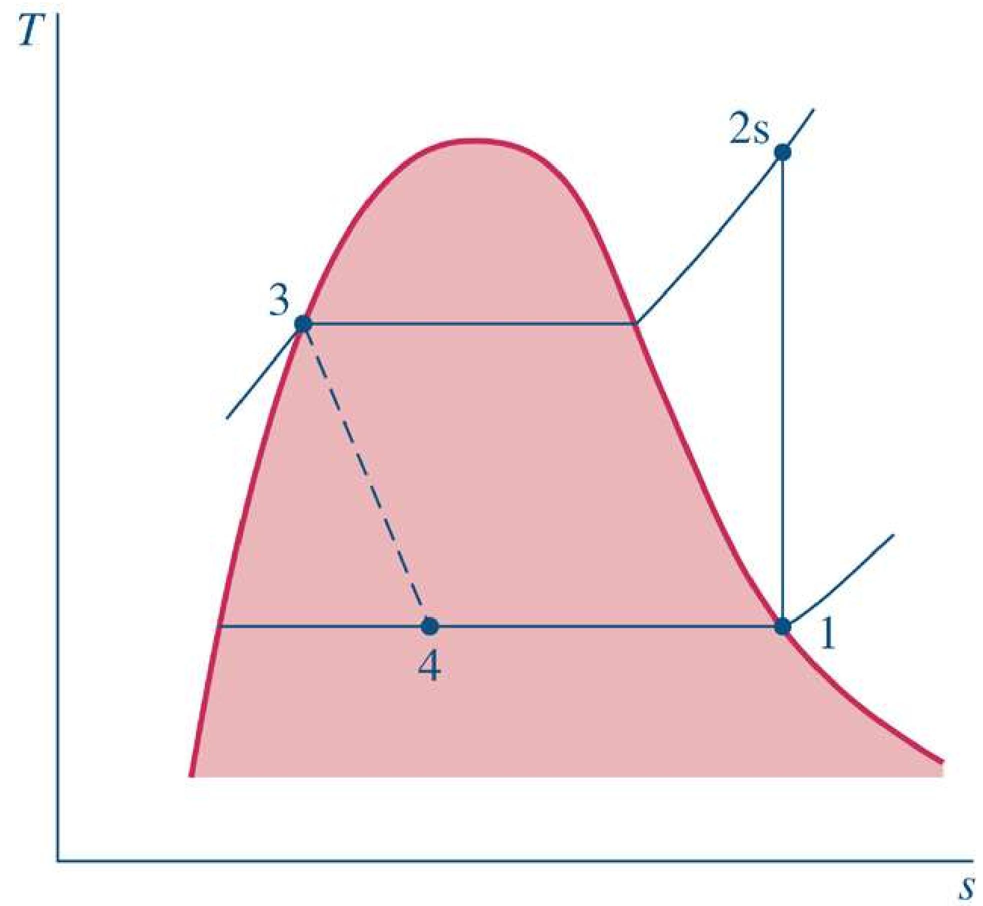
- Vapor-compression heat pumps:





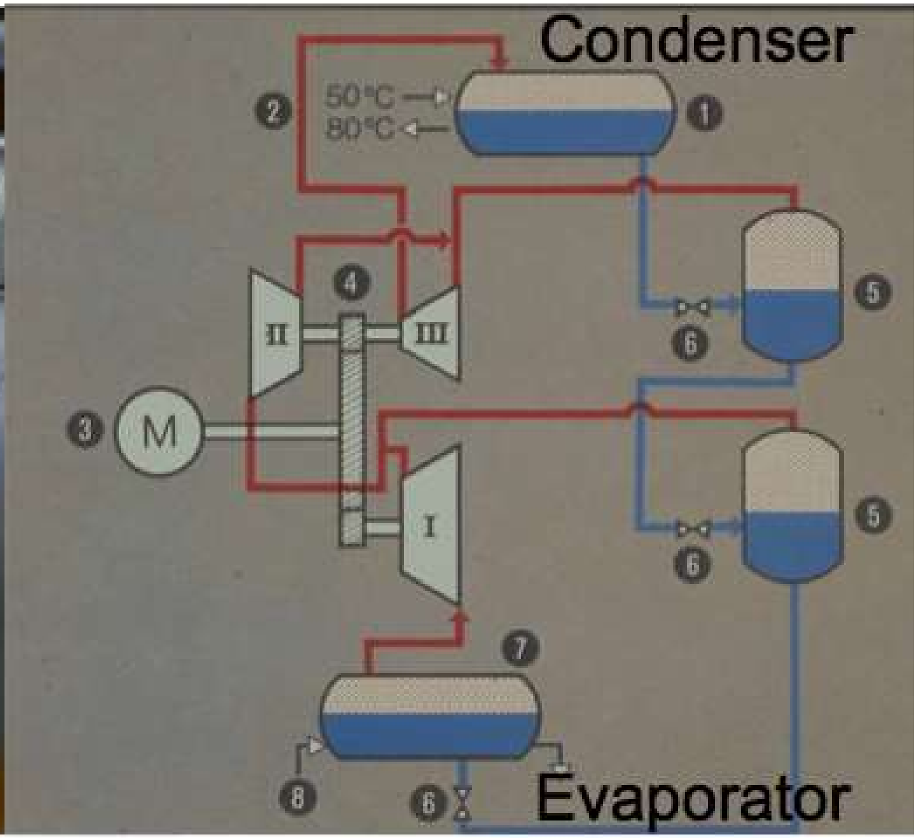
Heat pump systems

- 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: $\mathrm{COP}_{hm} = \frac{\dot{Q}_{out} / \dot{m}}{\dot{W}_c / \dot{m}} = \frac{h_2 - h_3}{h_2 - h_1}$



