

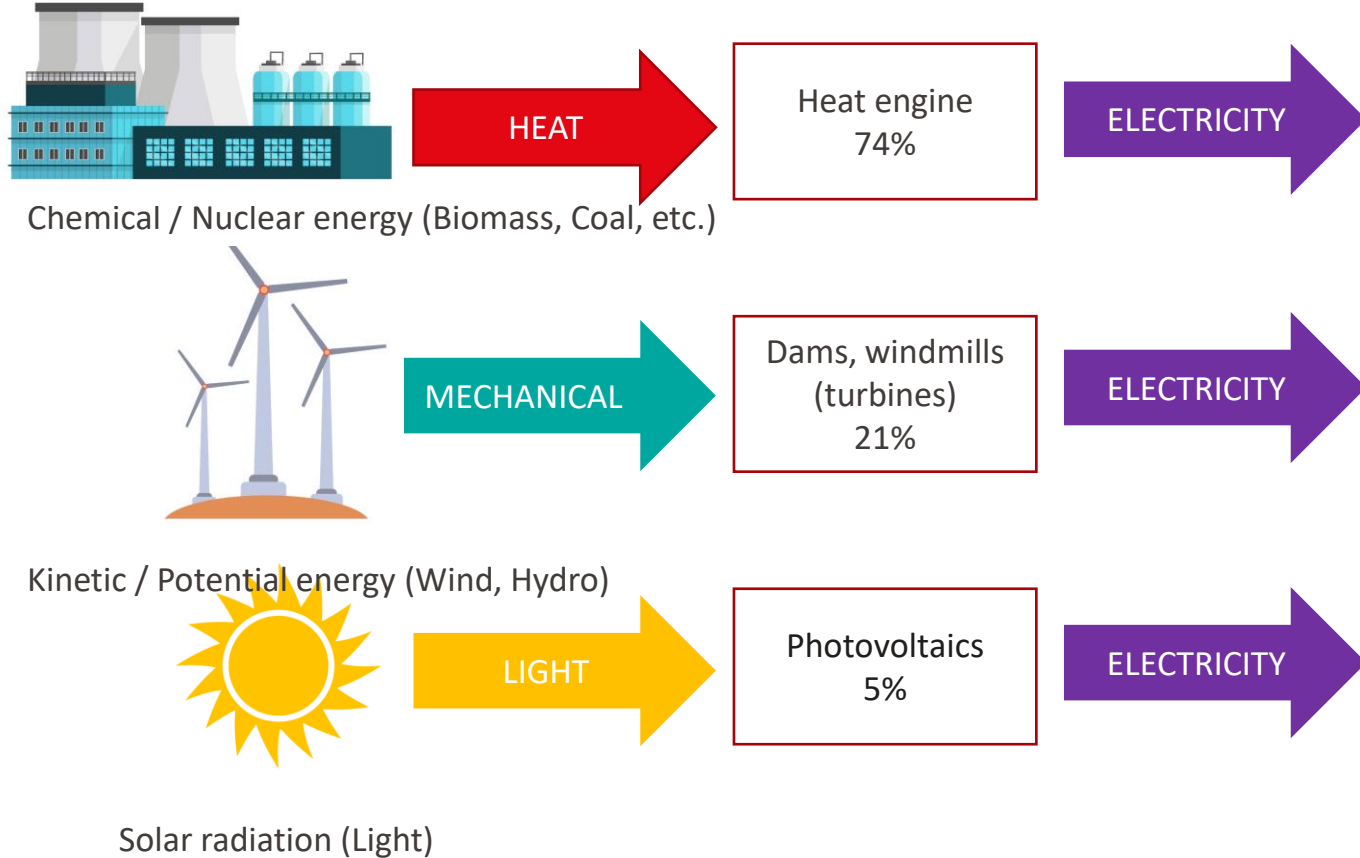


Heat to Electricity: Rankine cycles

François Marechal
EPFL

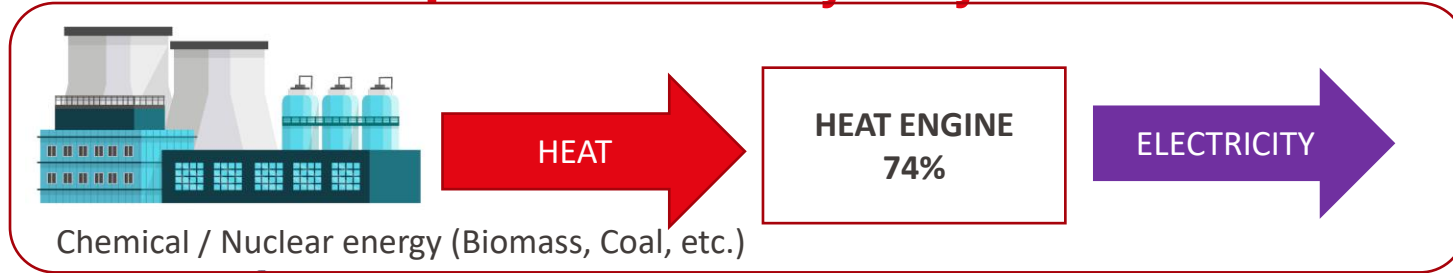
Introduction

- How do we produce electricity today?

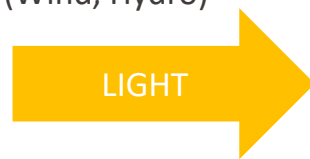


Introduction

- How do we produce electricity today?



Kinetic / Potential energy (Wind, Hydro)

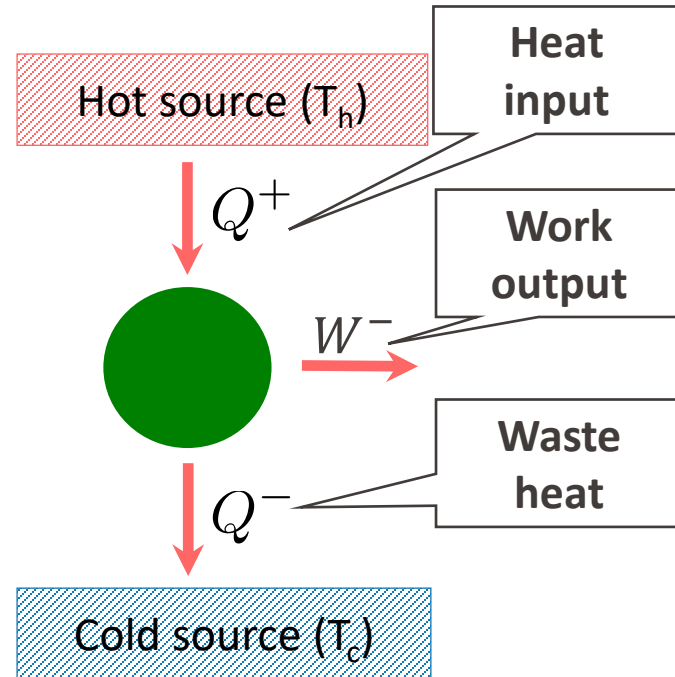
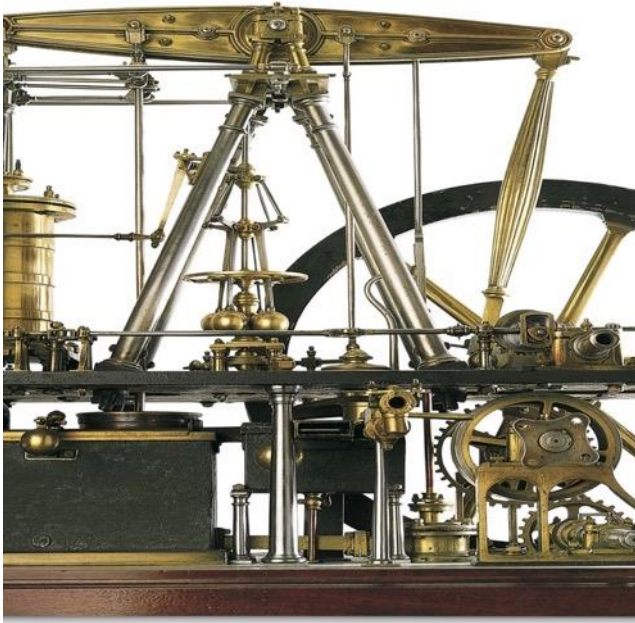


