# Renewable Energy

Prof. Sophia Haussener

MER Jan van Herle

Laboratory of Renewable Energy Sciences and Engineering

# 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

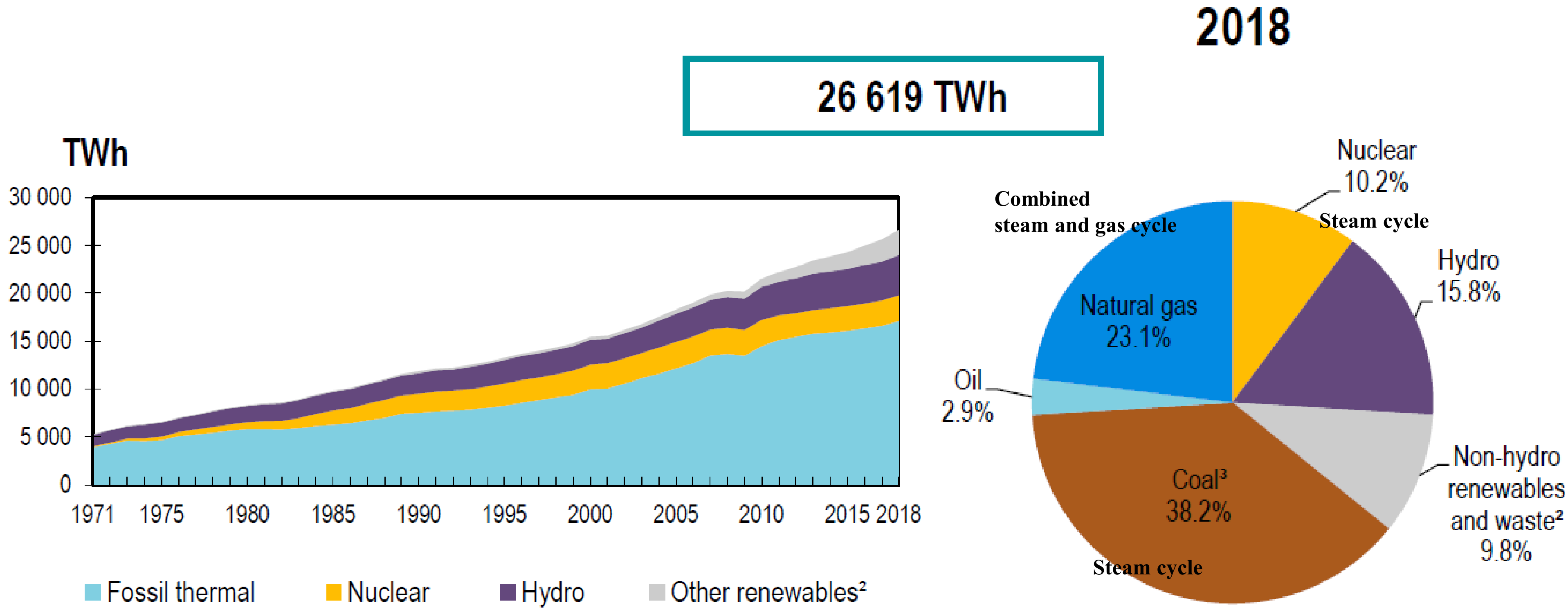
- Understand and apply 1st and 2nd law of thermodynamics, and exergy concept to various relevant systems and thermodynamics cycles

- Apply  theory to thermodynamic cycles relevant for renewable energy sources

# Motivation

- Current global power production[1]

IEA, World key energy statistics, 2020




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

https://webstore.iea.org/download/direct/4093?fileName=Key_World_Energy_Statistics_2020.pdf

# Motivation

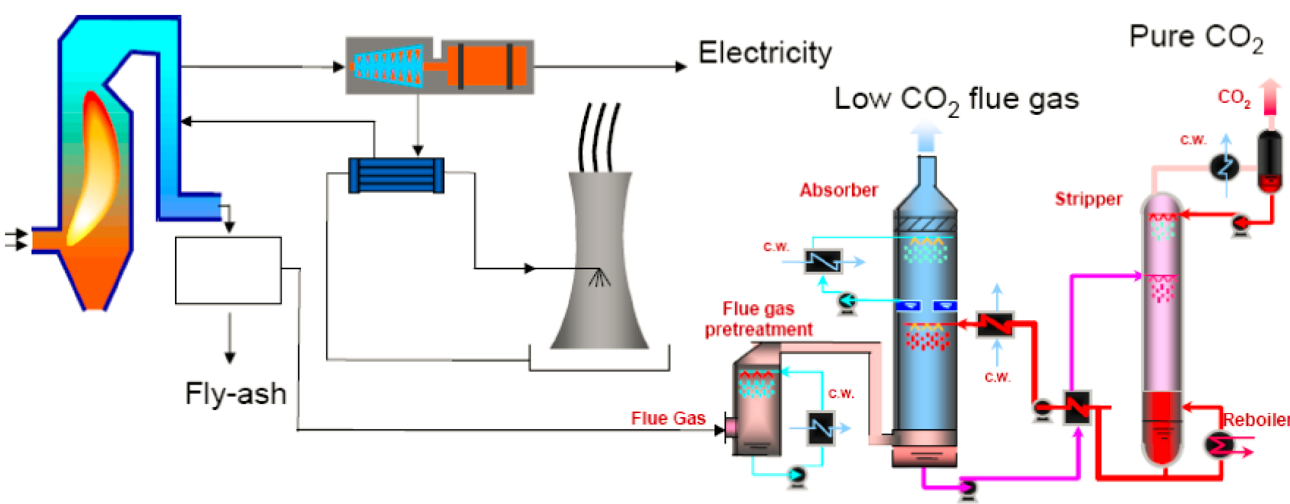
- Energy conversion systems overview

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

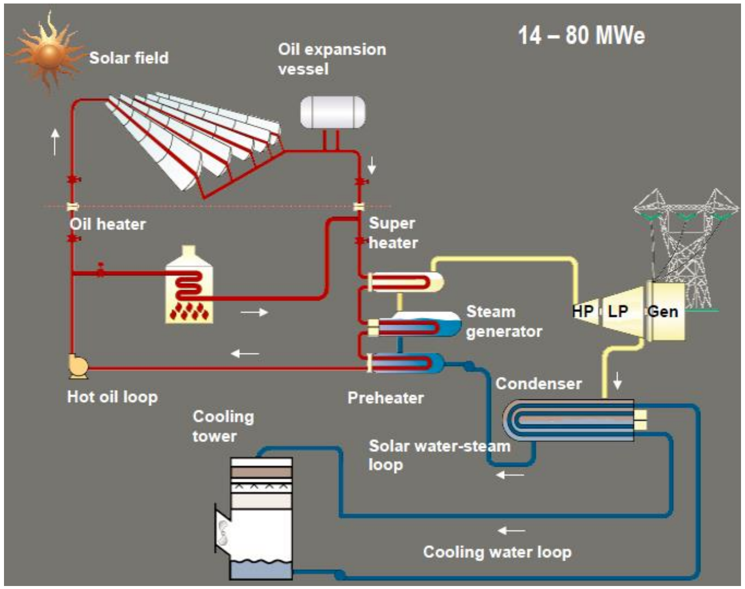
- Traditional and advanced rely on power cycles, traditional turbomachinery: heat → mechanical energy → electricity
- Advanced heating applications rely on heat pumping cycles

# Motivation

- Examples:
  - Coal plant with $CO_2$ capture



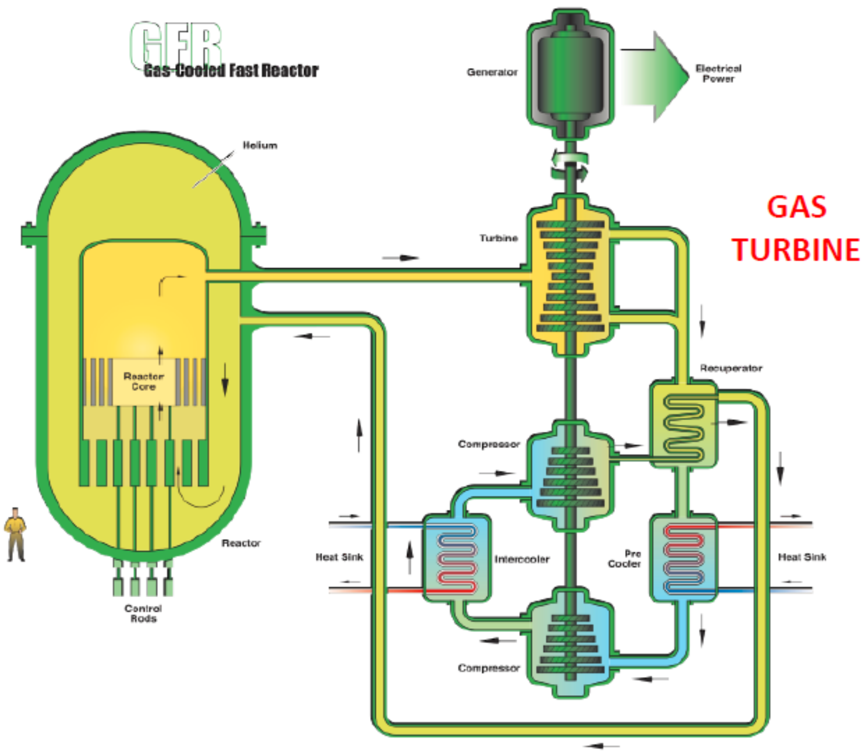

  - Concentrated solar power

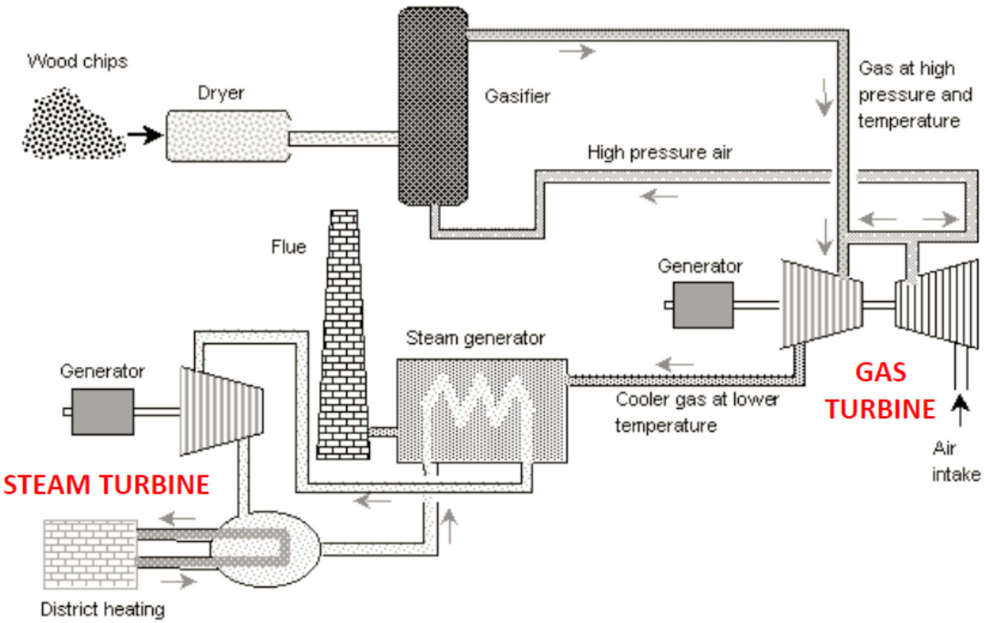


# Motivation

- Examples:
  - Nuclear

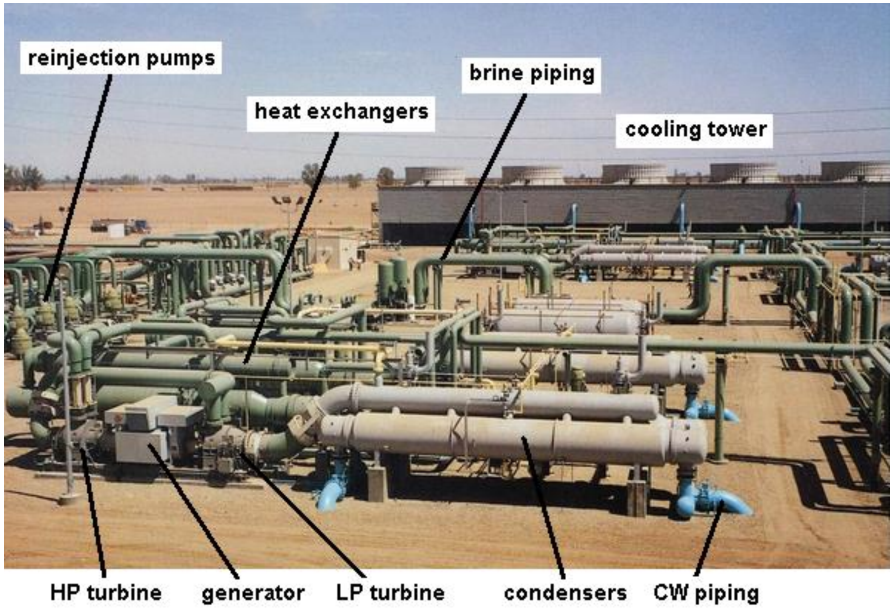
Biomass-fired combined cycle:

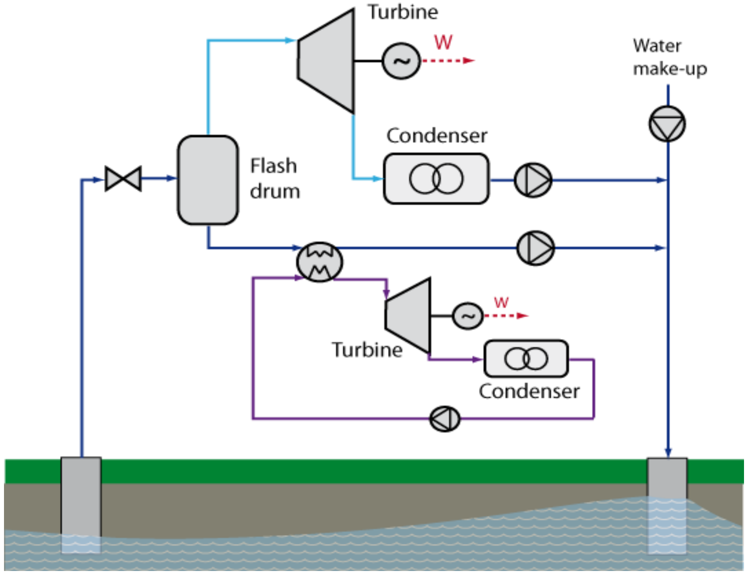


# Motivation

- 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:

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

  - Energy conservation:

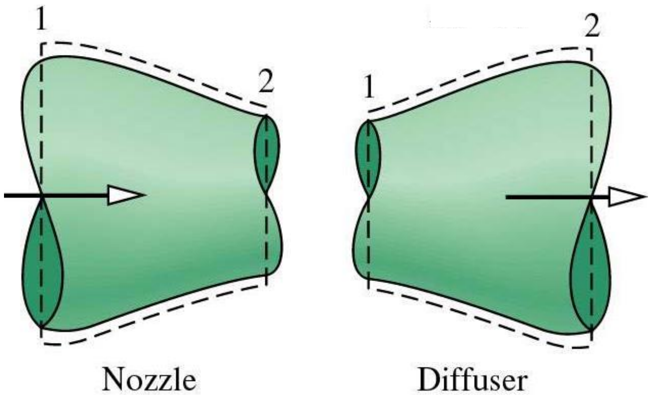
$$\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W} + \sum_i \dot{m}_i \left( u_i + \frac{w_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left( u_e + \frac{w_e^2}{2} + gz_e \right)$$

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

# 1st law for closed and open systems

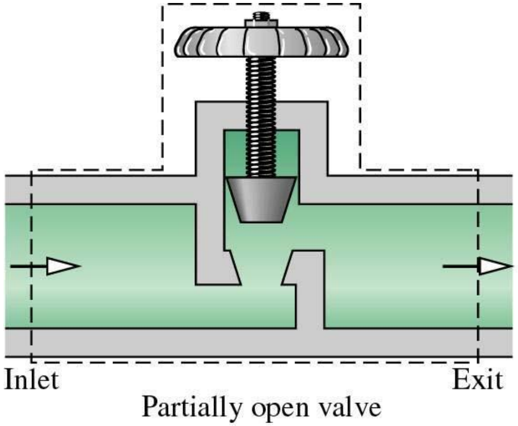
- Energy conservation for open systems, applications:
  - Nozzle, diffusor

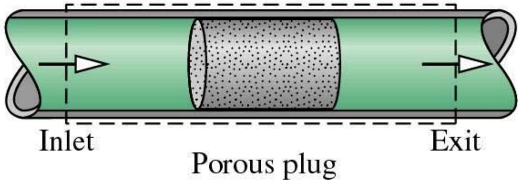
$$h_i + \frac{w_i^2}{2} = h_e + \frac{w_e^2}{2}$$




  - Throttling valves

$$h_i = h_e$$



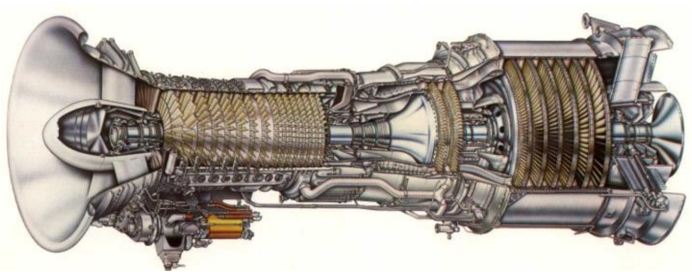



# 1st law for closed and open systems

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

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

GE, 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 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:

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

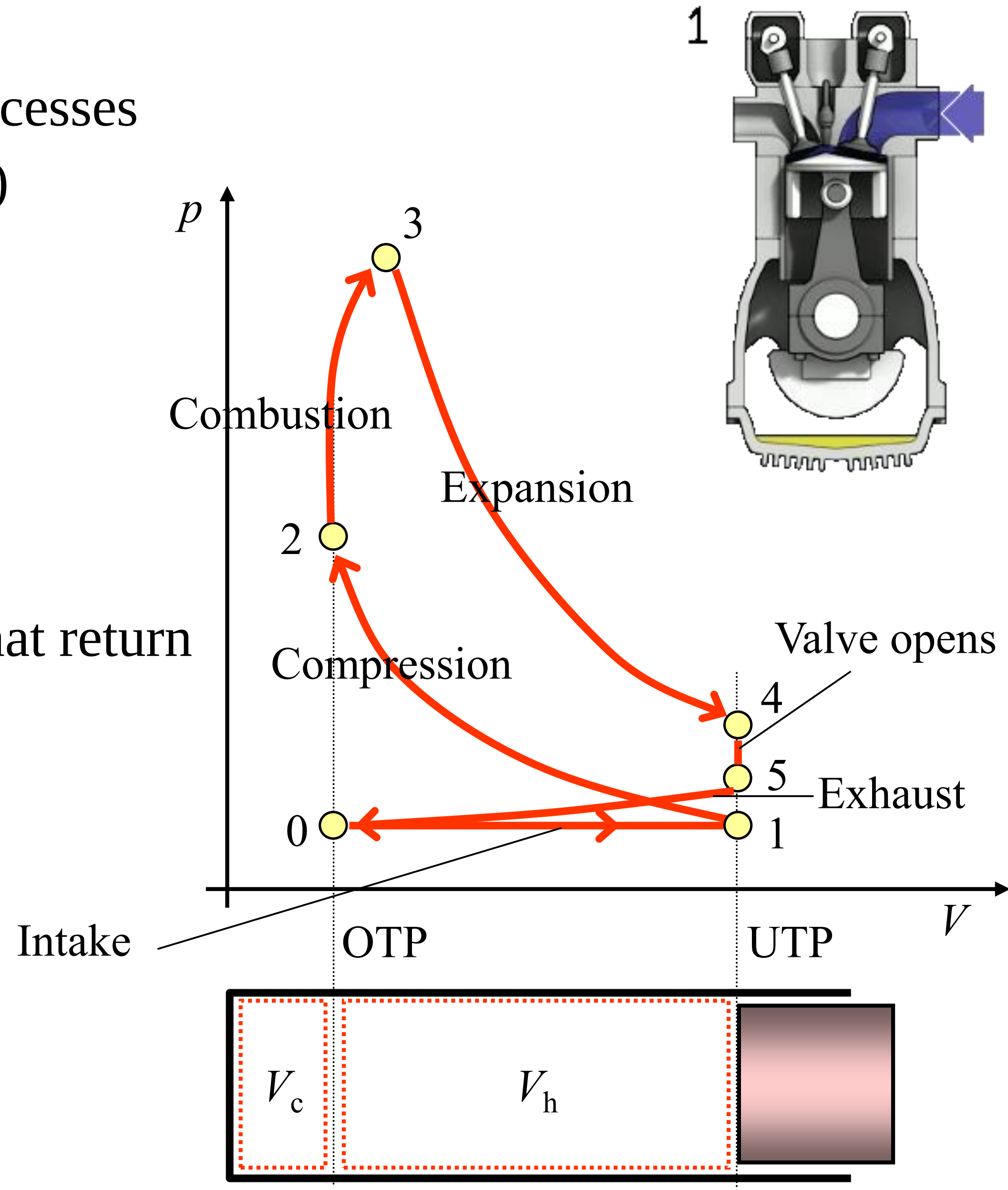
- Heating values (HV):
  - High heating values (HHV): water is condensed (furnaces etc.)
  - Low heating values (LHV): water is vapor (cars, jet engines, etc.)

| 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 | |

# 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

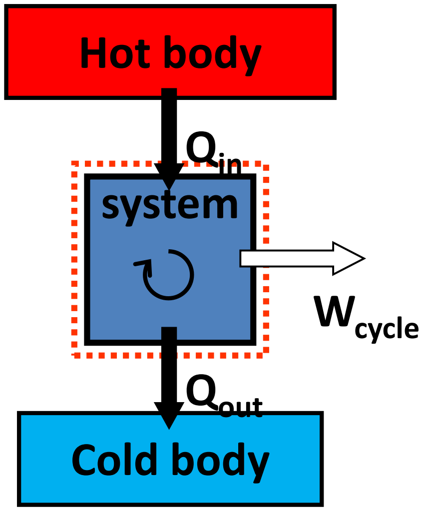


# Energy for closed systems

- Cycle analysis:

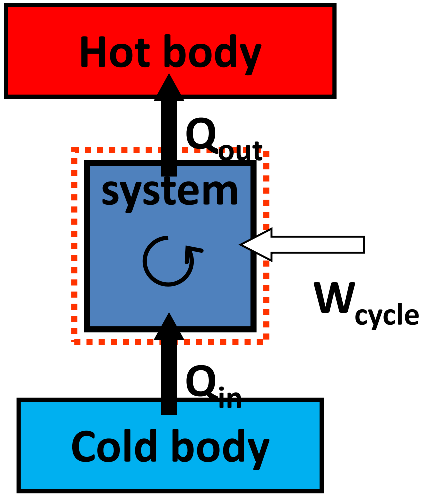
$$\Delta E = 0 = Q_{\text{cycle}} - W_{\text{cycle}}$$

  - 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:

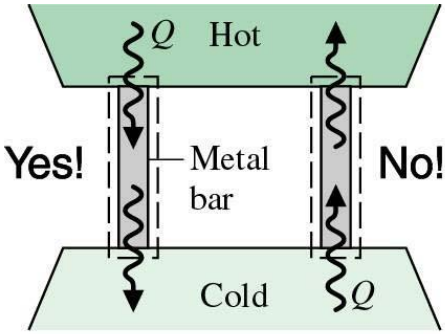



$$\text{COP}_{\text{cm}} = \frac{Q_{\text{in}}}{|W_{\text{cycle}}|} = \frac{Q_{\text{in}}}{|Q_{\text{out}}| - Q_{\text{in}}}$$

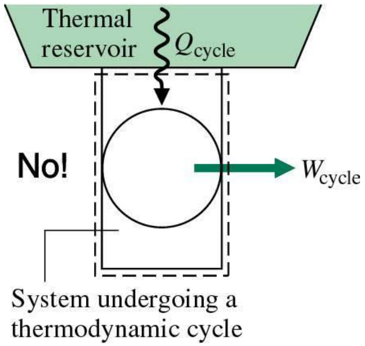
$$\text{COP}_{\text{hm}} = \frac{Q_{\text{out}}}{W_{\text{cycle}}} = \frac{|Q_{\text{out}}|}{|Q_{\text{out}}| - Q_{\text{in}}} = \text{COP}_{\text{cm}} + 1$$

# $2^{nd}$ 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.

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

# Entropy balance – closed systems

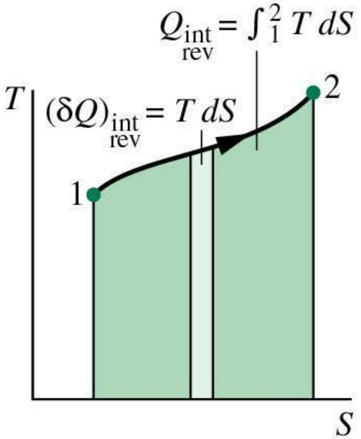
$$\begin{bmatrix} \text{change in the} \\ \text{amount of entropy} \\ \text{contained within system} \\ \text{during time interval} \end{bmatrix} = \begin{bmatrix} \text{net amount of entropy} \\ \text{transferred in across} \\ \text{system boundary} \\ \text{during time interval} \end{bmatrix} + \begin{bmatrix}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

- General:

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

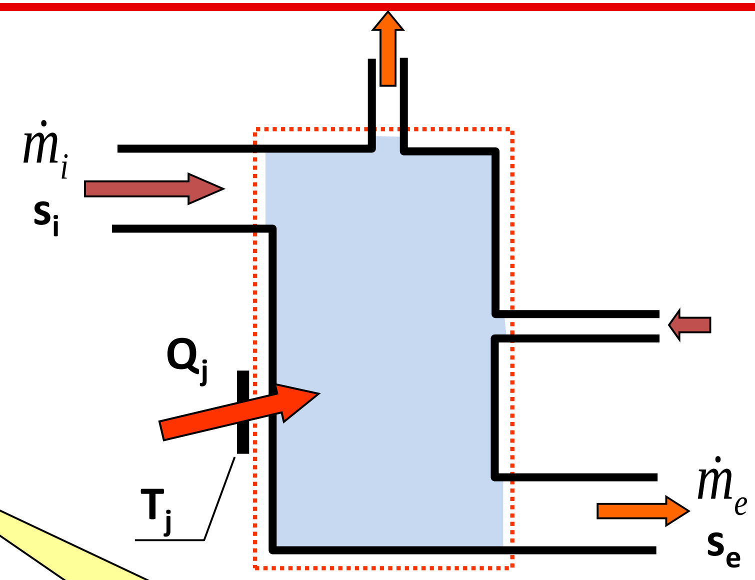
- Internally reversible processes:

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



# Entropy balance – open systems

- Entropy balance for an open system:




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

**Rate of entropy change** in control volume

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

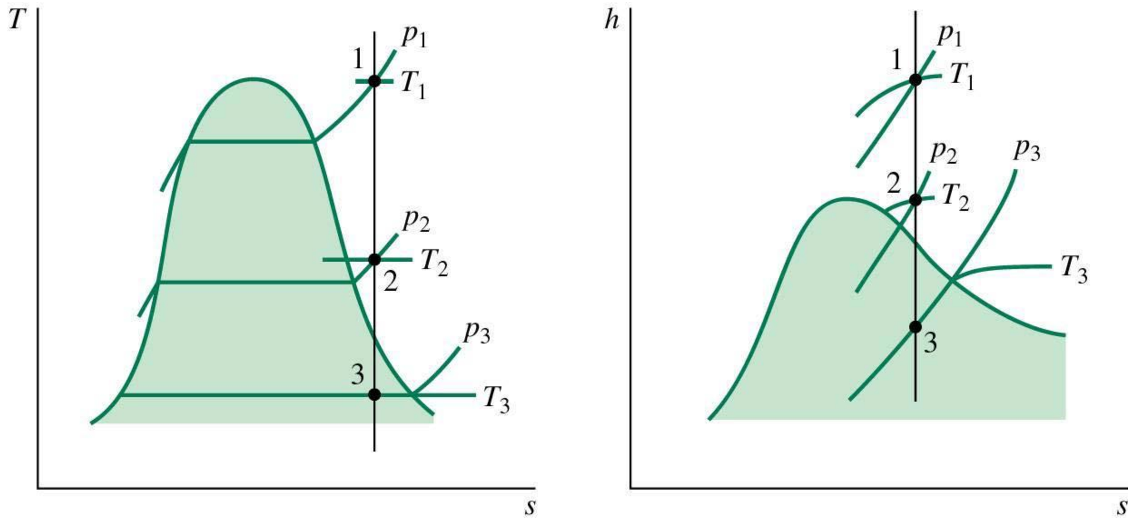
**Convective entropy transport**

**Entropy production** within the control volume

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

# Isentropic processes

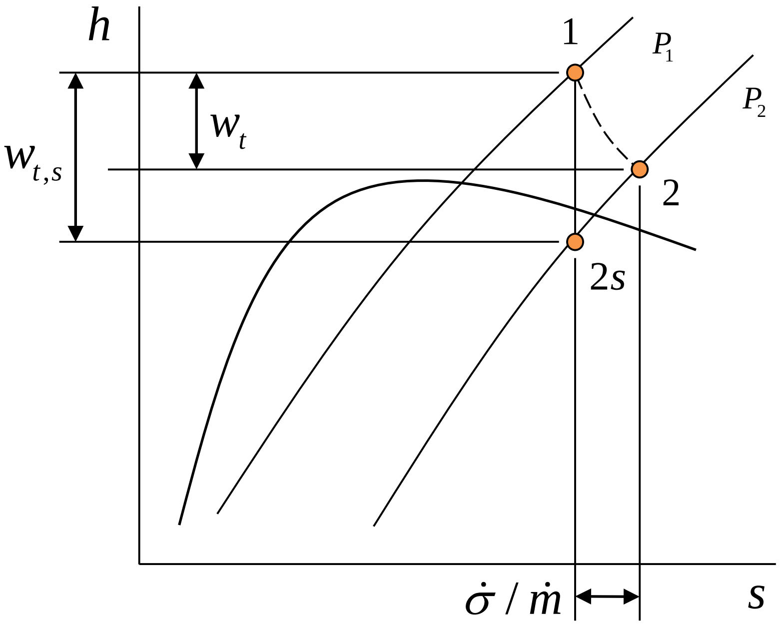
- Isentropic means constant entropy.
- Isentropic processes are processes where the entropy at the initial and final state are equal.
- Isentropic processes, e.g.: closed system, reversible and adiabatic process



# 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:

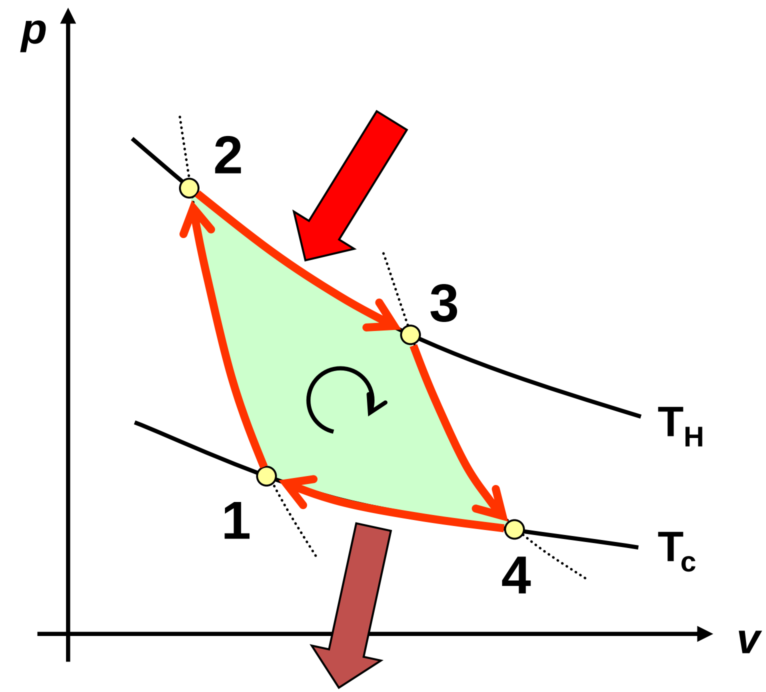
$$\eta_{\mathrm{c/p,s}} = \frac{\left(-\dot{W}/\dot{m}\right)_{\mathrm{s}}}{-\dot{W}/\dot{m}} = \frac{h_{2,\mathrm{s}} - h_1}{h_2 - h_1}$$

- 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

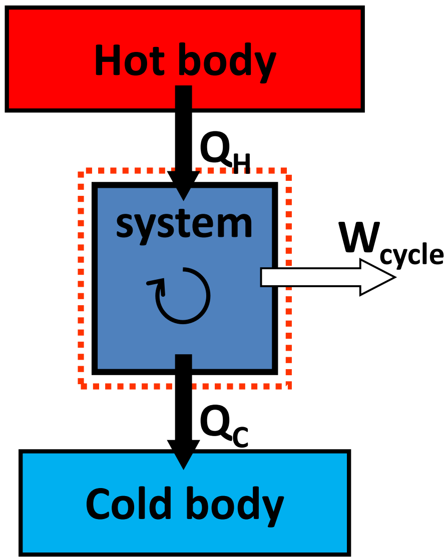
- Two adiabatic processes

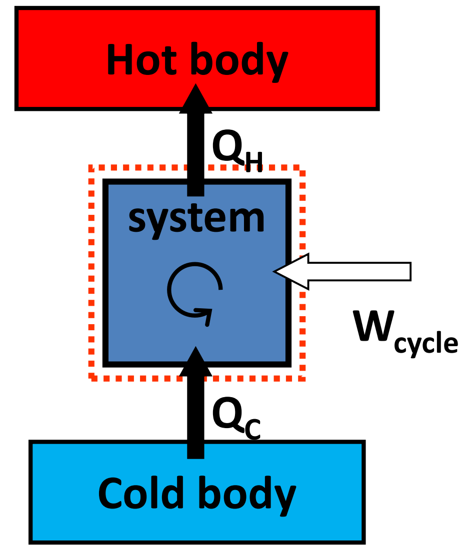
- Reverse direction: refrigeration or heat pump cycle

- Efficiency given by Carnot efficiency or COP

# Carnot efficiency

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



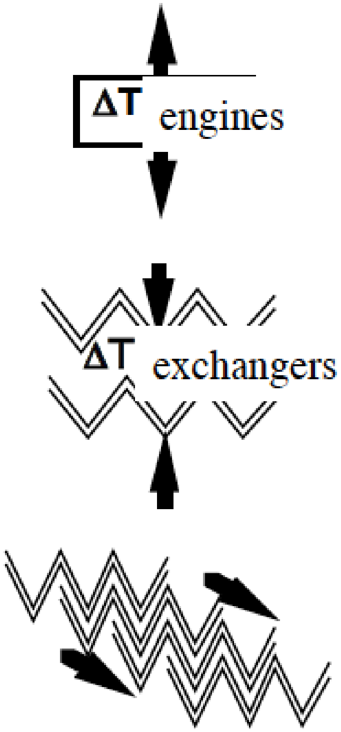




| | | | |
|---|---|---|---|
| Efficiency | $\eta_{th} = \frac{W_{cycle}}{Q_H} = 1 - \frac{Q_C}{Q_H}$ | $COP_{cm} = \frac{Q_C}{W_{cycle}} = \frac{Q_C}{Q_H - Q_C}$ | $COP_{hm} = \frac{Q_H}{W_{cycle}} = \frac{Q_H}{Q_H - Q_C}$ |
| Max. efficiency (Carnot) | $\eta_{th,max} = 1 - \left(\frac{Q_C}{Q_H}\right)_{\substack{rev\\cycle}}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

# Consequences of the 2nd Law

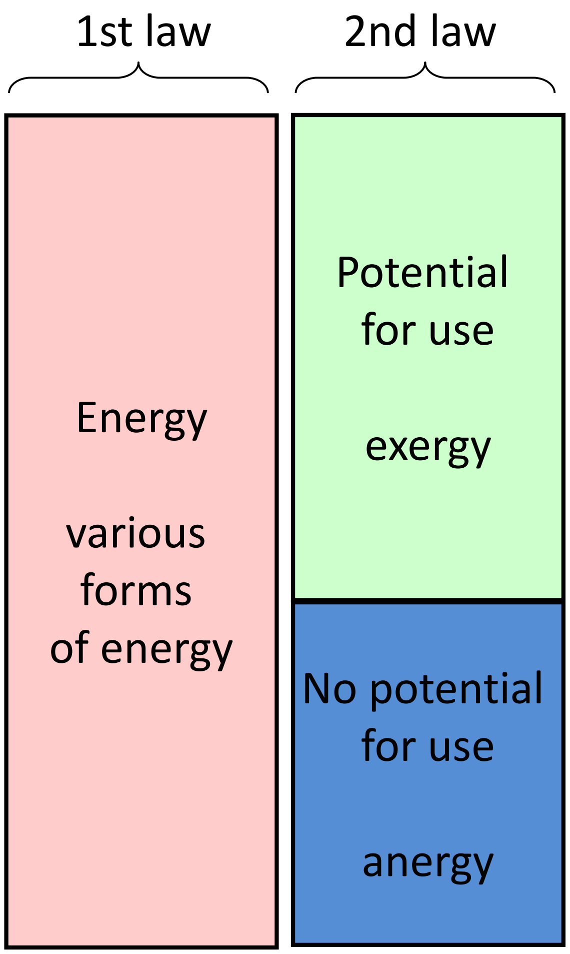
**Practical implications from the second law:**