Heat pump

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



Goteborg: 45 MW_{th}

Absorption heat pump

- Idea: achieve the pressure raise from low (BP) → high (HP) not by a *compressor*, but by the 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

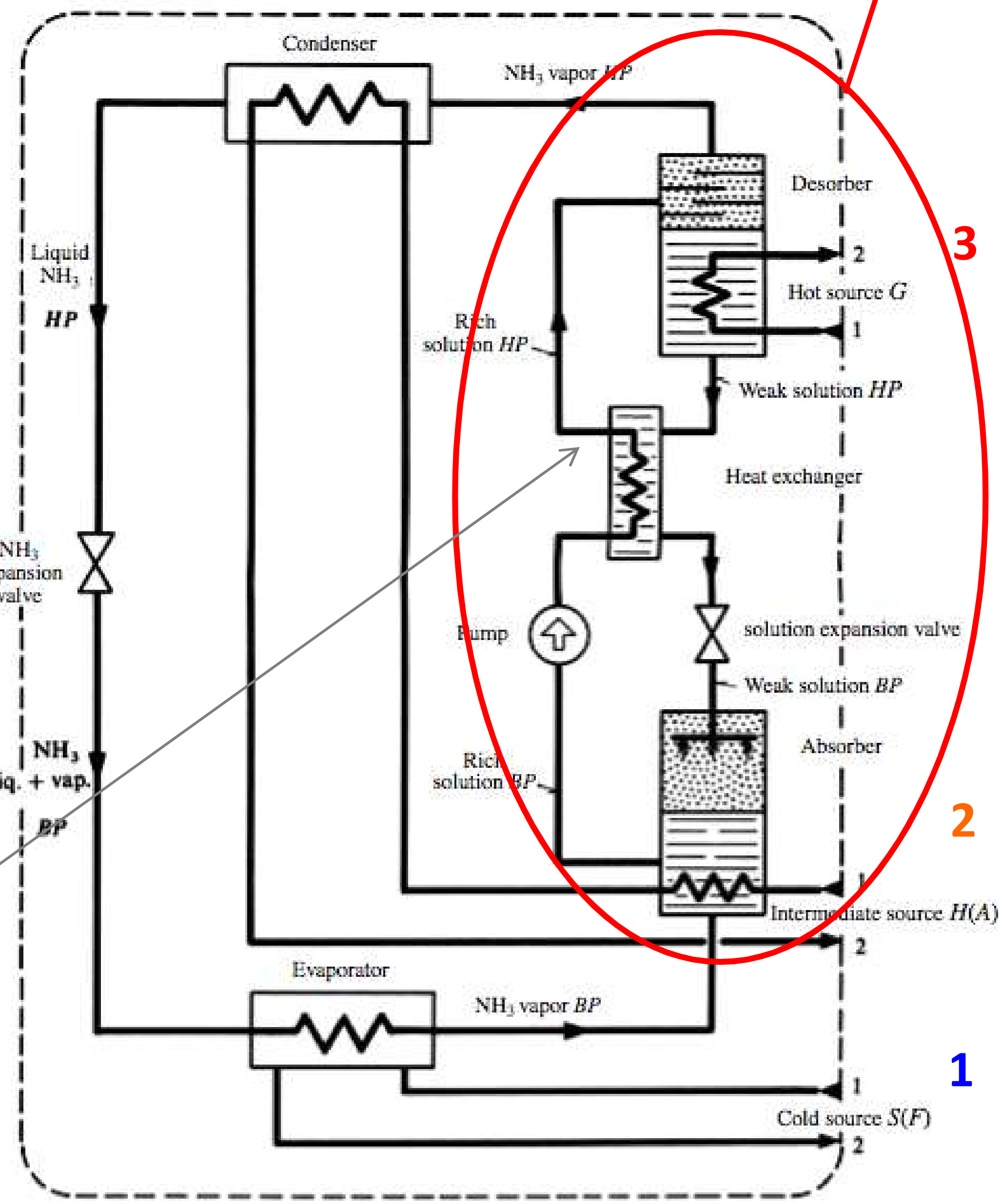
Often low temperature (~100°C), ideal for many renewables

Absorption heat pump

replaces a compressor

- absorber (water):
  receives low p NH_3 vapor (BP)
  ⇒ 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
    - Gaspower systems:
      - Internal combustion engines
      - Gas turbine power plants
- Examples of relevant power cycles for renewable sources
- Exemplary thermodynamic cooling and heating systems:
  - Refrigeration and heat pump systems