Solar radiation (Light)

Introduction

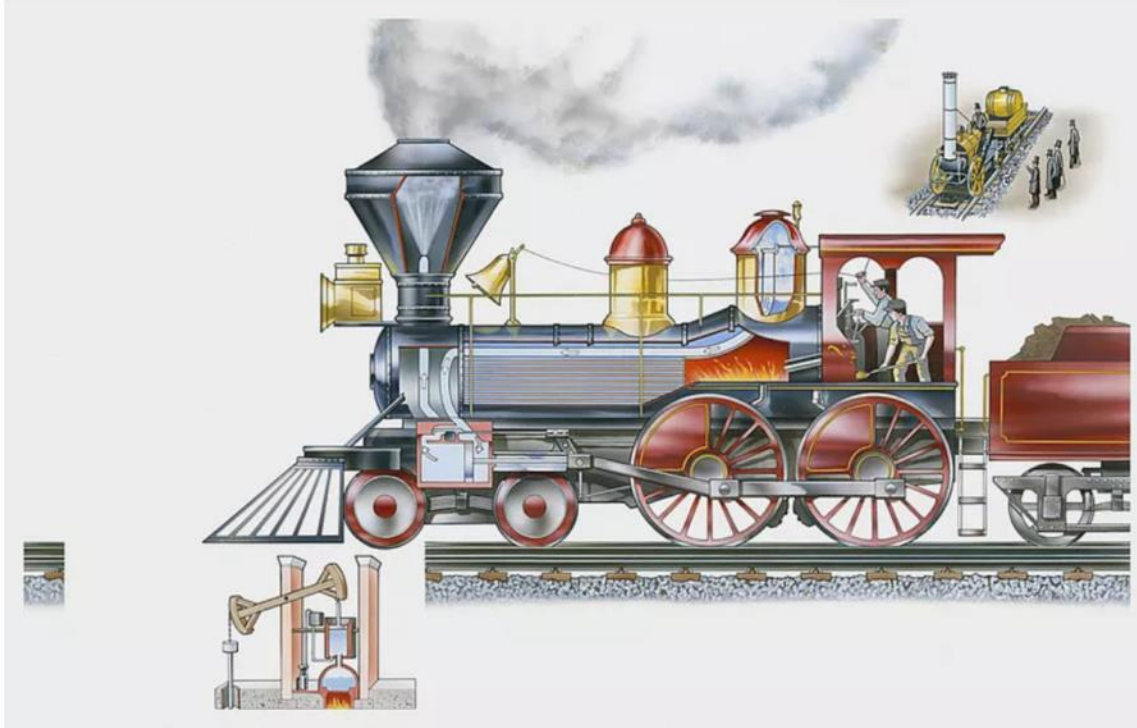
- Heat engines

- Conversion of heat to work (electrical, mechanical)