- **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 ($\eta$)

- Components:
  - Turbine:

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

  - Compressor/pump:

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

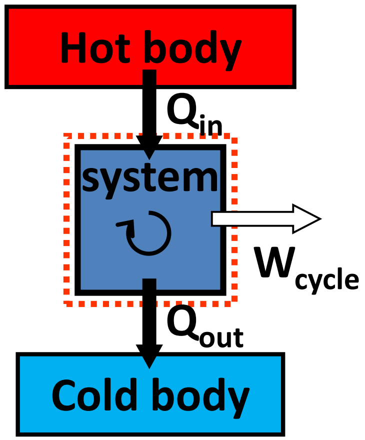
  - Heat exchanger: (non/mixing)

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

# Example thermodynamic power cycles

# Power systems

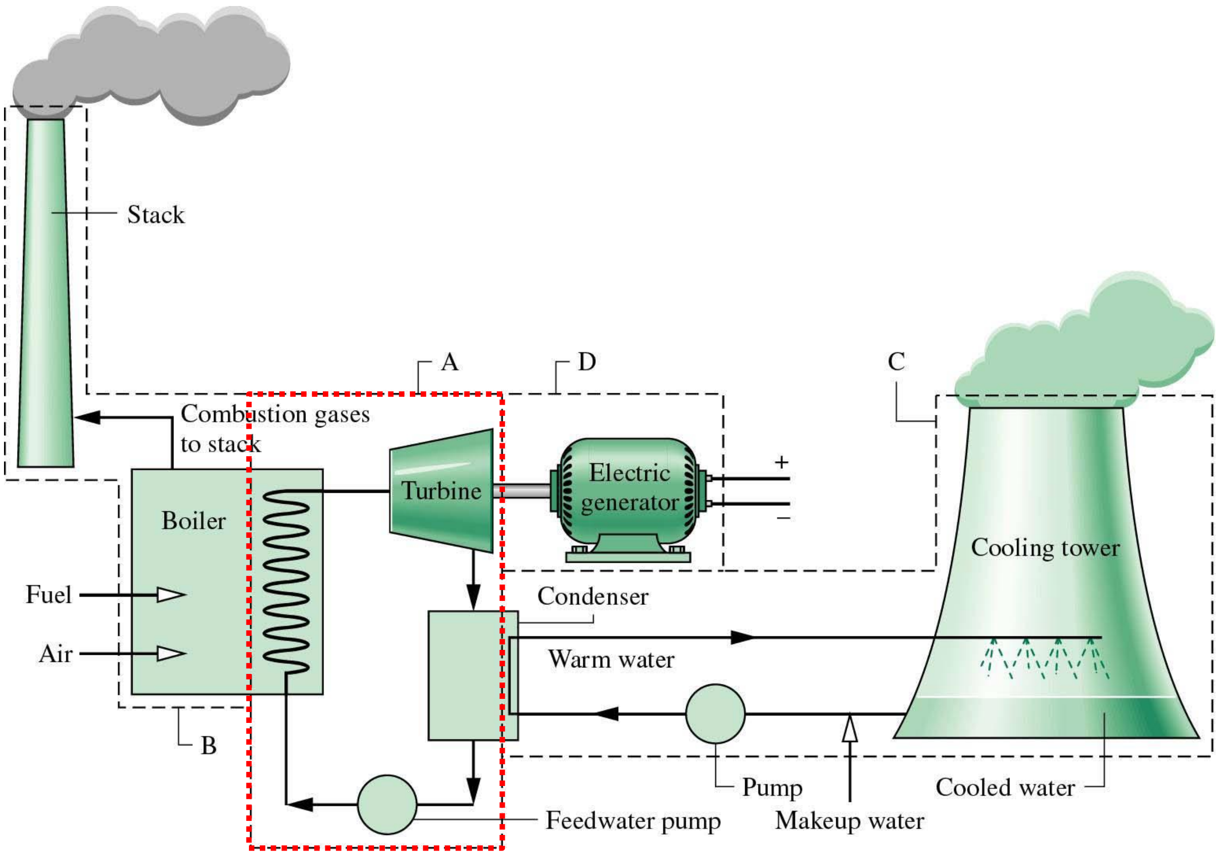
- Produce net power output from a energy source, such as fossil fuel, nuclear, or solar power




- 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




EPFL

# 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

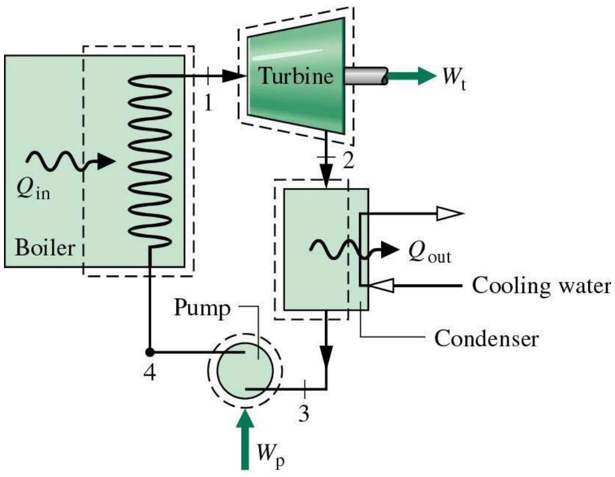
$$\dot{W}_p / \dot{m} = (h_3 - h_4)$$

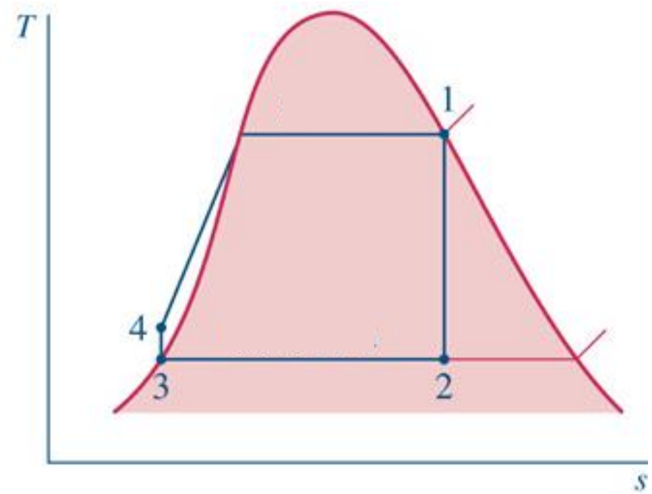
  - Boiler: *isobaric* heat transfer

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

  - Efficiency:

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



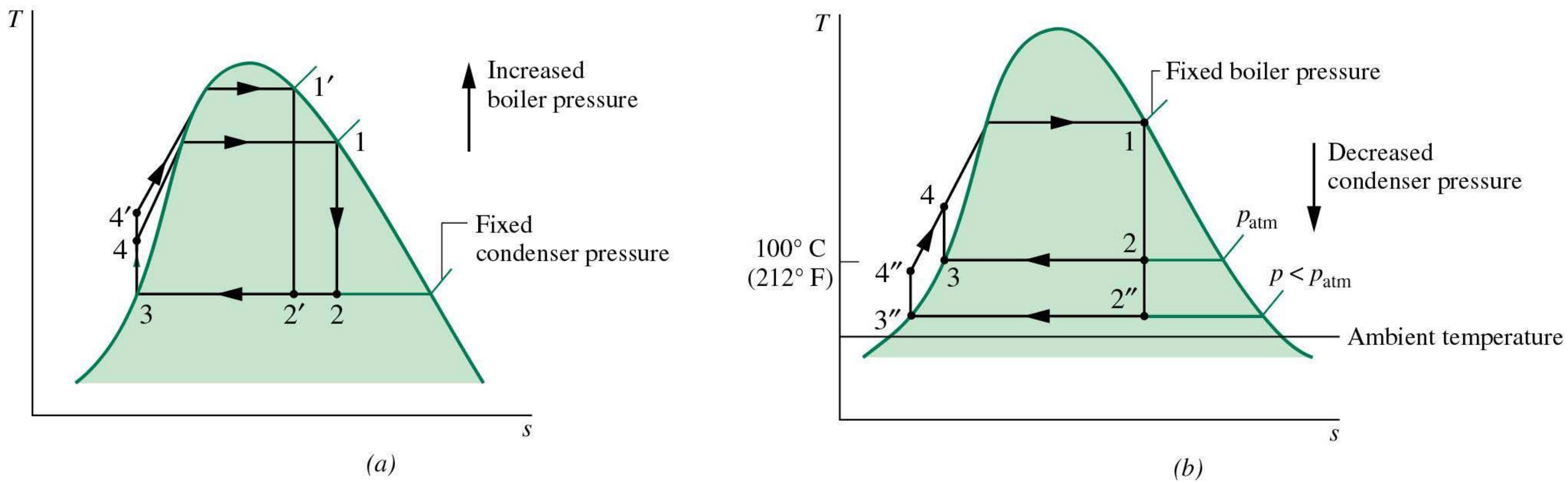



# Vapor power systems

- 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):

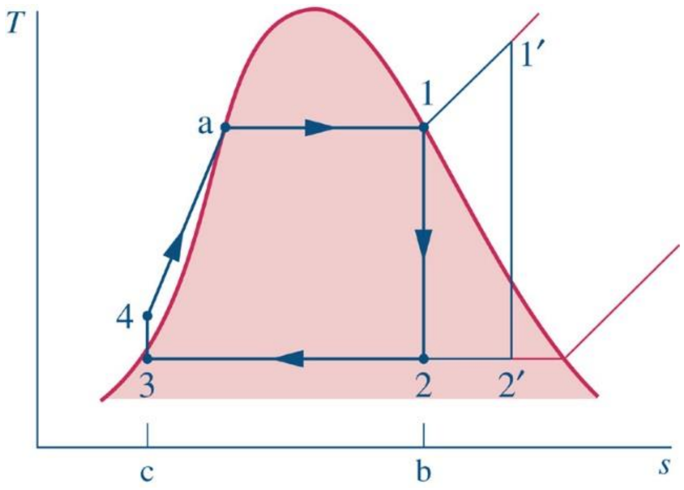
$$\eta_{\text{ideal}} = \frac{(\dot{Q}_{\text{in}}/\dot{m})_{\text{int,rev}} - (\dot{Q}_{\text{out}}/\dot{m})_{\text{int,rev}}}{(\dot{Q}_{\text{in}}/\dot{m})_{\text{int,rev}}} = 1 - \frac{\overline{T}_{\text{out}}}{\overline{T}_{\text{in}}}$$

  - Increase in boiler pressure and decrease in condenser pressures:



# Vapor power systems

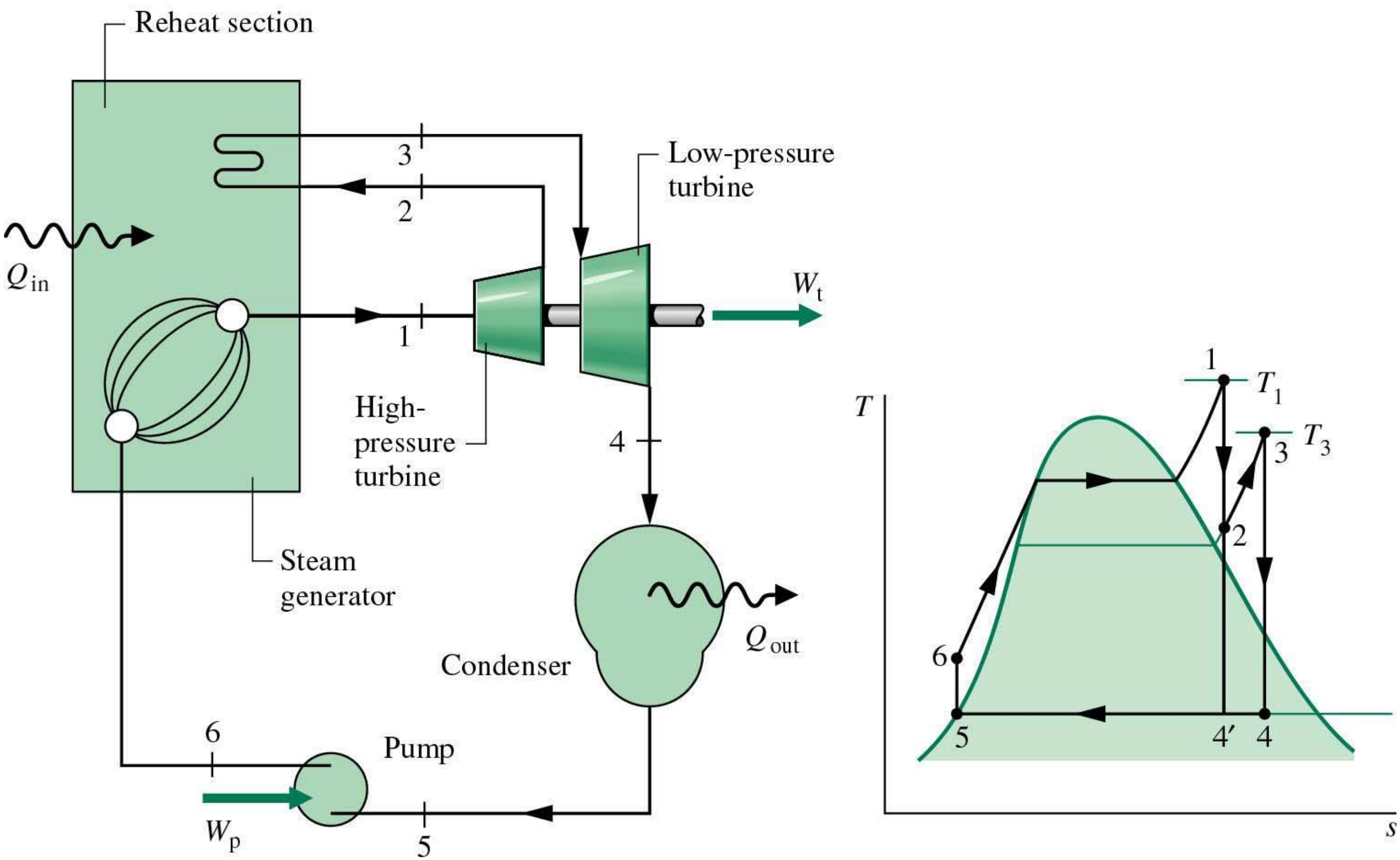
- Rankine cycle: improving performance:
  - Superheating (using additional heat exchanger, combination of boiler and heat exchanger is called steam generator)




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

# Vapor power systems

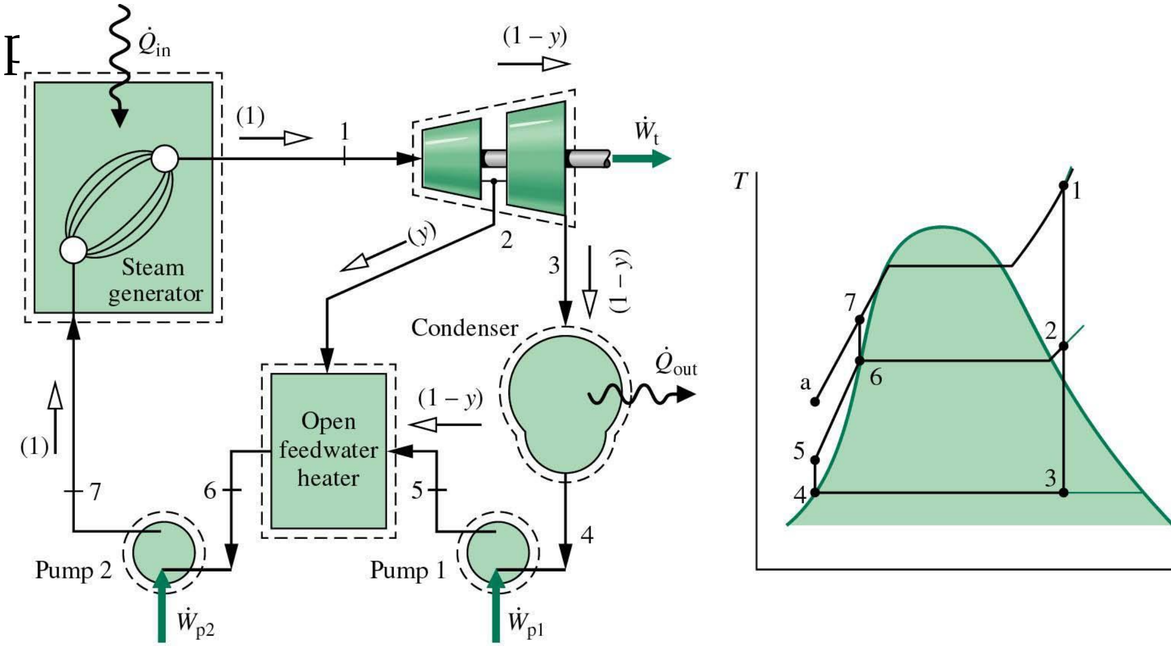
- Rankine cycle: improving performance:
  - Reheating