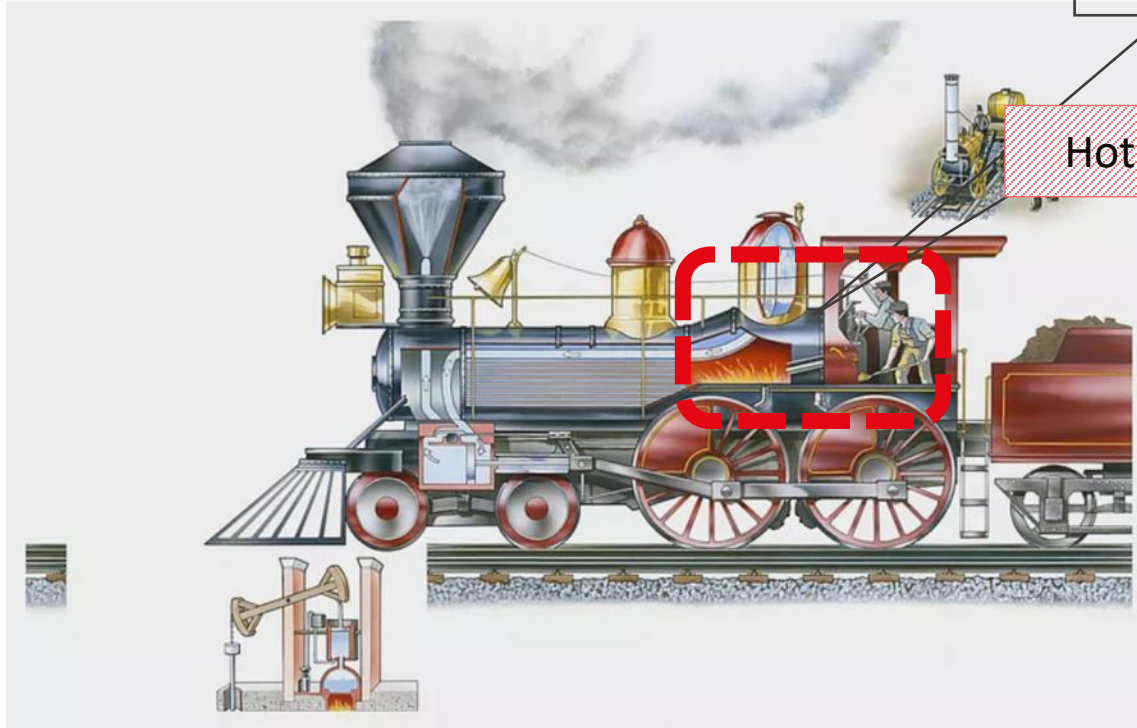
Introduction

- The example of the steam train



Introduction

- The example of the steam train

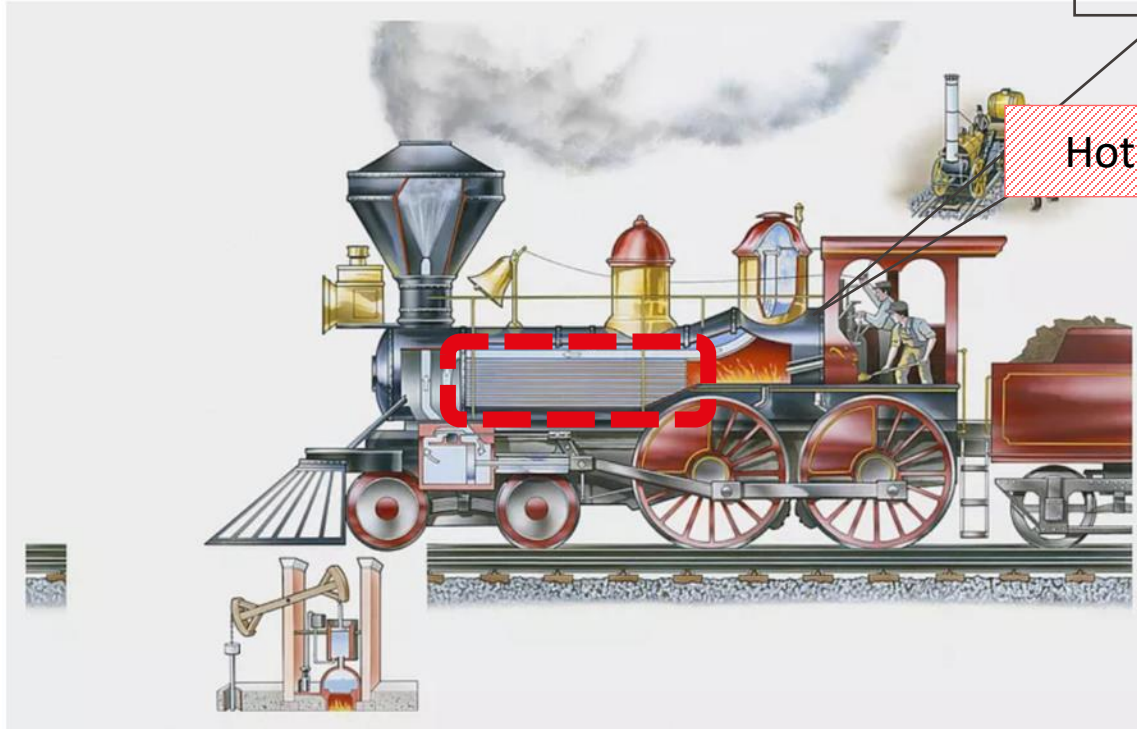


Solid fuel –
Heat **generation** =
combustion

Hot source (T_h)

Introduction

- The example of the steam train



Steam generation
Heat **input** = boiler

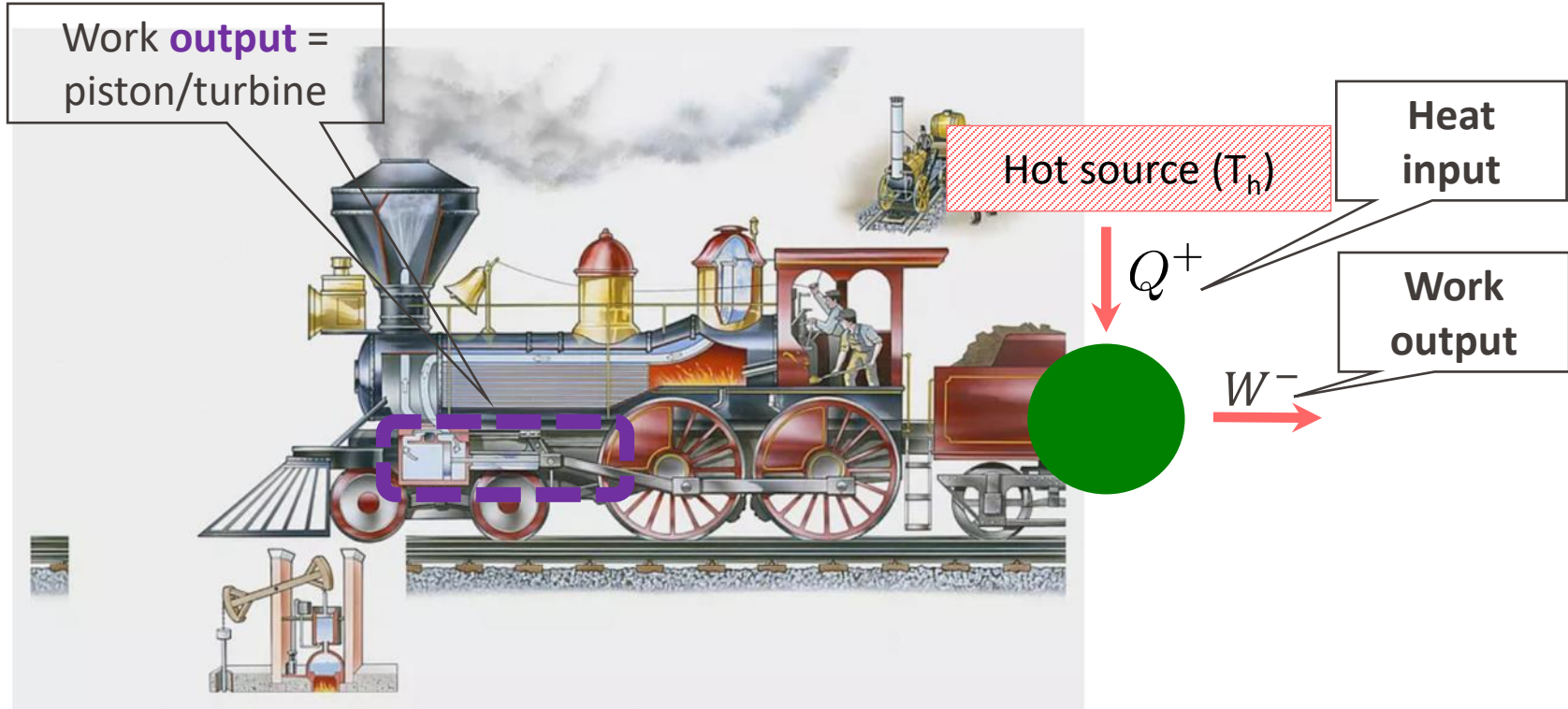
Hot source (T_h)