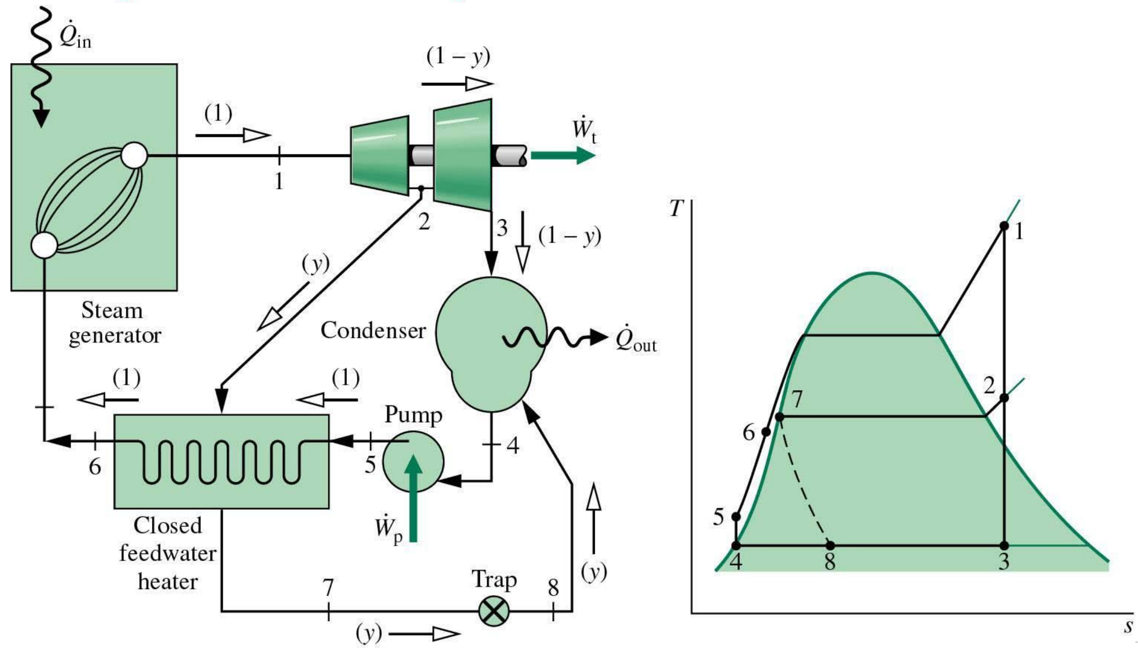
# Vapor power systems

- Rankine cycle: improving p
  - Regeneration via

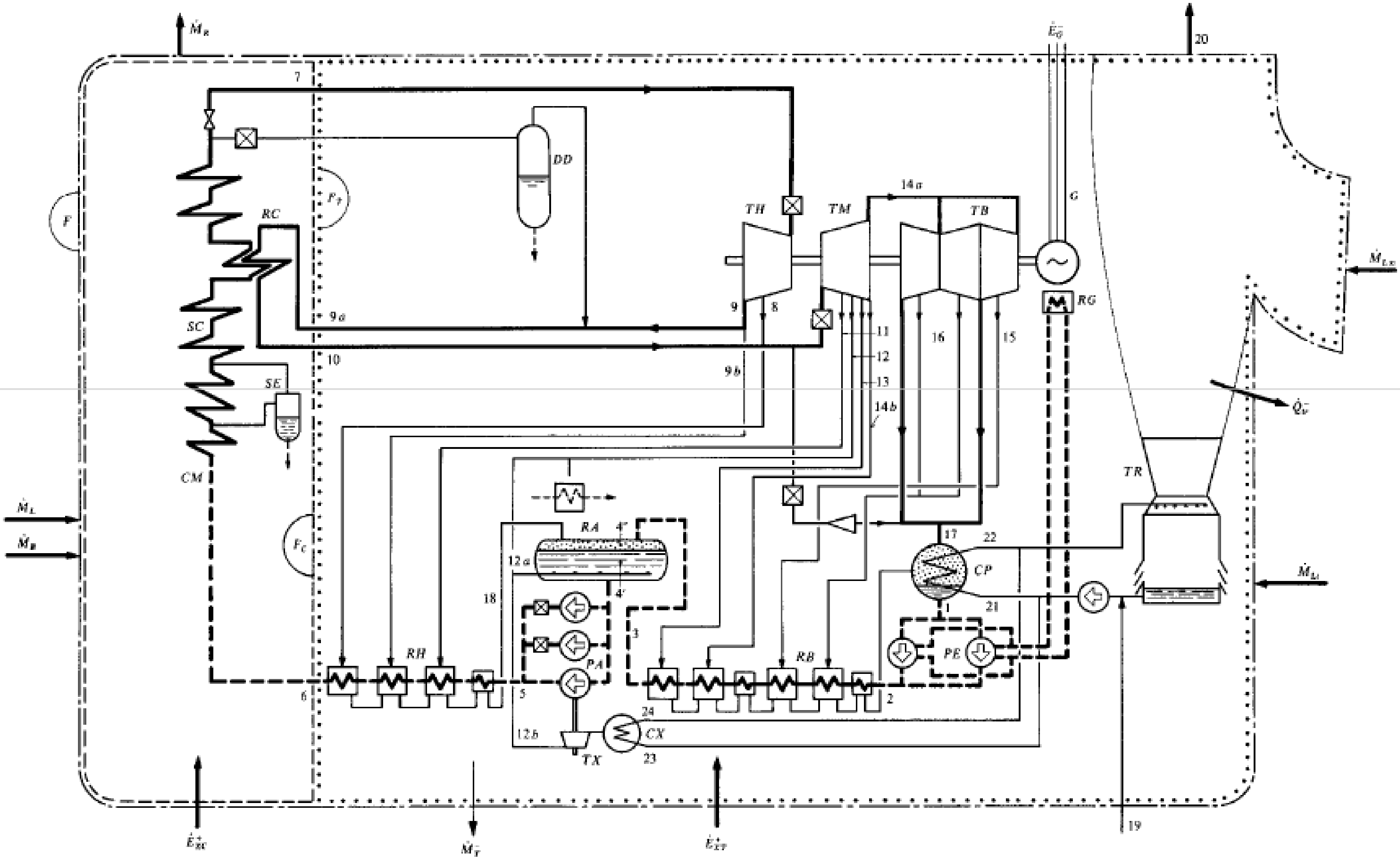
    open feedwater heaer




closed feedwater heater



# Real steam plant example:



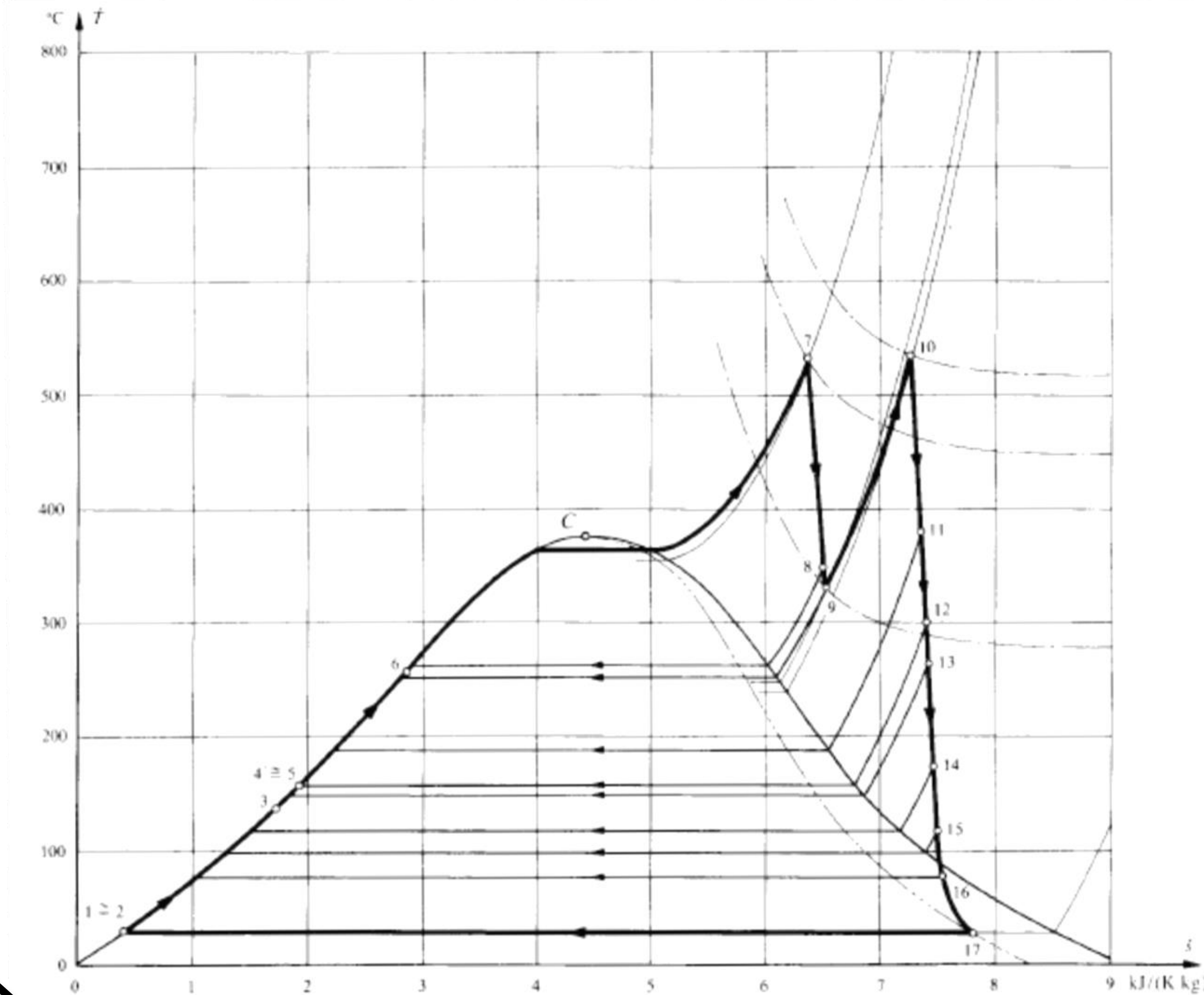
# Real steam plant example:

- 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

$\varepsilon_{Turbogroup} = 75\%$

$\varepsilon_{Boiler} = 52\%$

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



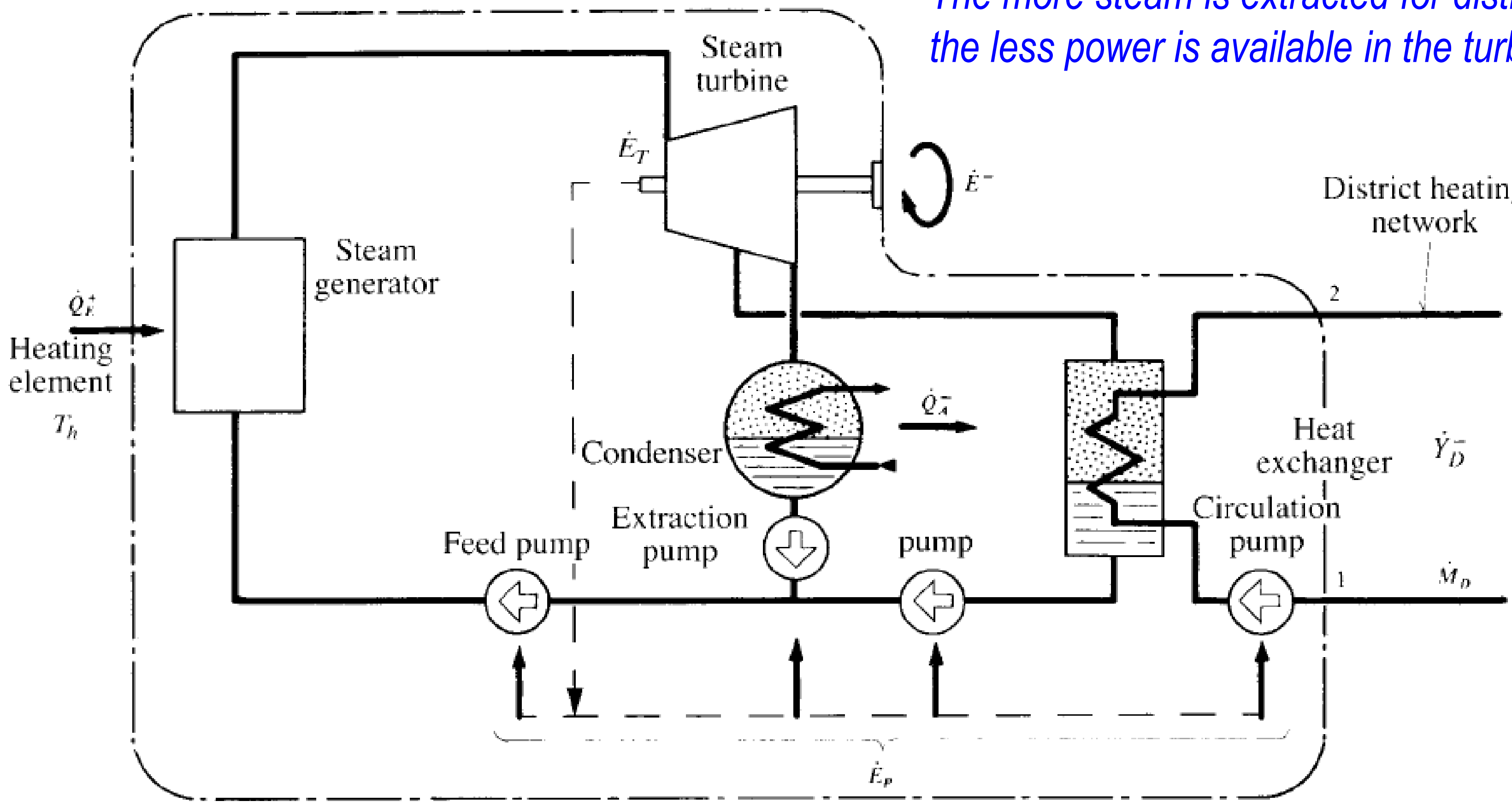

= still the main exergy loss (large $T$ drop) ←→ 1st law : 94%

EPFL

# Co-generation

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

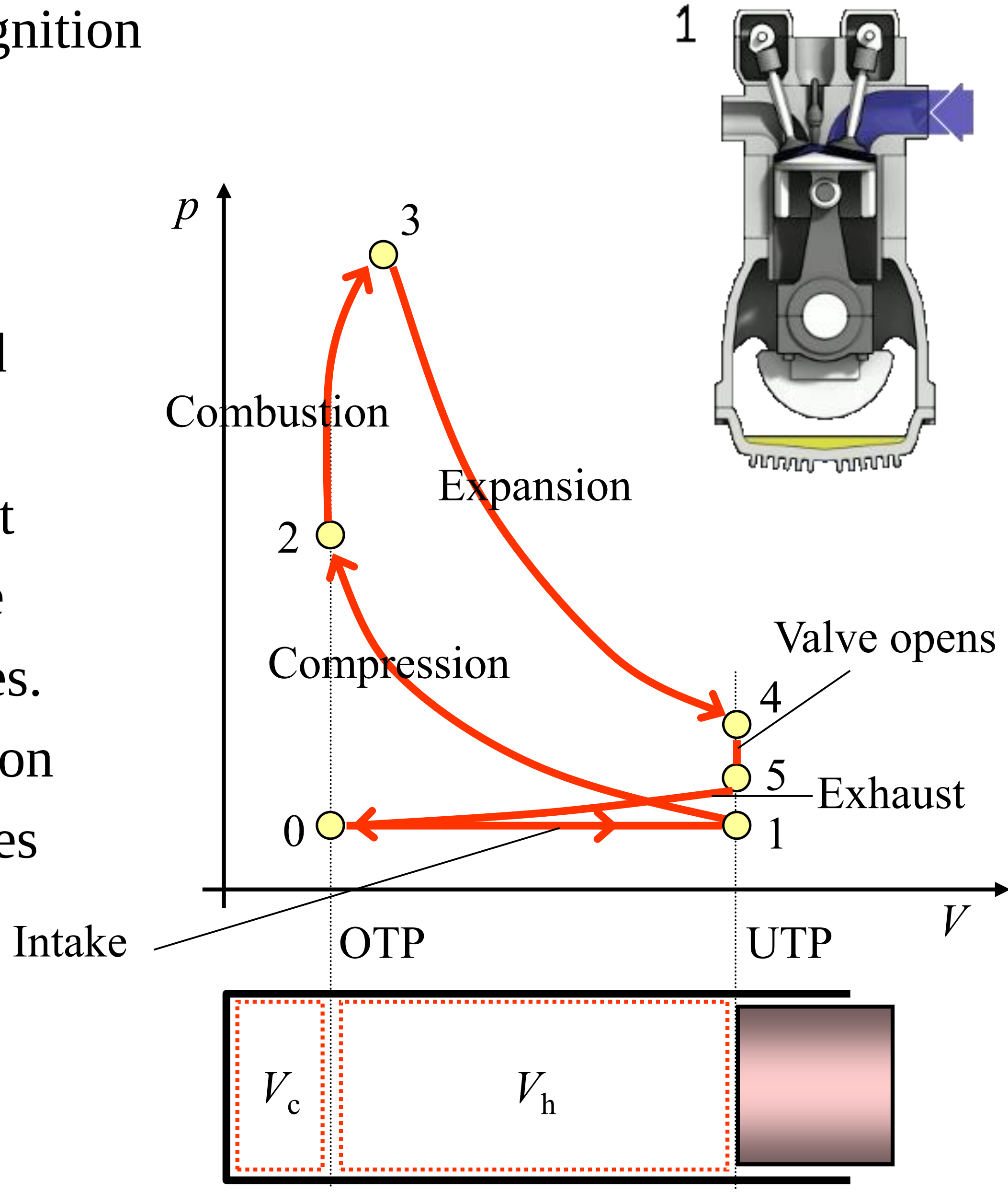
*The more steam is extracted for district heating, the less power is available in the turbine*



# 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

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

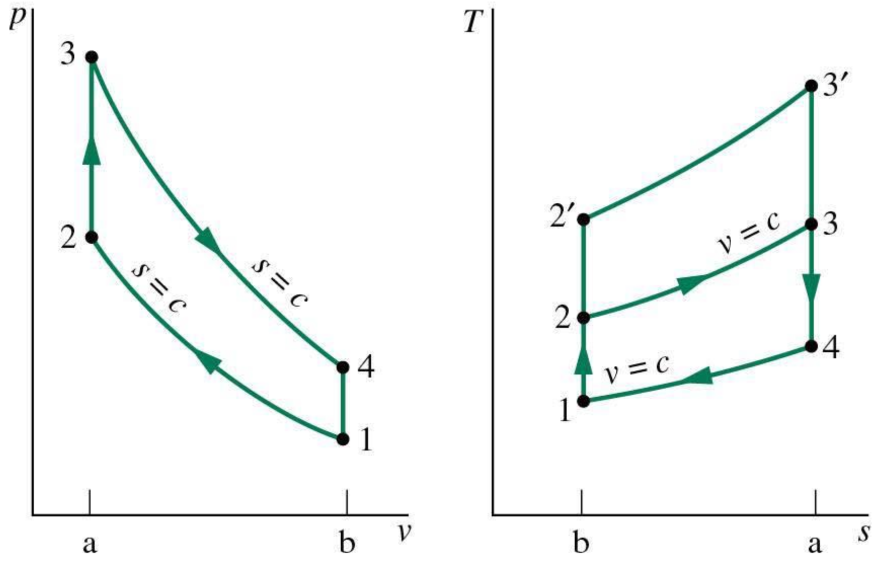
  - 3-4: Isentropic expansion

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

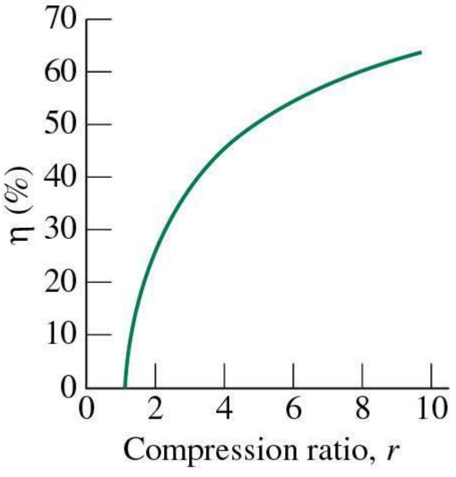
  - 4-1: Constant-volume heat

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

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




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

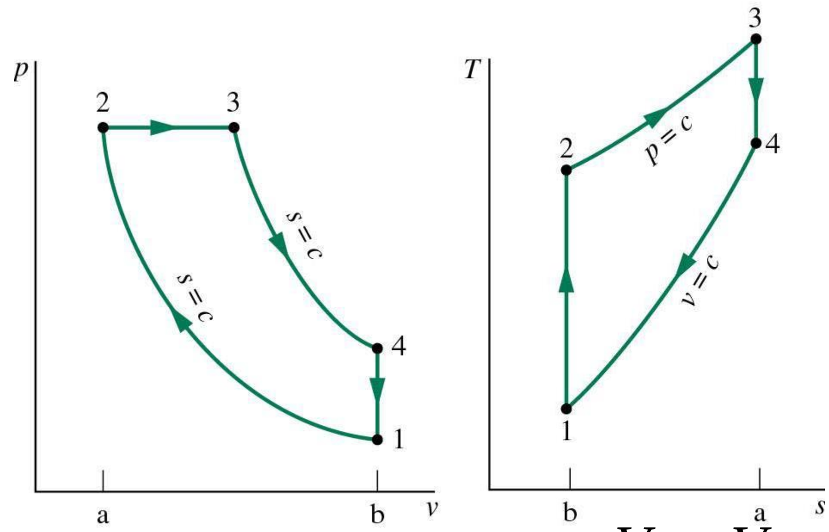
$$\frac{W_{34}}{m} = u_3 - u_4$$

  - 4-1: Constant-volume heat rejection

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

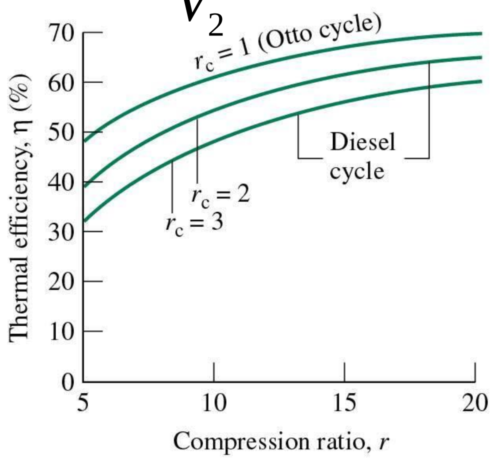
  - Cycle efficiency:

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



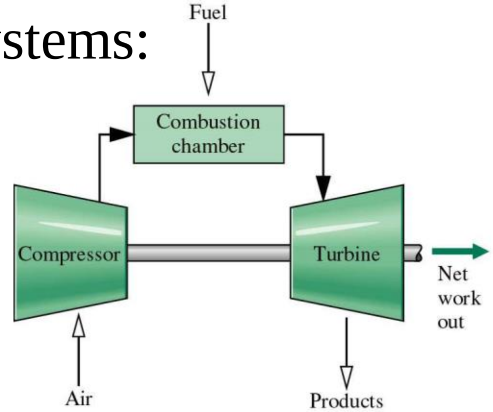

Compression ratio: $r = \frac{V_1}{V_2} = \frac{V_4}{V_3}$

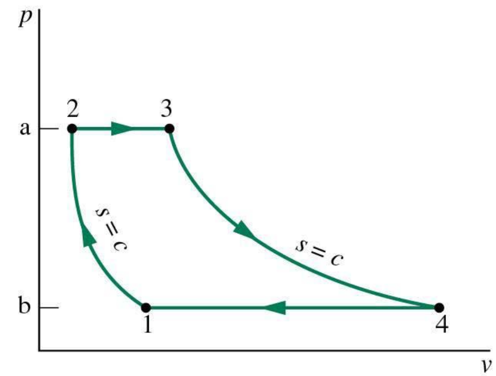
Cut-off ratio: $r_c = \frac{V_3}{V_2}$

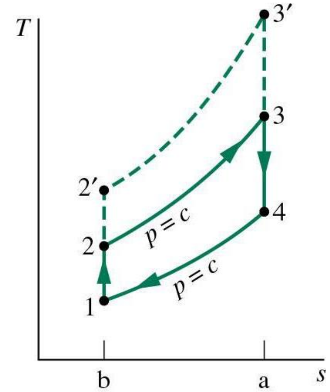


# Gas turbine power plants

- Gas turbine systems:



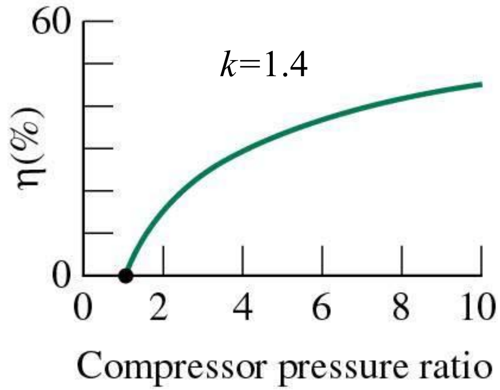

- Air-standard Brayton cycle (ideal):
  - 1-2: Isentropic compression $\frac{\dot{W}_{12}}{\dot{m}} = h_1 - h_2$
  - 2-3: Isobaric heat transfer $\frac{Q_{23}}{m} = h_3 - h_2$
  - 3-4: Isentropic expansion $\frac{\dot{W}_{34}}{\dot{m}} = h_3 - h_4$
  - 4-1: Isobaric heat transfer $\frac{Q_{41}}{m} =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

Cycle efficiency:

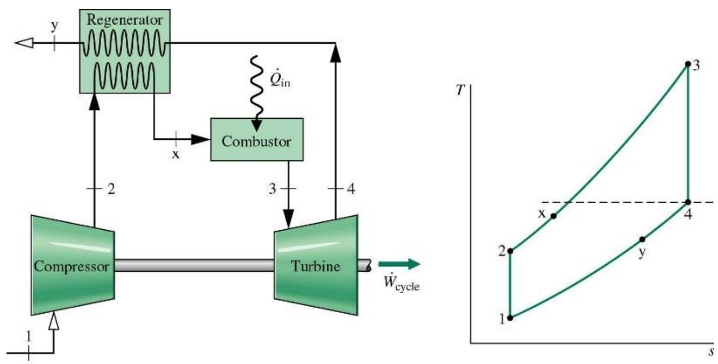
$$\eta = \frac{W_{\text{cycle}}}{Q_{23}} = \frac{h_3 - h_4 + h_1 - h_2}{h_3 - h_2}$$

# Gas turbine power plants

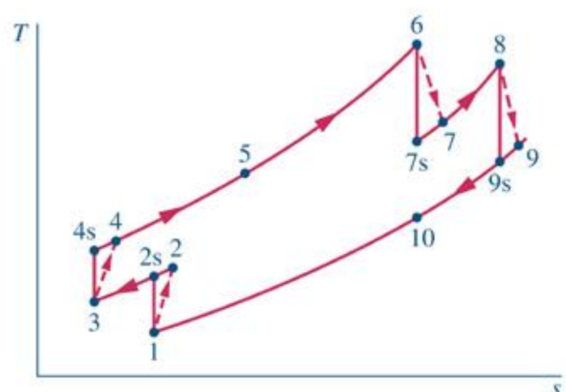
- Air-standard Brayton cycle: pressure ratio effect on performance
  - Efficiency increases with increasing pressure ratio




  - Regeneration:



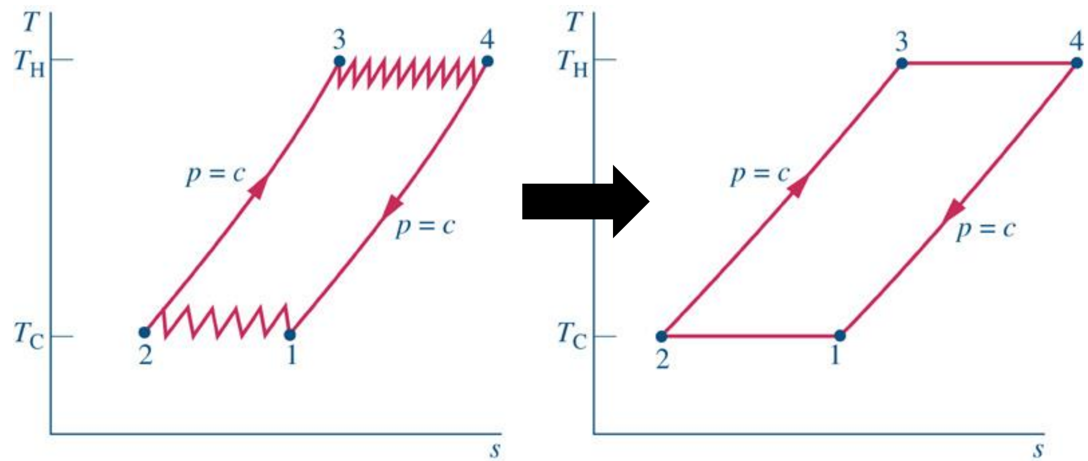

  - Reheating and intercooling:



# Internal combustion engines

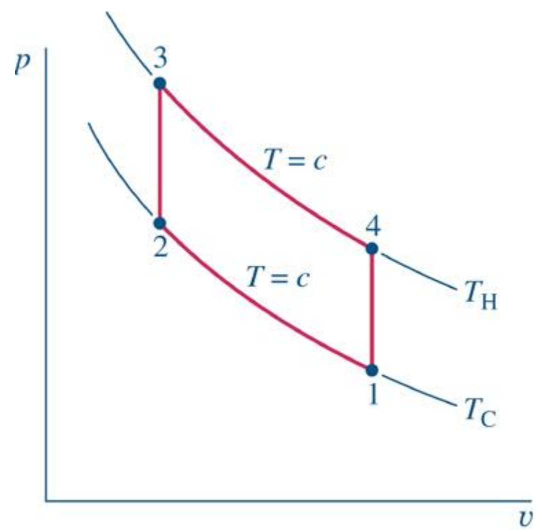
- Ericsson and Stirling cycle (both with same features as Carnot):
  - In the limit of large number of multi-stage compression with inter-cooling, and multi-stage expansion with re-heating, with ideal regeneration

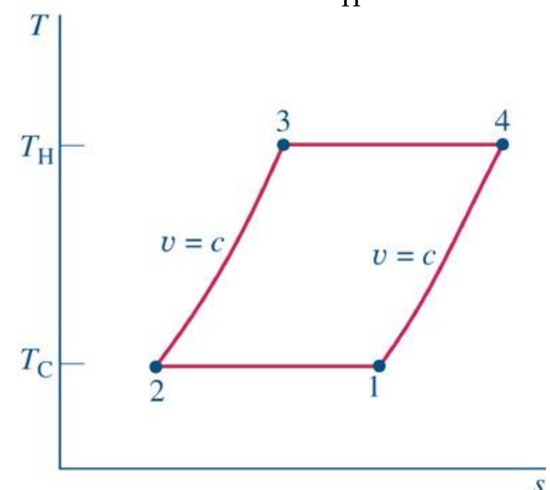
Ericsson cycle




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

  - 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)

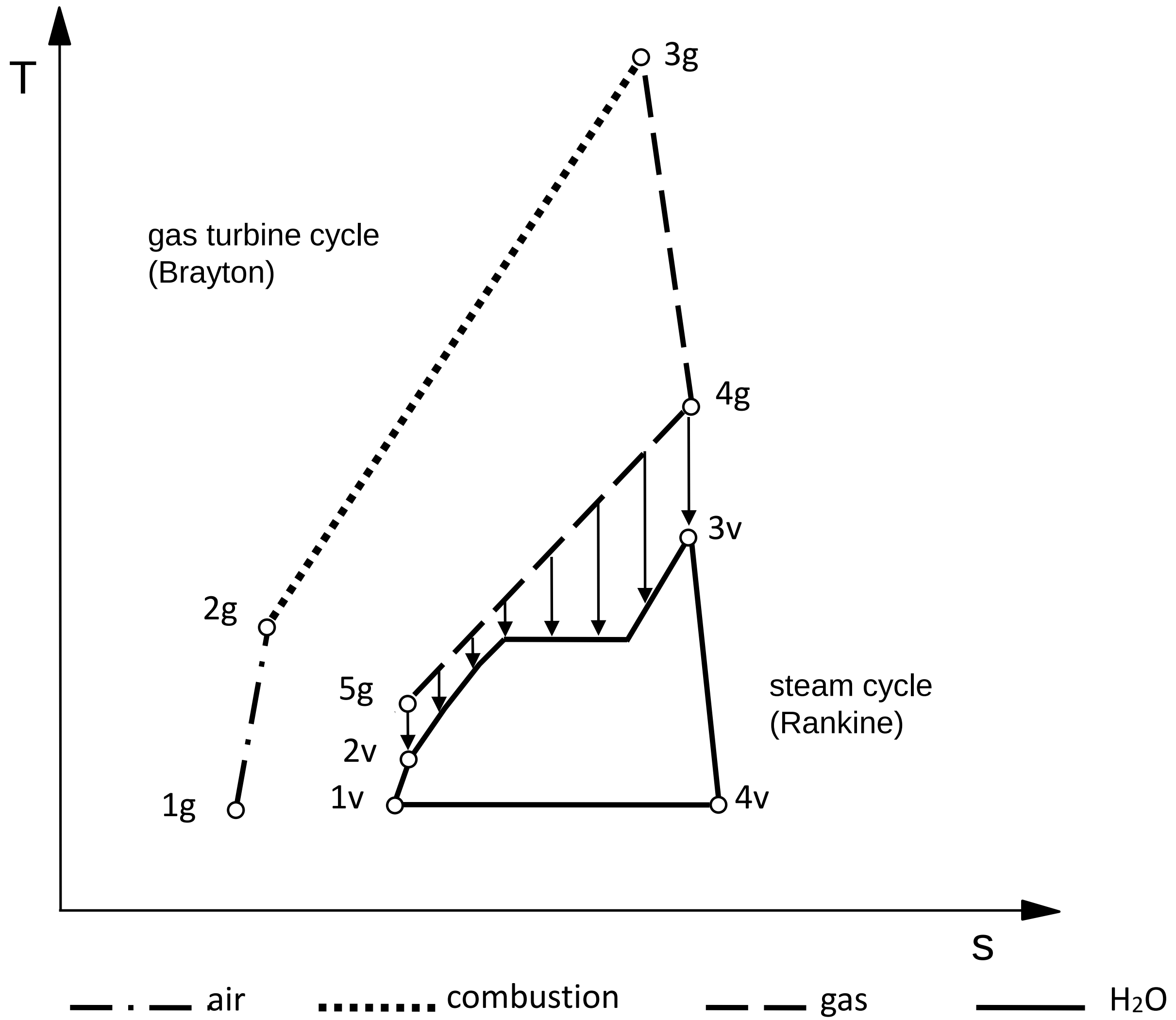
→ ***'win'–'win'*** combination between both cycles