Heat
input

Q^+

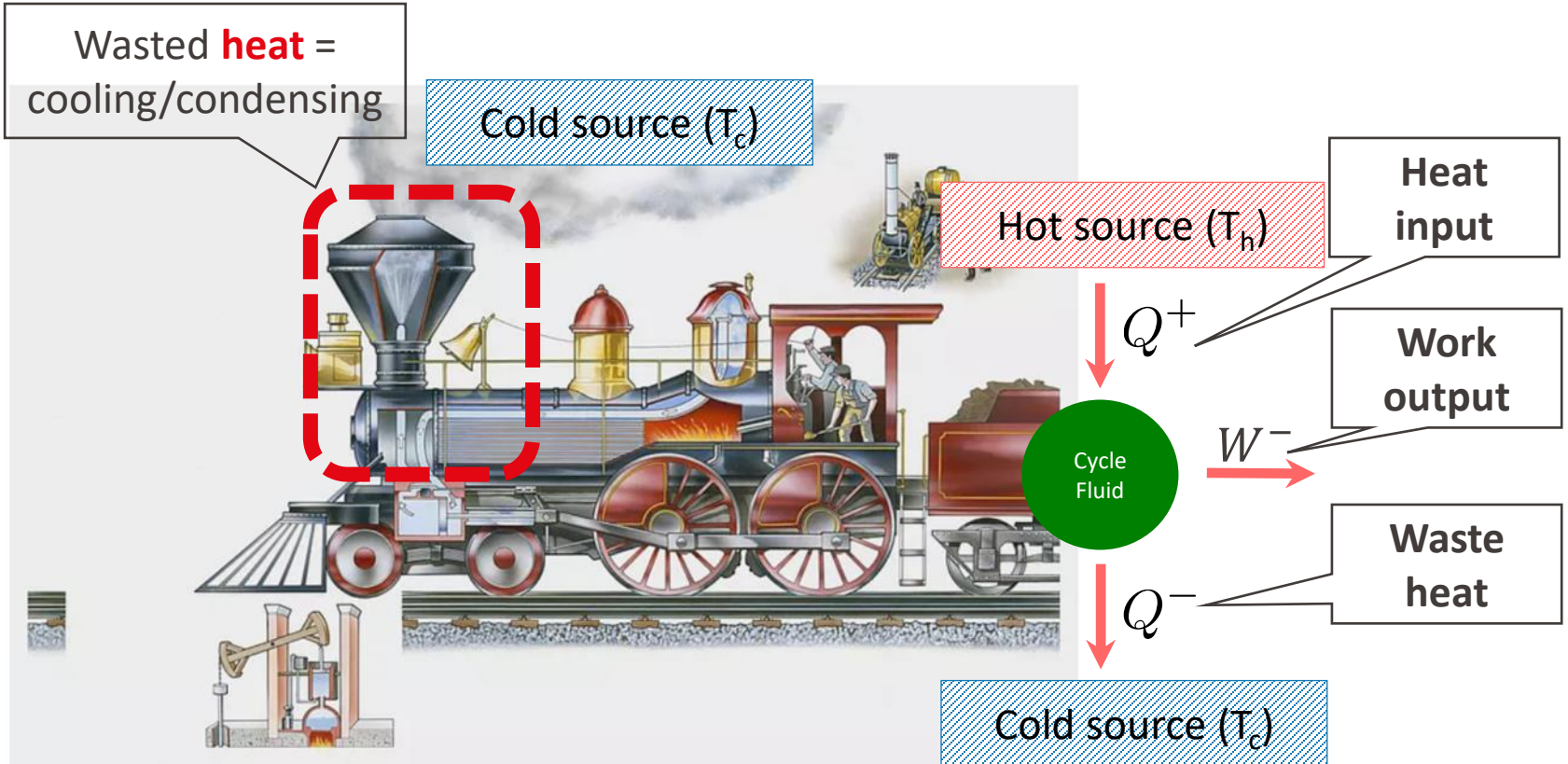
Introduction

- The basic concept



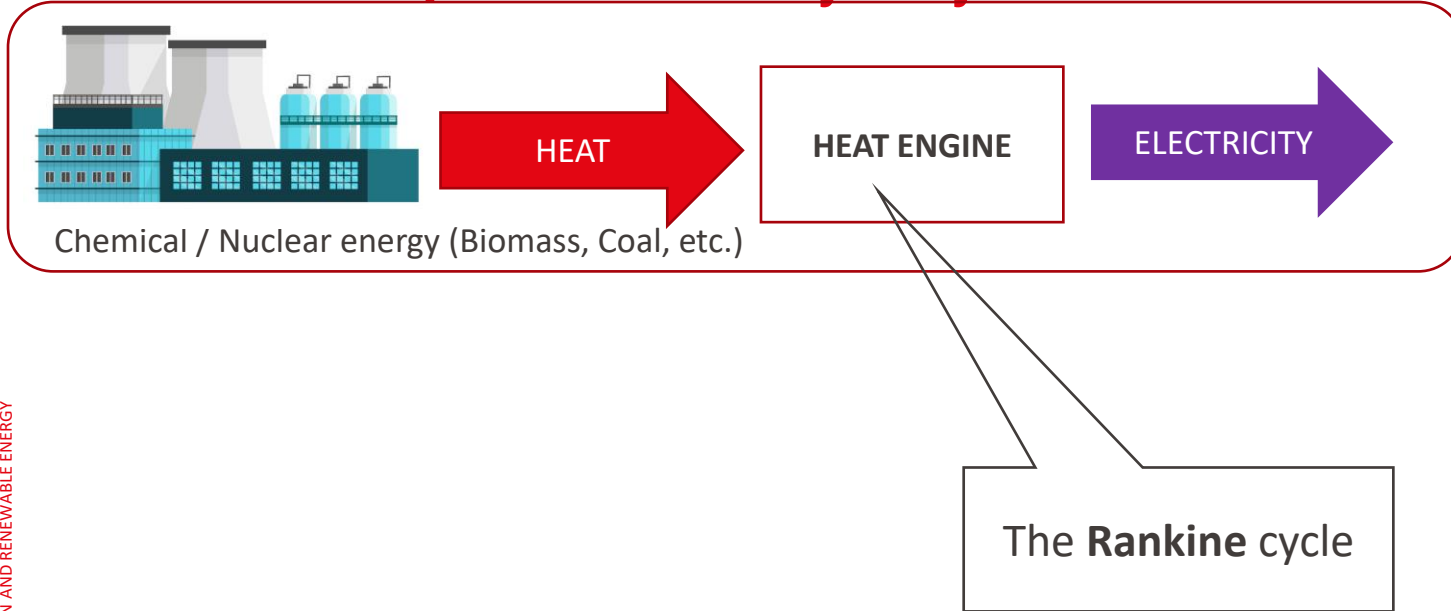
Introduction

- The basic concept



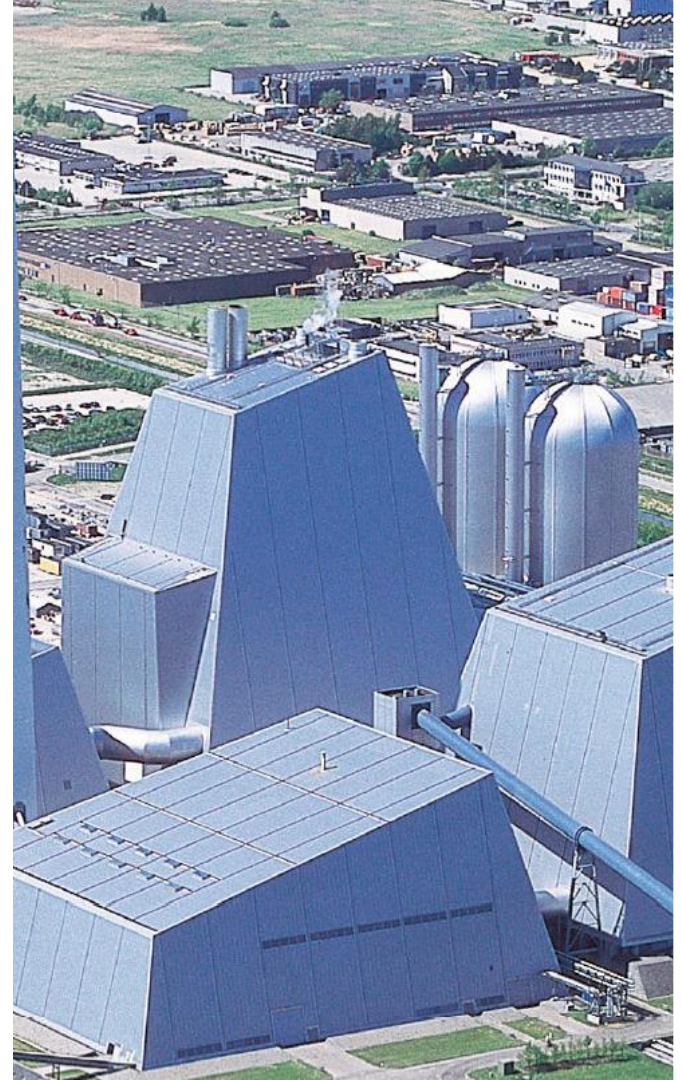
Introduction

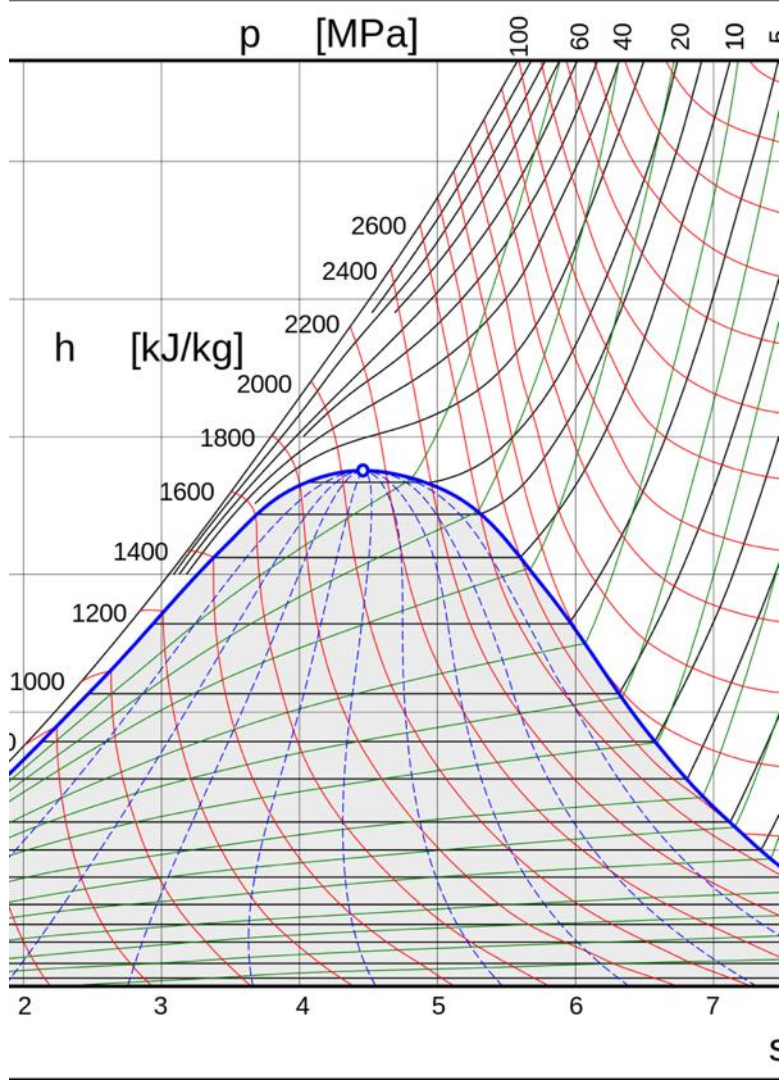
- How do we produce electricity today?



Goals

- **Use** thermodynamic diagrams
- **Describe** the standard Rankine cycle
- **Calculate** the corresponding efficiencies
- **Compare** possible improvements for designing state-of-the-art plants





Working Fluid Thermodynamic diagrams

State variables

Temperature-entropy (T - s)

Pressure-enthalpy (p - h)

Fluids : Thermodynamic diagrams

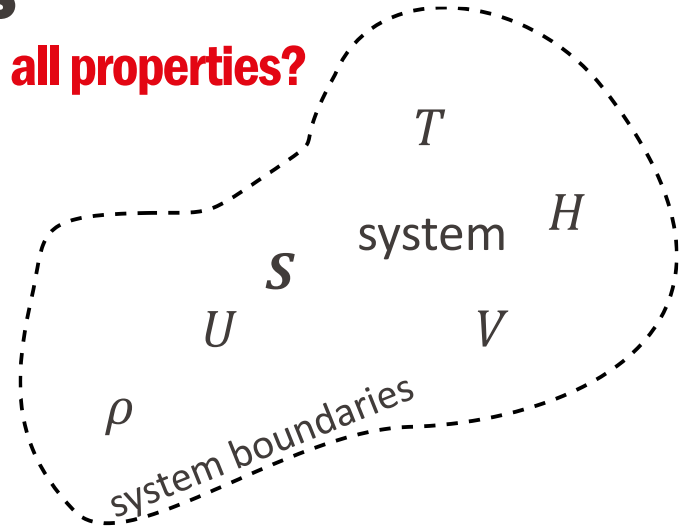
- How much information is required to derive all properties?

■ Intensive properties

- Temperature
- Pressure
- Density
- Internal energy
- Melting point

■ Extensive properties

- Mass
- Volume
- ...