→ 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

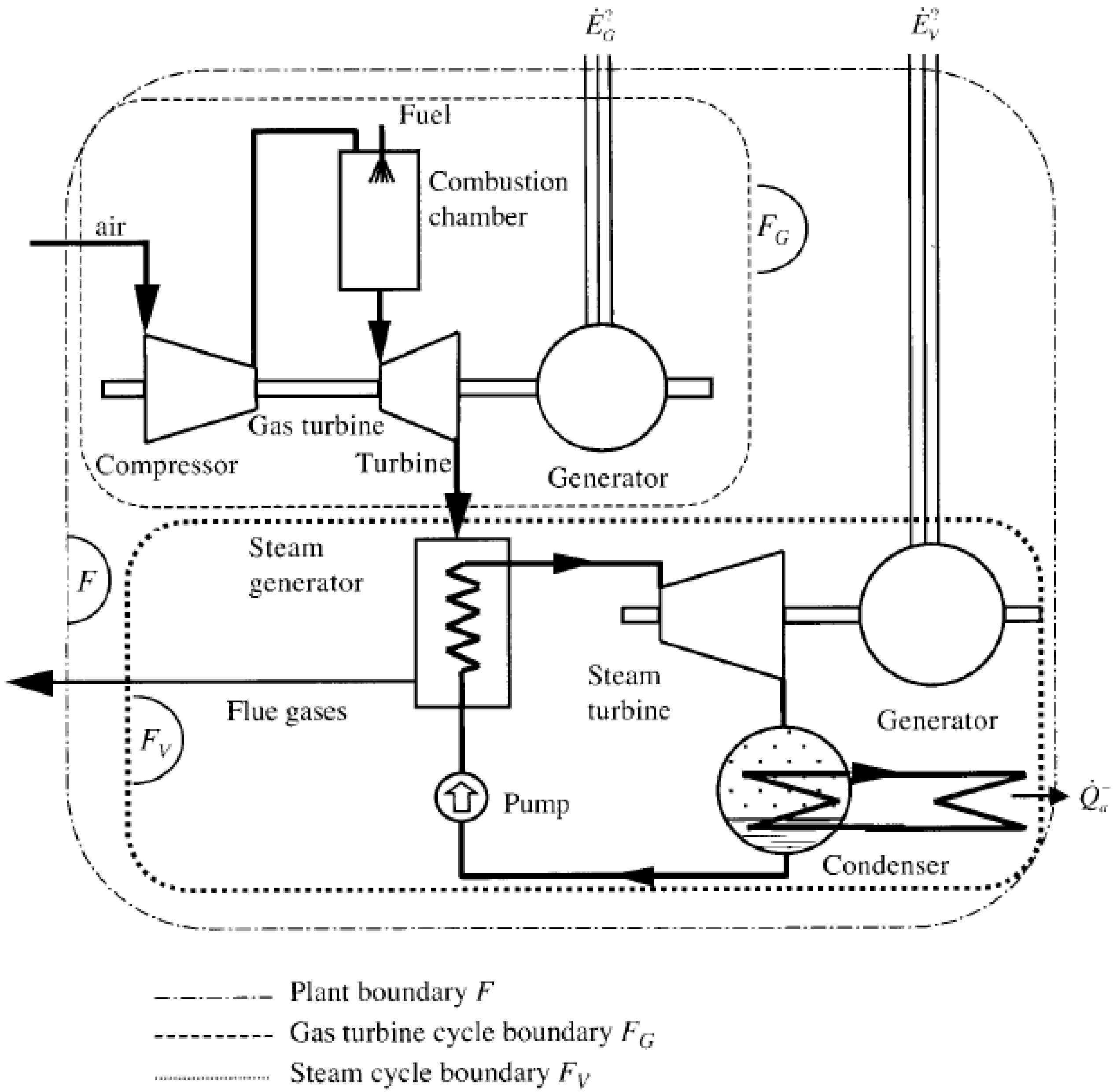
EPFL

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

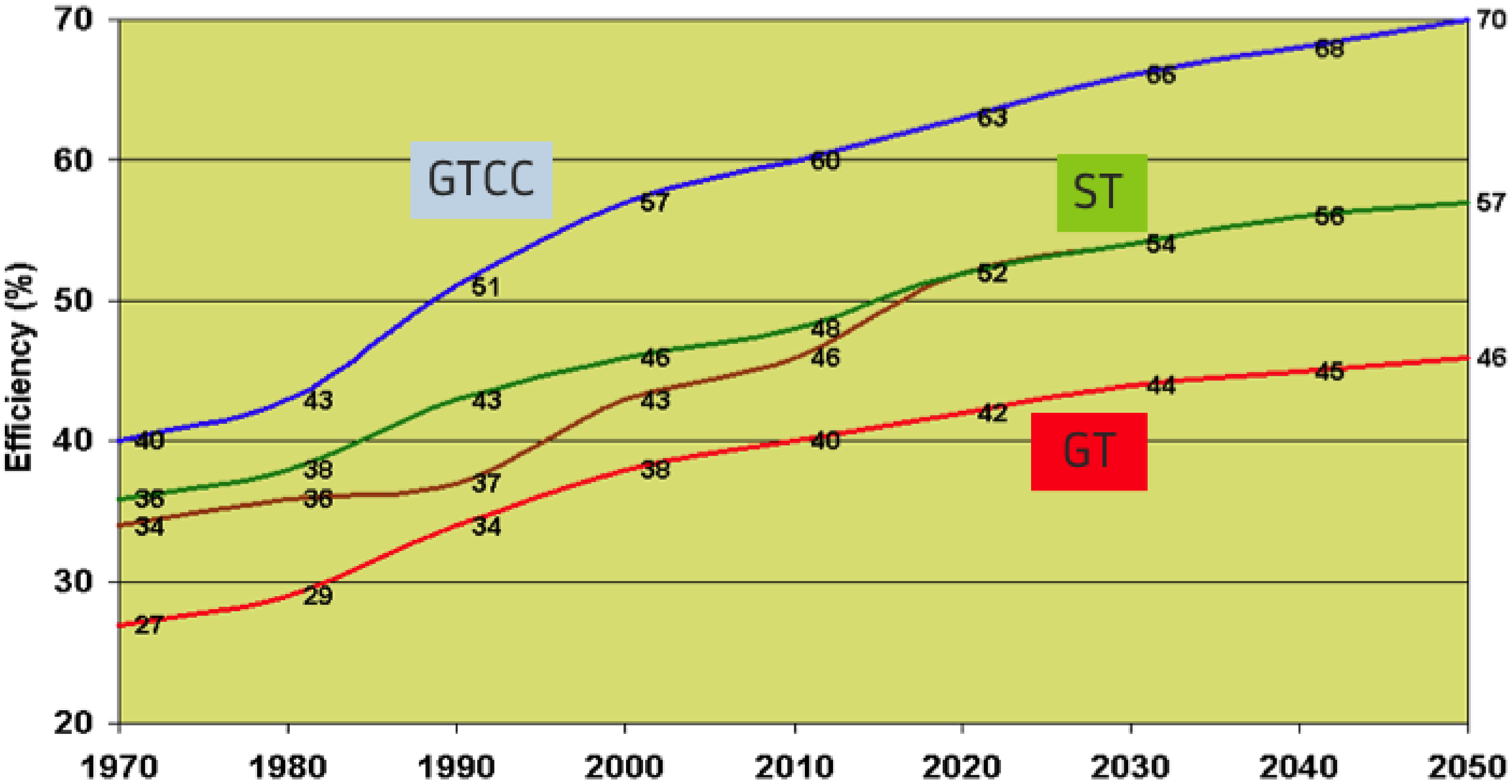


# Layout

(no cogen.)



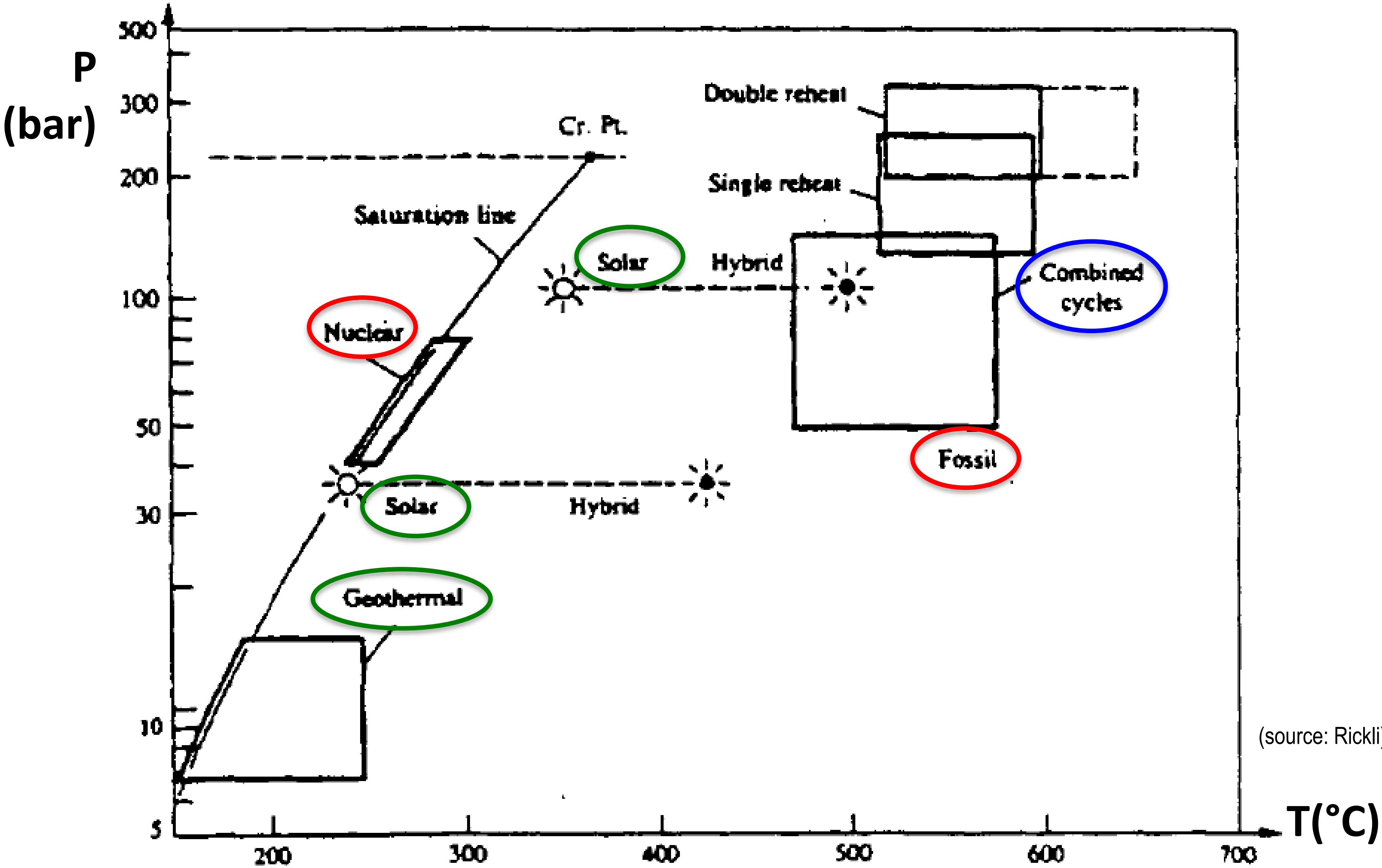
# Efficiency evolution and perspectives




(T. Kaiser, Alstom)

# Thermodynamic power cycles for renewable sources

# Steam *P-T* diagram for various cycle applications

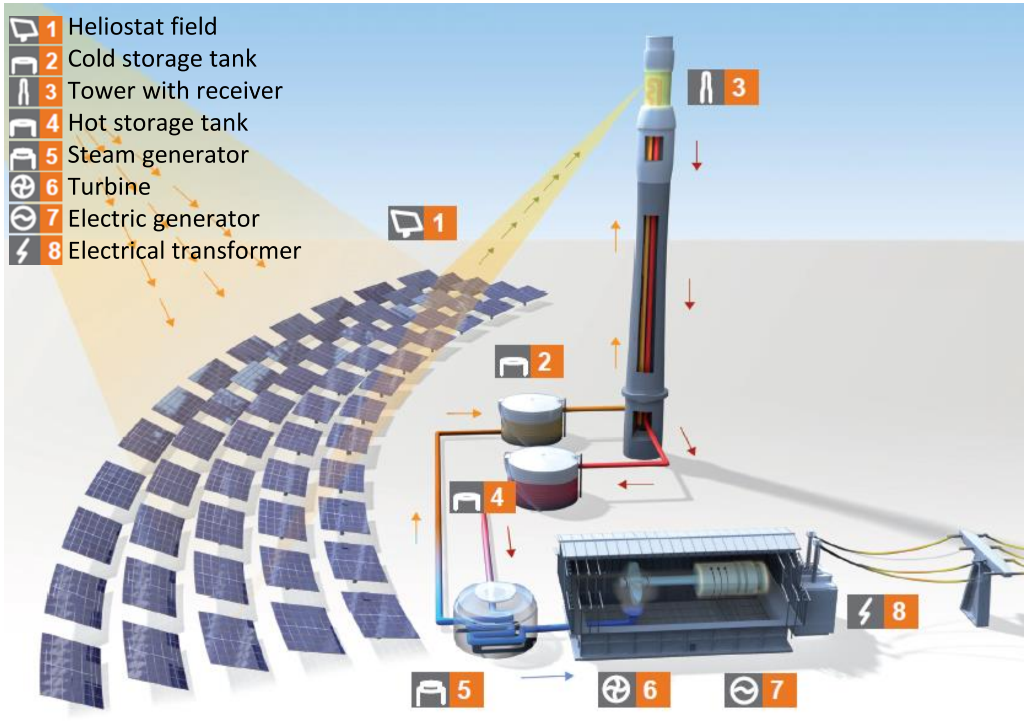


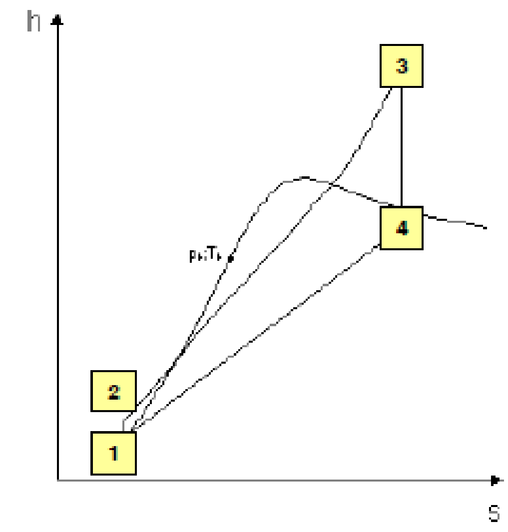

(source: Rickli)

EPFL

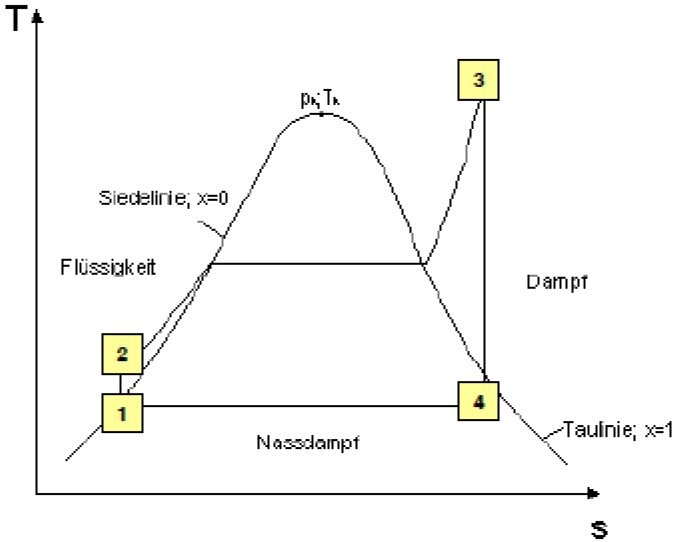
# Concentrated Solar Power - Centralized

- Traditional Rankine cycle:




h-s-Diagramm

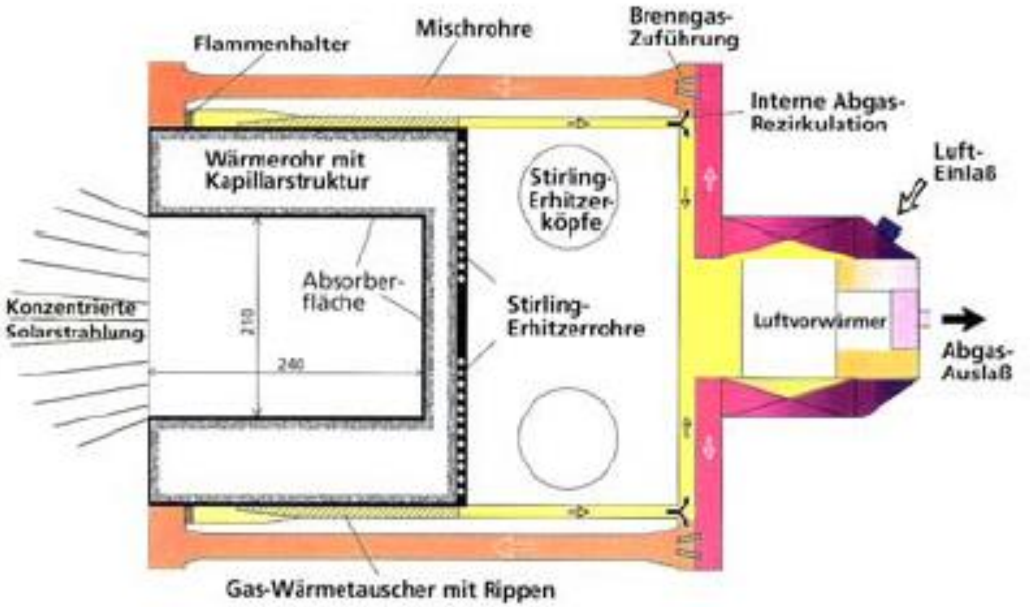


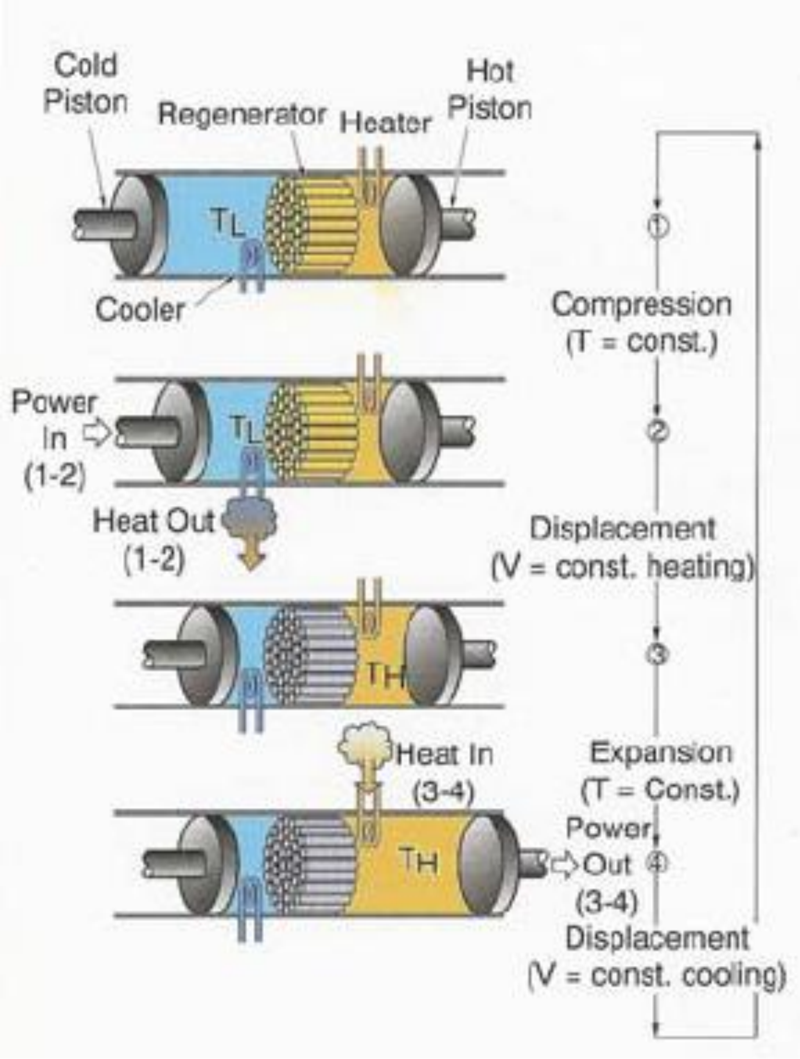

T-s-Diagramm

→ see lecture solar

# Concentrated Solar Power - Decentralized

- Stirling cycle:

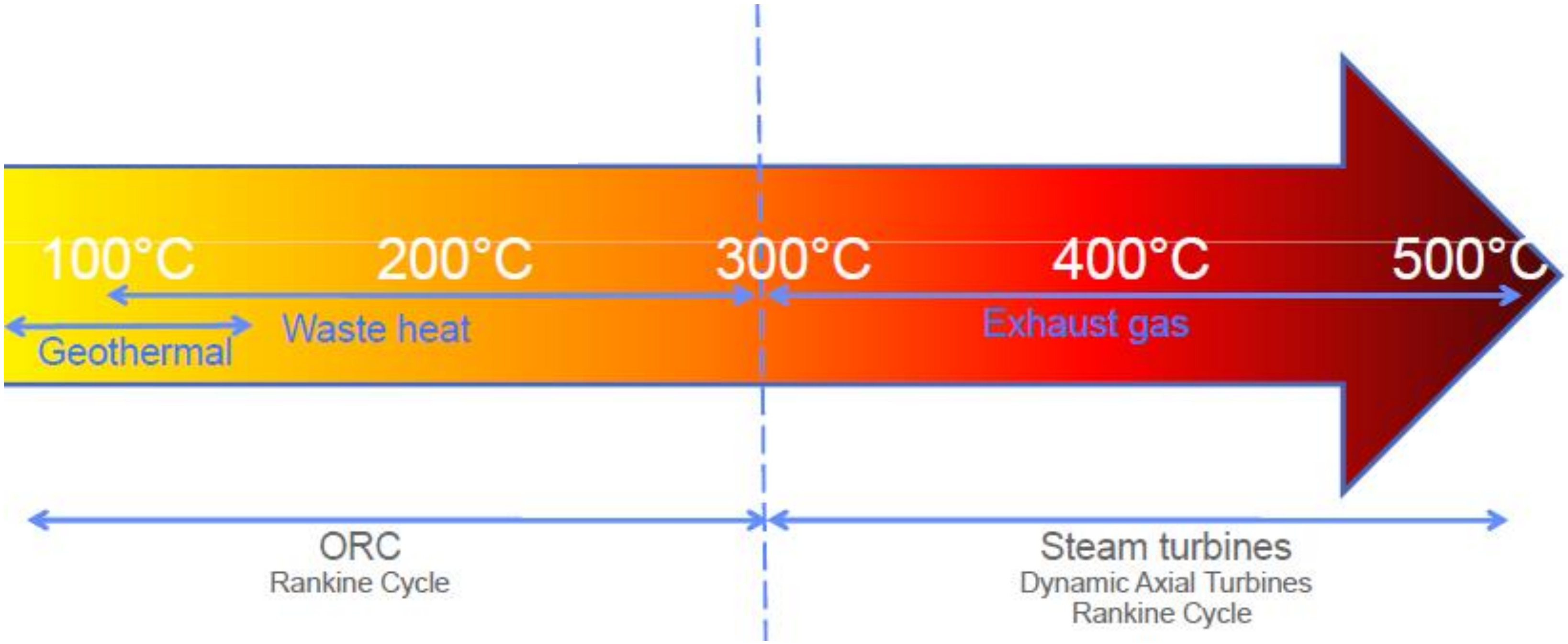



→ see lecture solar

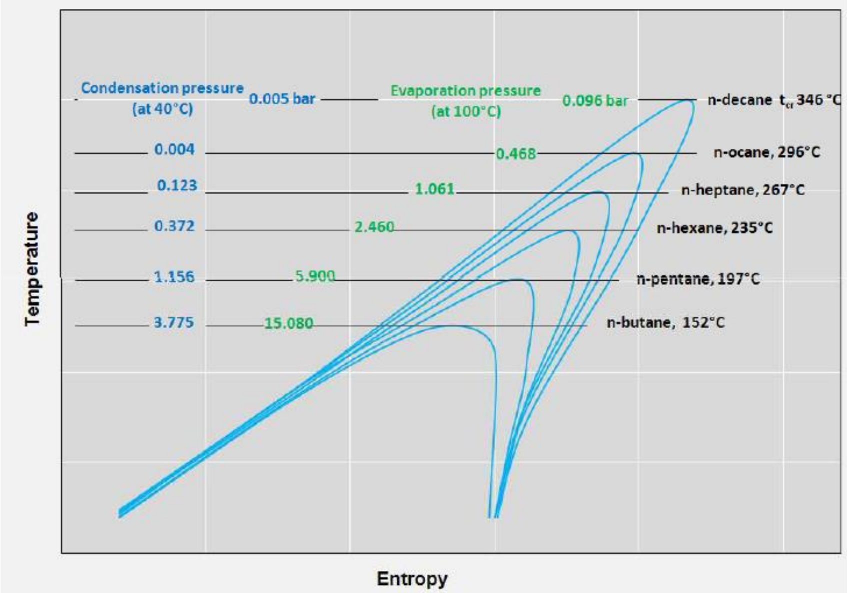
# Low temperature sources

- 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

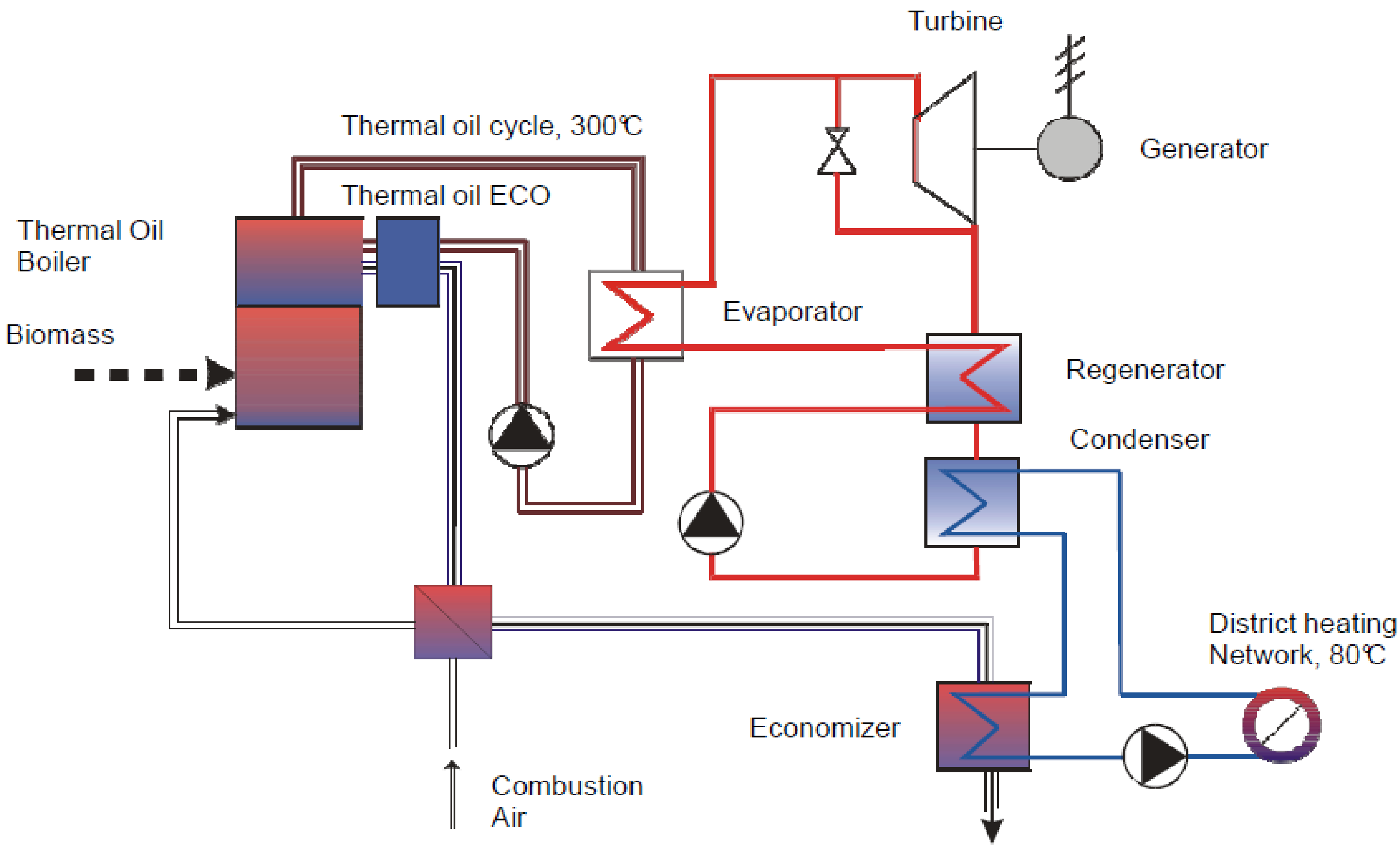



| | R245 fa | R152A | R32 | Pen-tane | Iso-Butane | Toluene |
|---|---|---|---|---|---|---|
| Saturated pressure at 120℃ (bar) | 19.2 | 42 | 58 | 9 | 28 | 1.3 |
| Service temperature (℃) | 140 | 140 | 140 | 140 | 140 | 140 |
| Saturated pressure at 50℃ (bar) | 3.5 | 11 | 31 | 1.6 | 6.8 | 0.1 |
| Expander 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

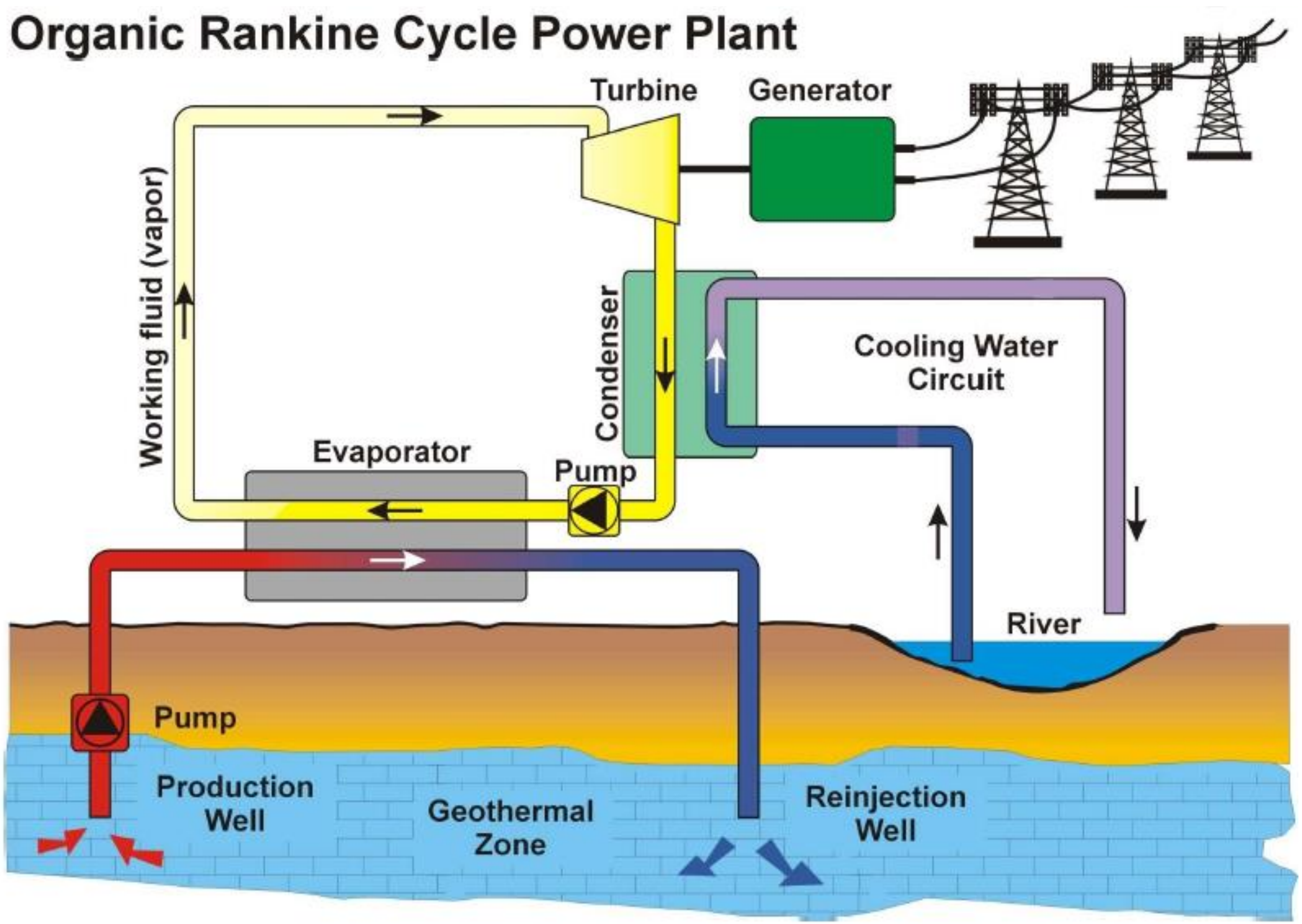
- Biomass: Working fluid silicone oil




M. Kane

# ORC example

- Geothermal

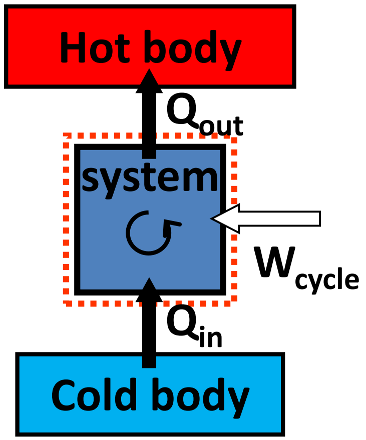


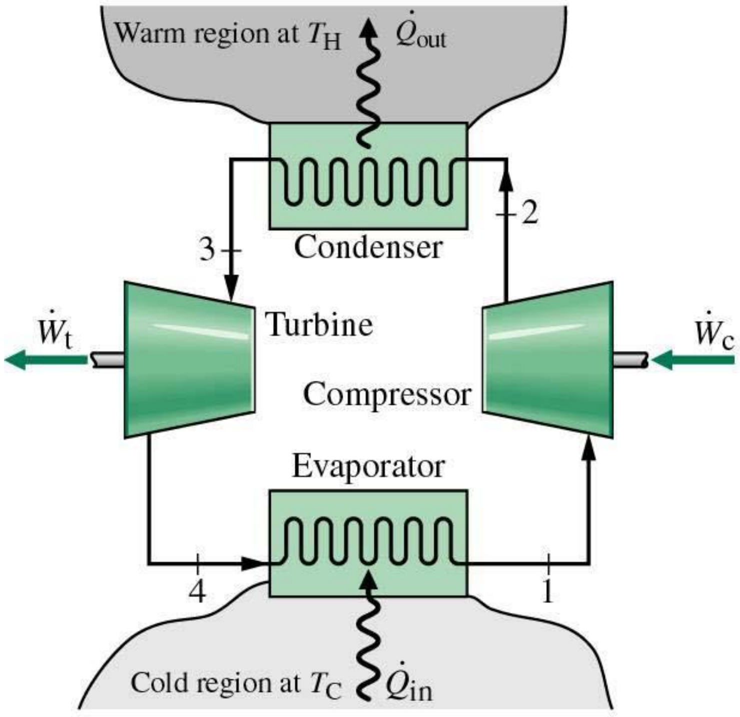

M. Kane

# 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

$$h_3 = h_4$$

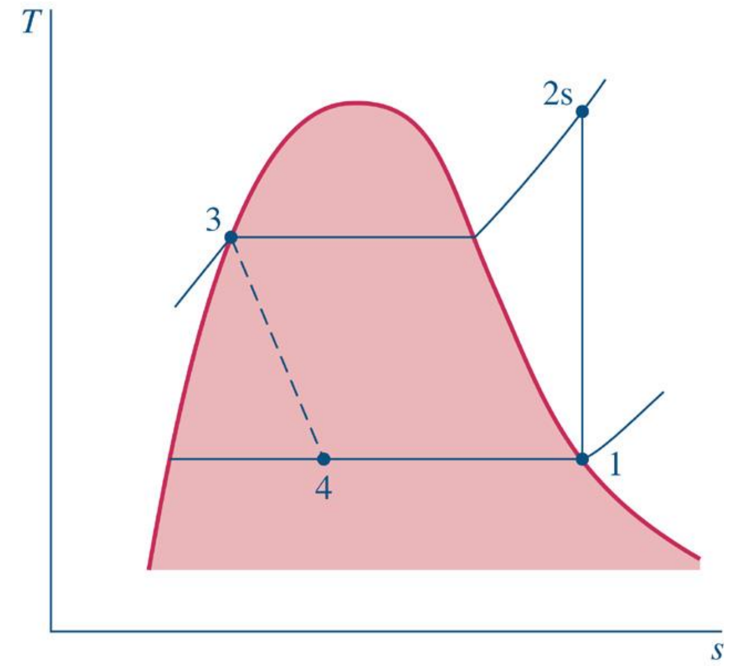
  - 4-1: Isobaric heat addition

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

  - 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

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

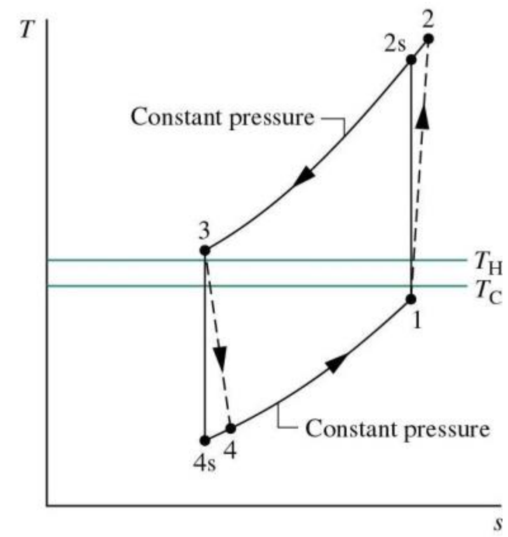
  - 3-4: (Isentropic) expansion

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

  - 4-1: Isobaric evaporation

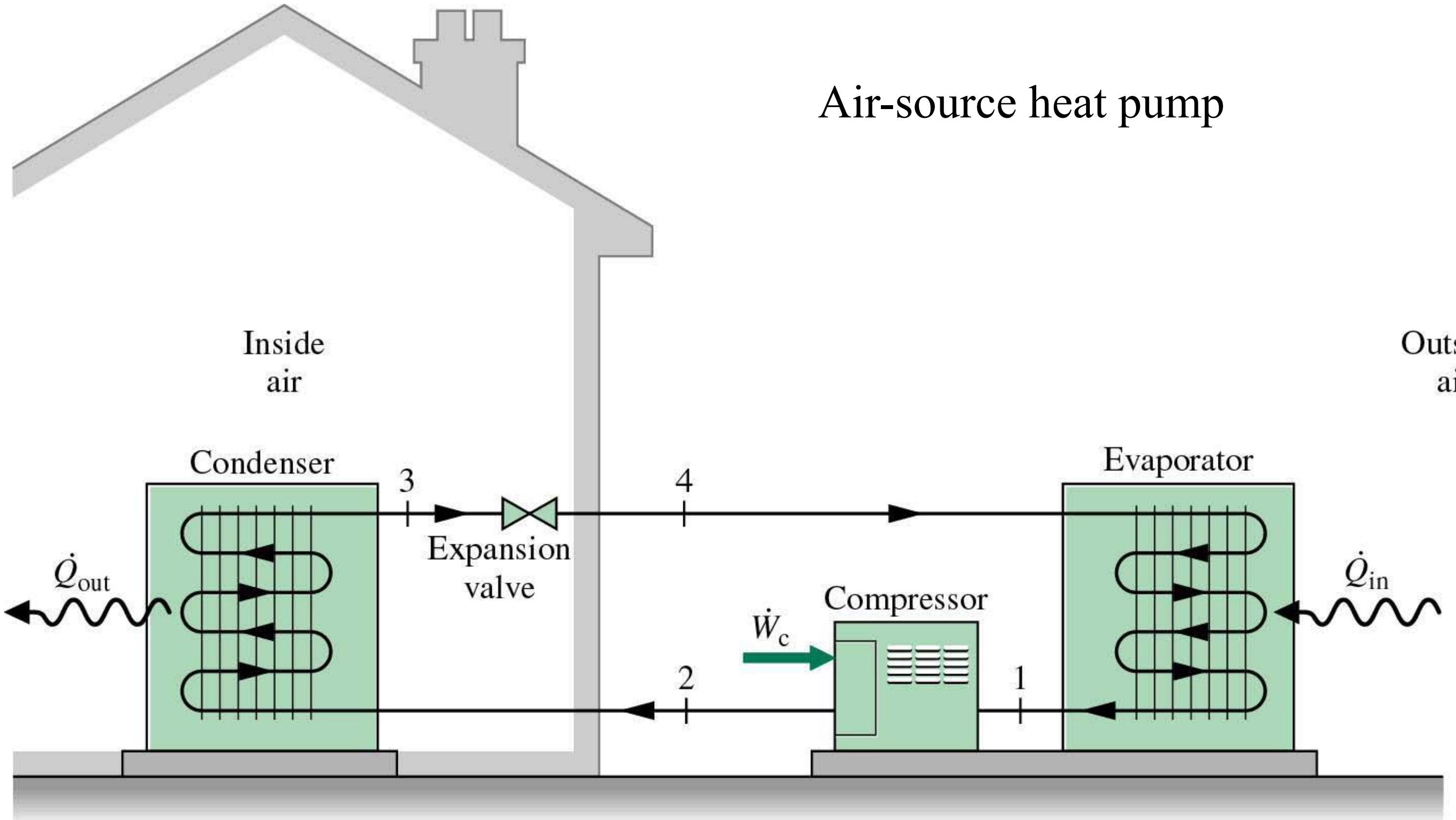
$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