Thermodynamic diagrams

- The degrees of freedom

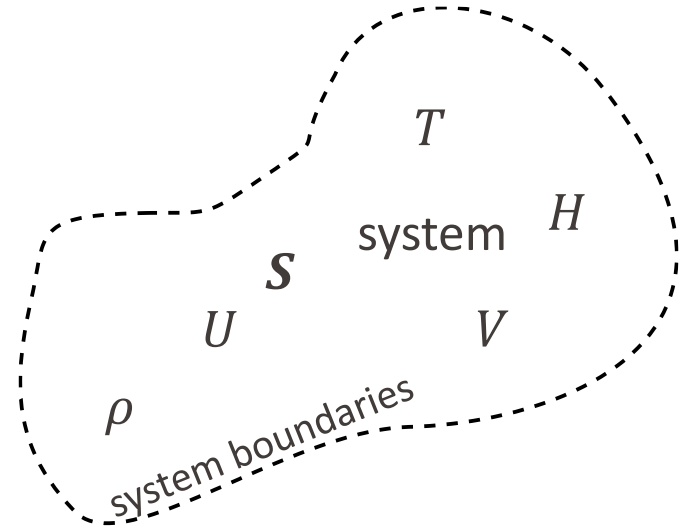
■ Gibbs' phase rule

- F: # degrees of freedom
- C: # compounds (e.g. water)
- P: # phases

■ Degrees of freedom

- $F = C + 2$
- In which one extensive variable

nb of values to fix to define the state



$$T = 25^{\circ}\text{C}$$

$$p = 1 \text{ atm}$$

$$M = 1 \text{ kg}$$



$$\rho, \bar{v}, c_p \dots$$

Thermodynamic diagrams

- Tables : e.g. Water thermodynamic properties for 1 kg

p	T	v gas	h gas	s gas		p	T	v gas	h gas	s gas
Bar	Deg. C	m ³ /kg	kJ/kg	kJ/(kg K)		Bar	Deg. C	m ³ /kg	kJ/kg	kJ/(kg K)
40	200	0.0323	2476.9	5.4111		90	200	0.0011	855.3	2.3192
40	250	0.0497	2799.5	6.0669		90	250	0.0012	1085.1	2.7807
40	300	0.0588	2960.3	6.3611		90	300	0.0199	2719.4	5.6380
40	350	0.0664	3092.1	6.5817		90	350	0.0258	2956.2	6.0359
40	400	0.0734	3213.2	6.7687		90	400	0.0299	3117.4	6.2850
40	450	0.0800	3329.9	6.9360		90	450	0.0335	3256.3	6.4841
40	500	0.0864	3444.9	7.0897		90	500	0.0368	3385.7	6.6572
40	550	0.0927	3559.4	7.2333		90	550	0.0399	3510.7	6.8139
40	600	0.0988	3674.1	7.3686		90	600	0.0428	3633.4	6.9586
50	200	0.0012	853.6	2.3253		100	200	0.0011	855.7	2.3177
50	250	0.0366	2729.1	5.8507		100	250	0.0012	1085.1	2.7784
50	300	0.0453	2924.2	6.2081		100	300	0.0161	2631.2	5.4527
50	350	0.0519	3068.1	6.4490		100	350	0.0224	2923.1	5.9440
50	400	0.0578	3195.3	6.6456		100	400	0.0264	3096.1	6.2117
50	450	0.0633	3315.8	6.8183		100	450	0.0297	3240.5	6.4186
50	500	0.0686	3433.4	6.9756		100	500	0.0328	3373.3	6.5963

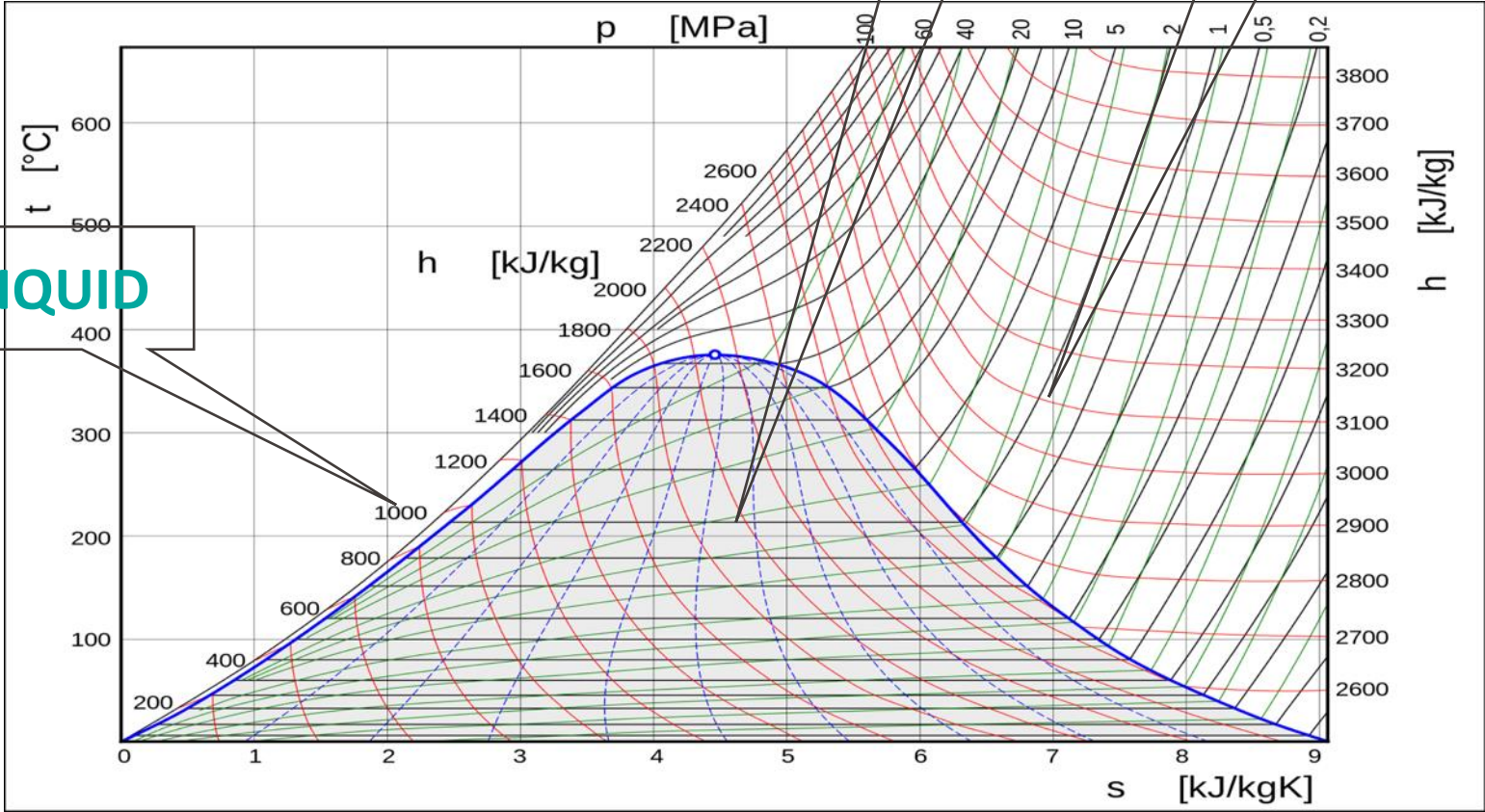
Thermodynamic diagrams

- T-s diagram

LIQUID+
GAS

GAS

LIQUID

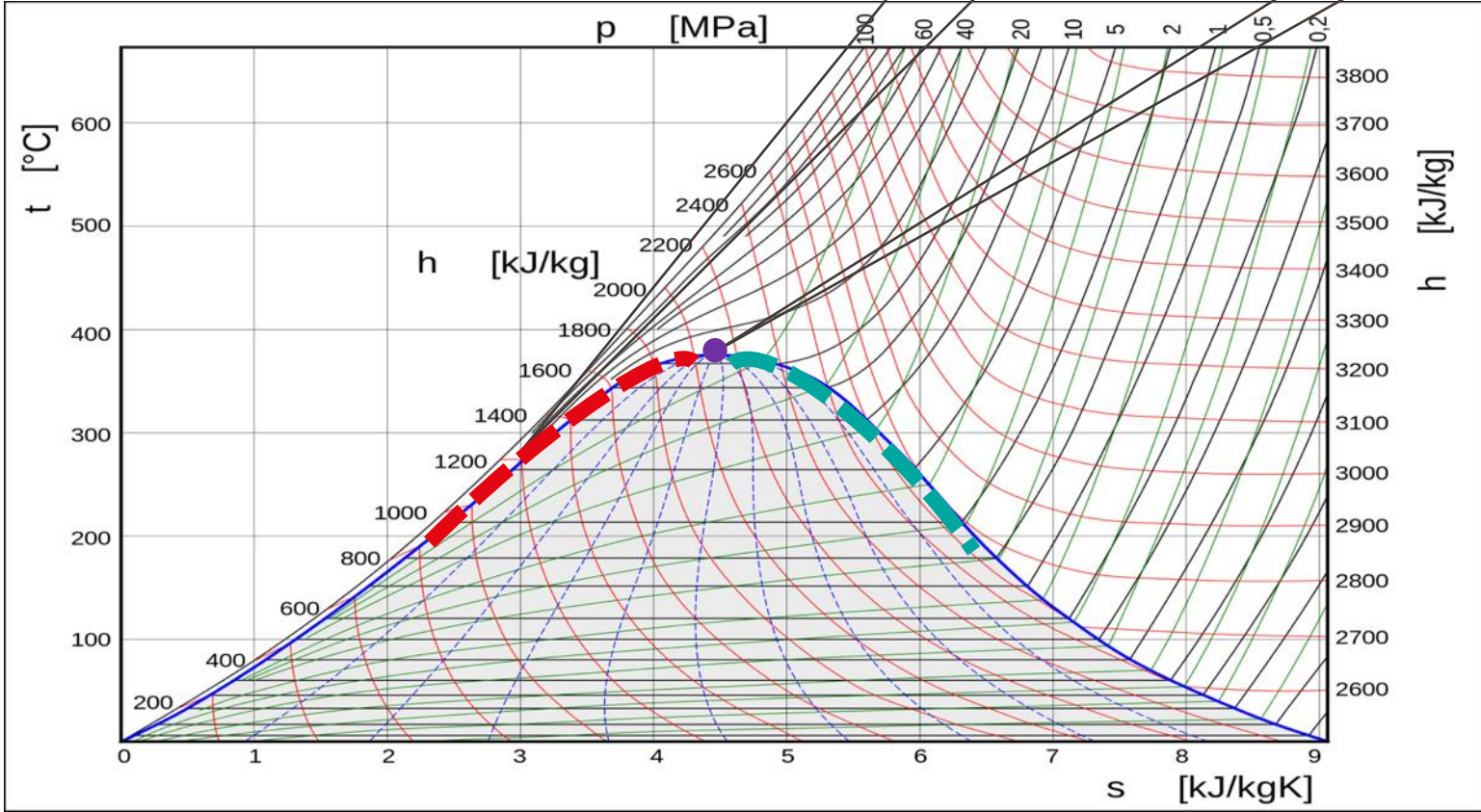


Thermodynamic diagrams