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



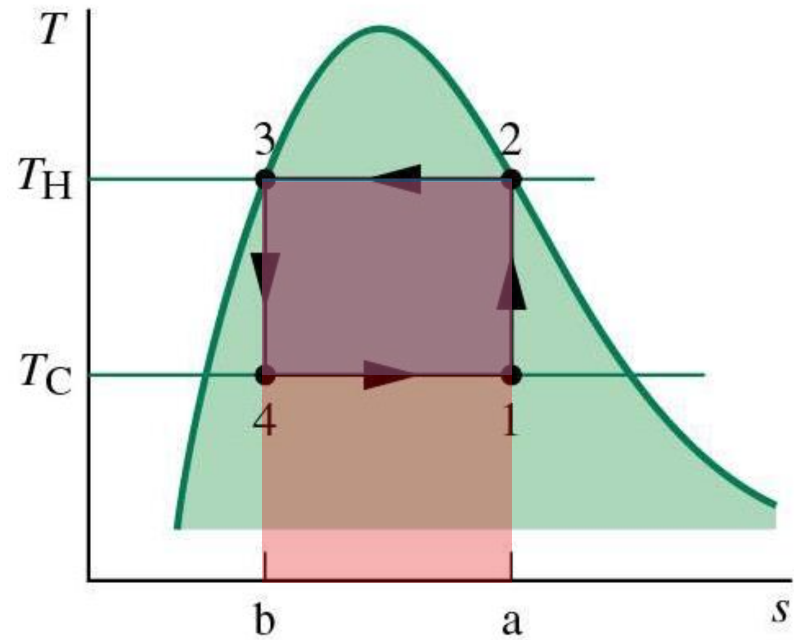
# Heat pump systems

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



# Heat pump systems

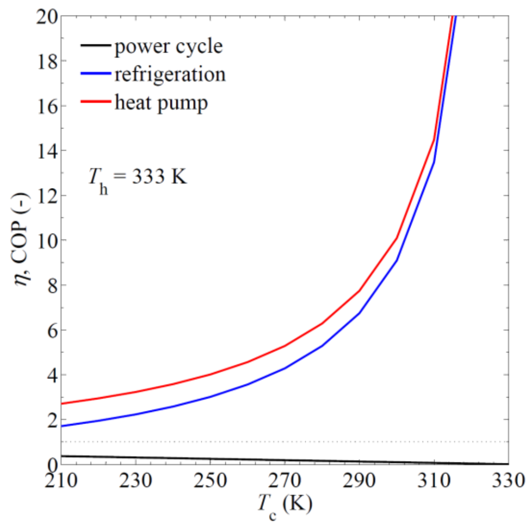
- Carnot heat pump cycle:
  - Same processes
  - Different purpose




  - Performance:

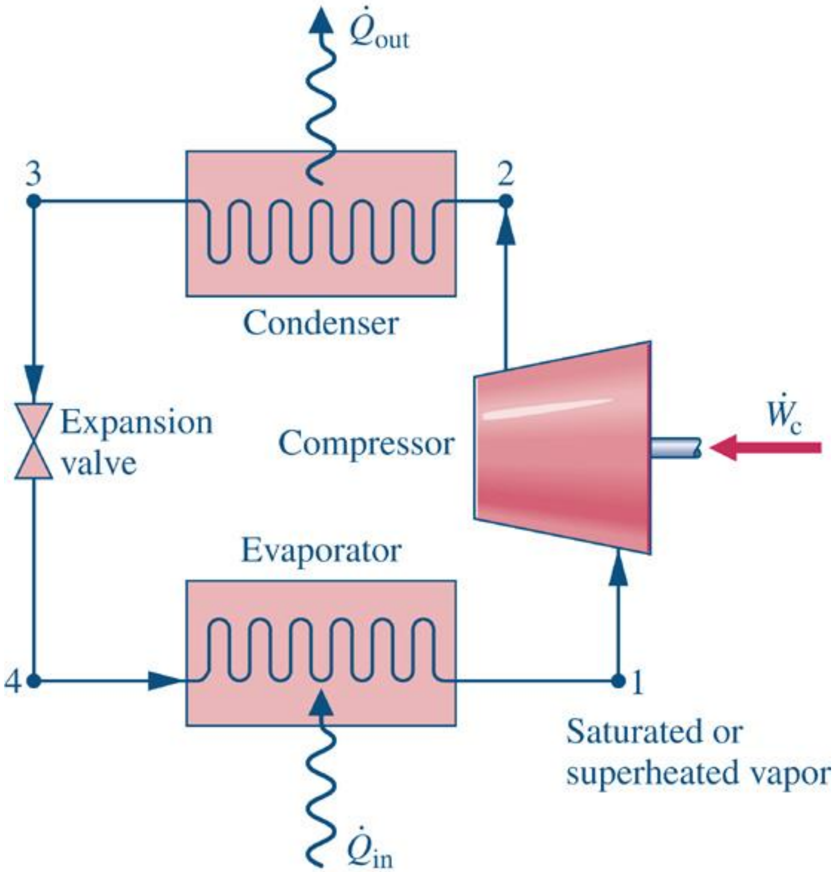
$$\mathrm{COP}_{\mathrm{hm,max}} = \frac{\dot{Q}_{\mathrm{out}}/\dot{m}}{\left|\dot{W}_{\mathrm{c}}/\dot{m} - \dot{W}_{\mathrm{t}}/\dot{m}\right|} = \frac{T_{\mathrm{H}}(s_a - s_b)}{(T_{\mathrm{H}} - T_{\mathrm{C}})(s_a - s_b)}$$

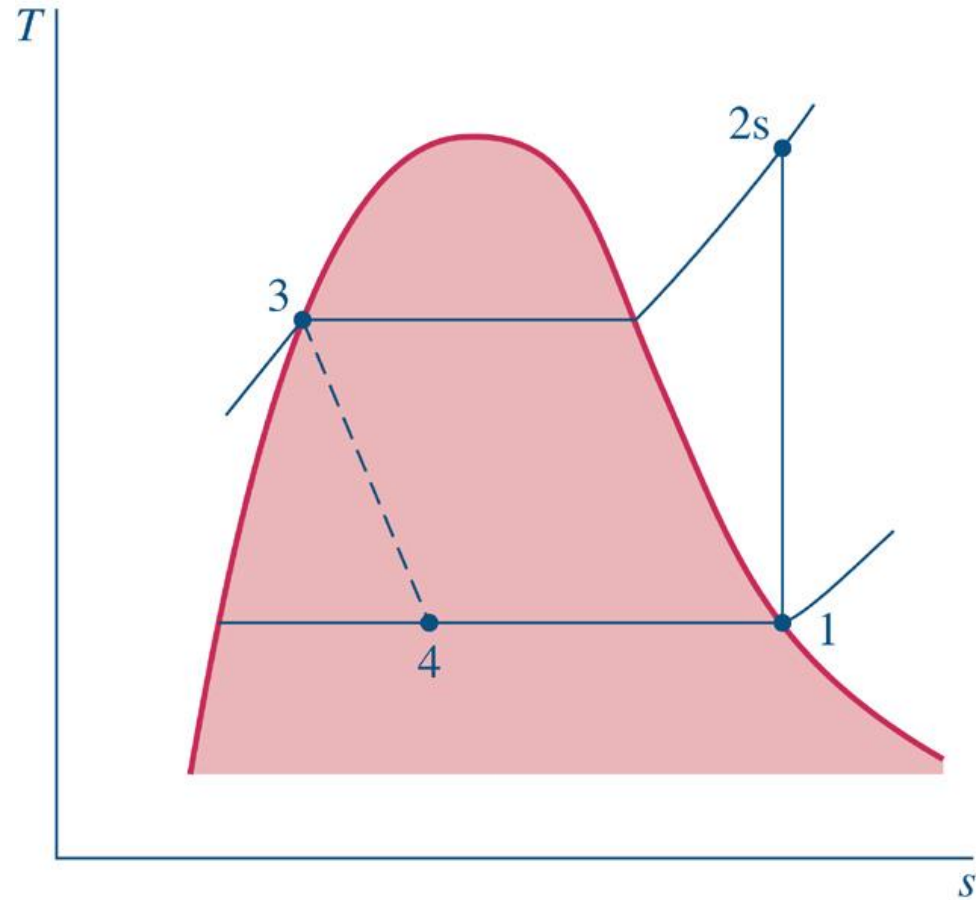
$$= \frac{T_{\mathrm{H}}}{T_{\mathrm{H}} - T_{\mathrm{C}}}$$



# Heat pump systems

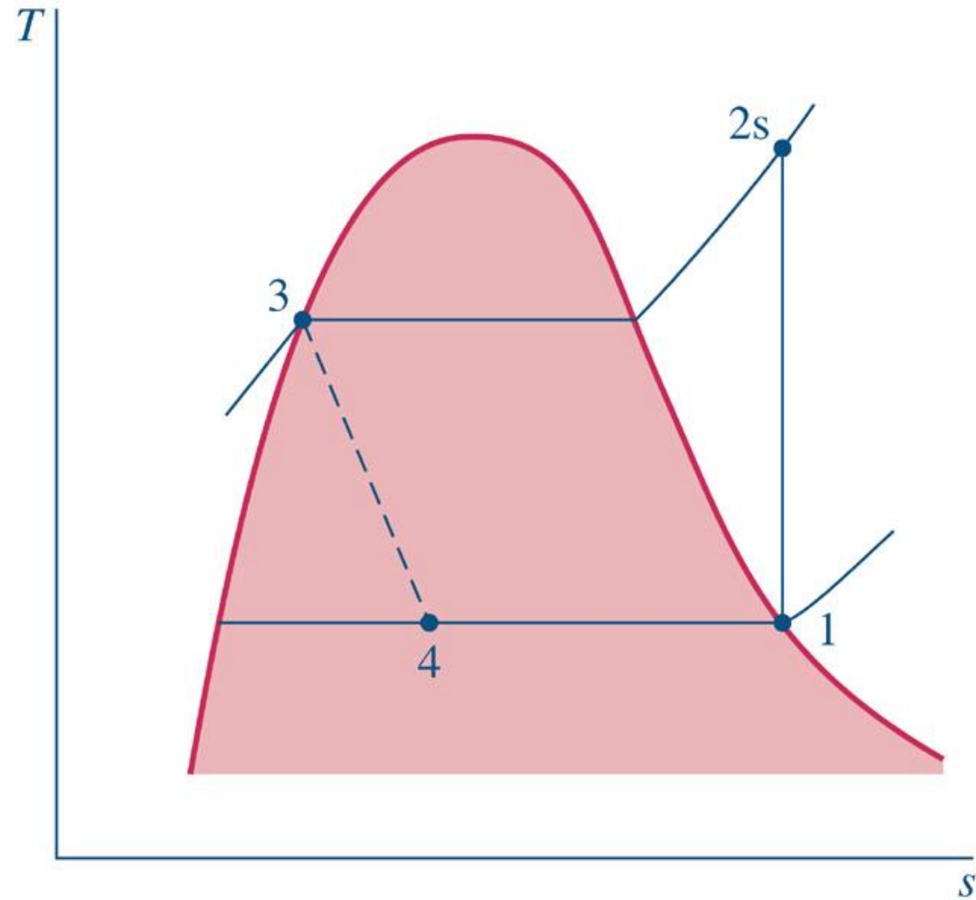
- Vapor-compression heat pumps:



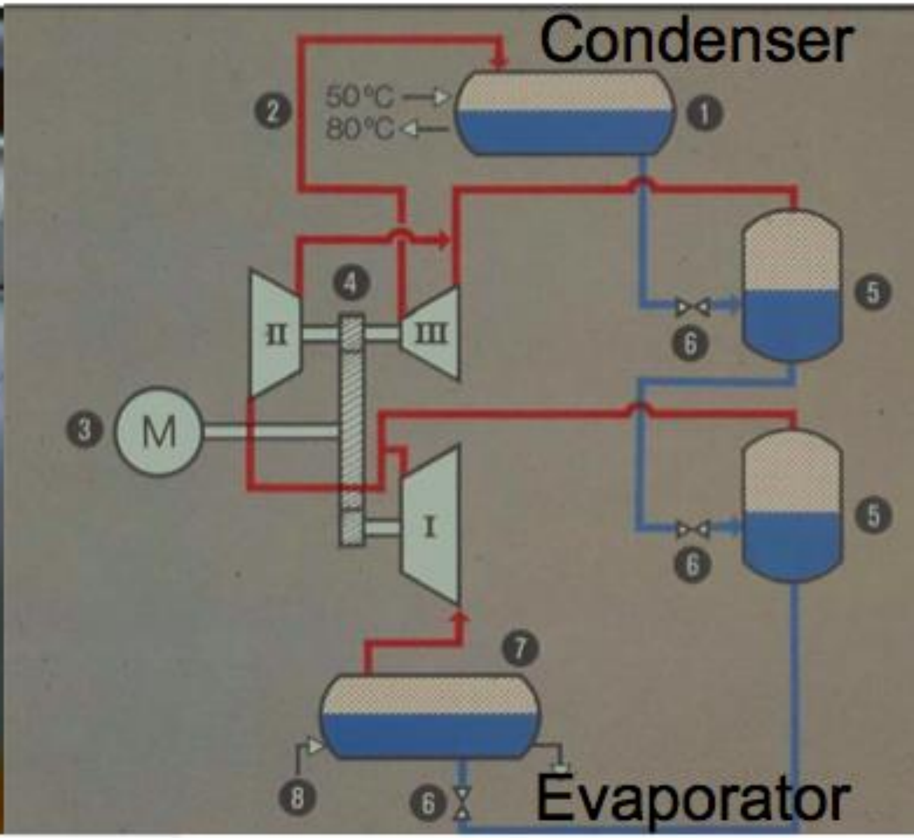



# Heat pump systems

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



# 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) <u>not</u> 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 $\mathbf{NH_3}$ with **water** as solvent
  - e.g. working fluid **water** with **LiBr** as solvent

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

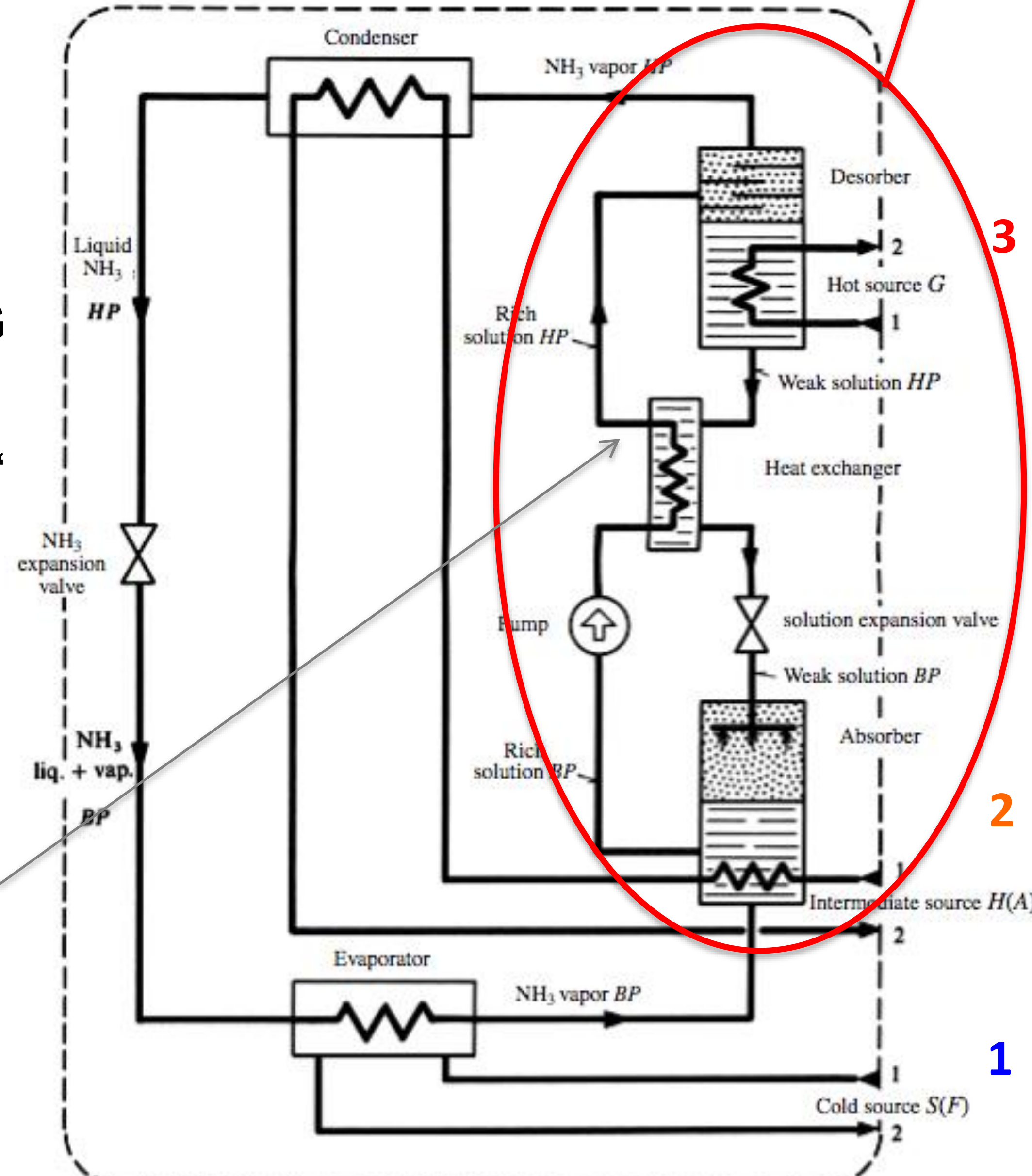
# Absorption heat pump

replaces a compressor

- absorber (water):
  receives low p $NH_3$ vapor (BP)

$\Rightarrow$ liberates absorption heat (H)

- liquid pump BP→HP
- boiler: delivers the absorption heat (G
- expander (liq.) HP→BP $\dot{E}_P^+$
- internal heat exchanger between the '
- tubing




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