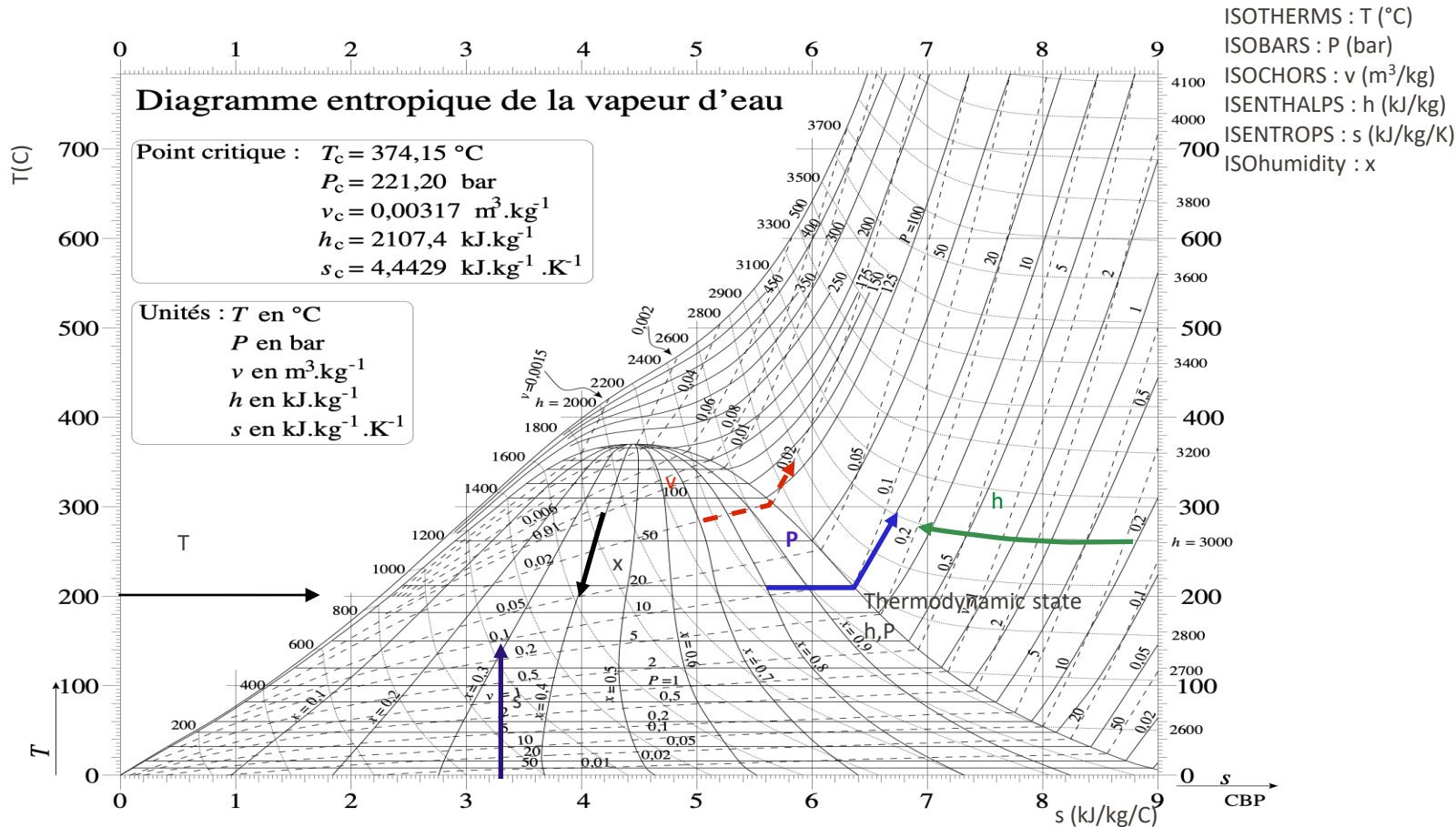
- T-s diagram

SATURATED LIQUID

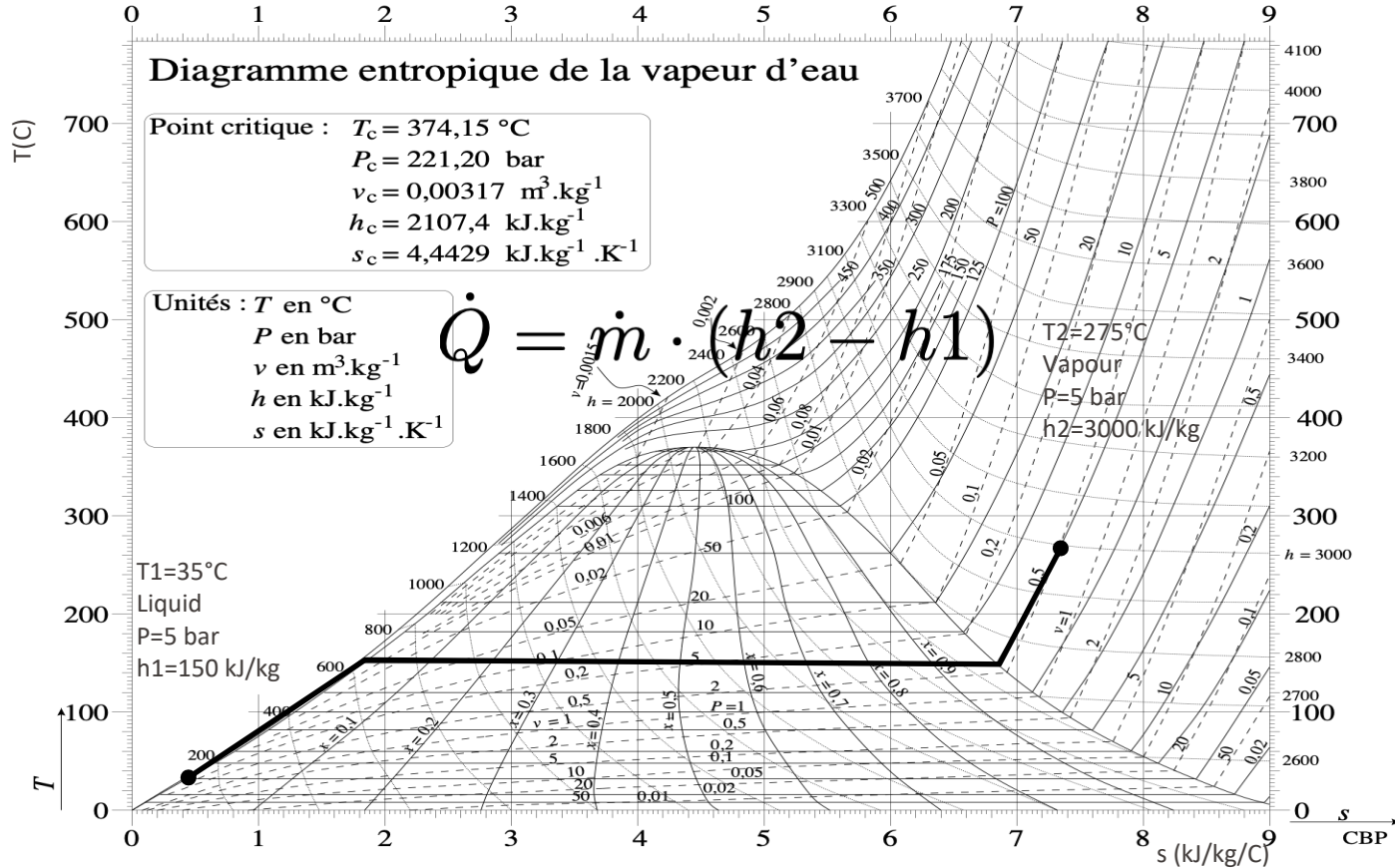
CRITICAL



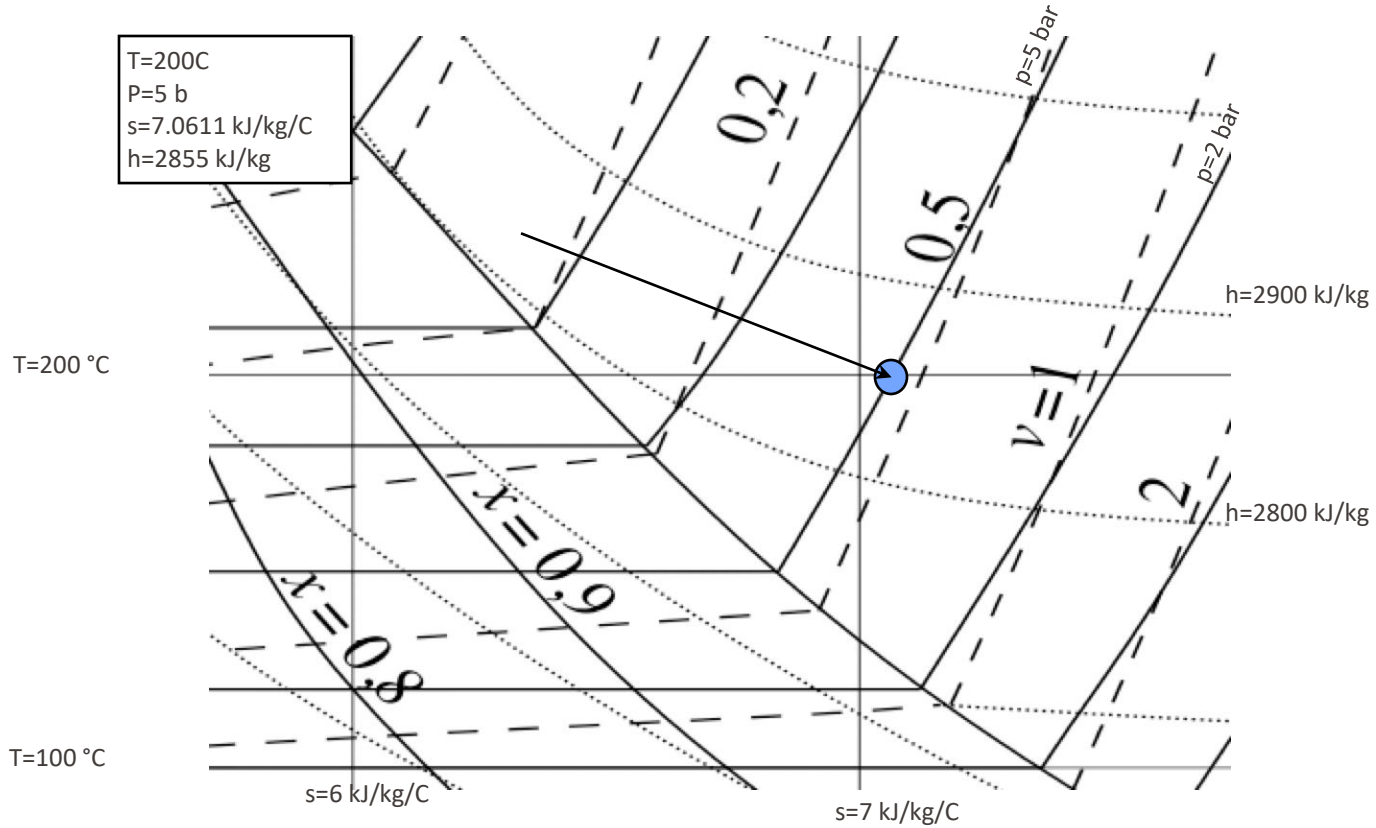
Thermodynamic properties of steam



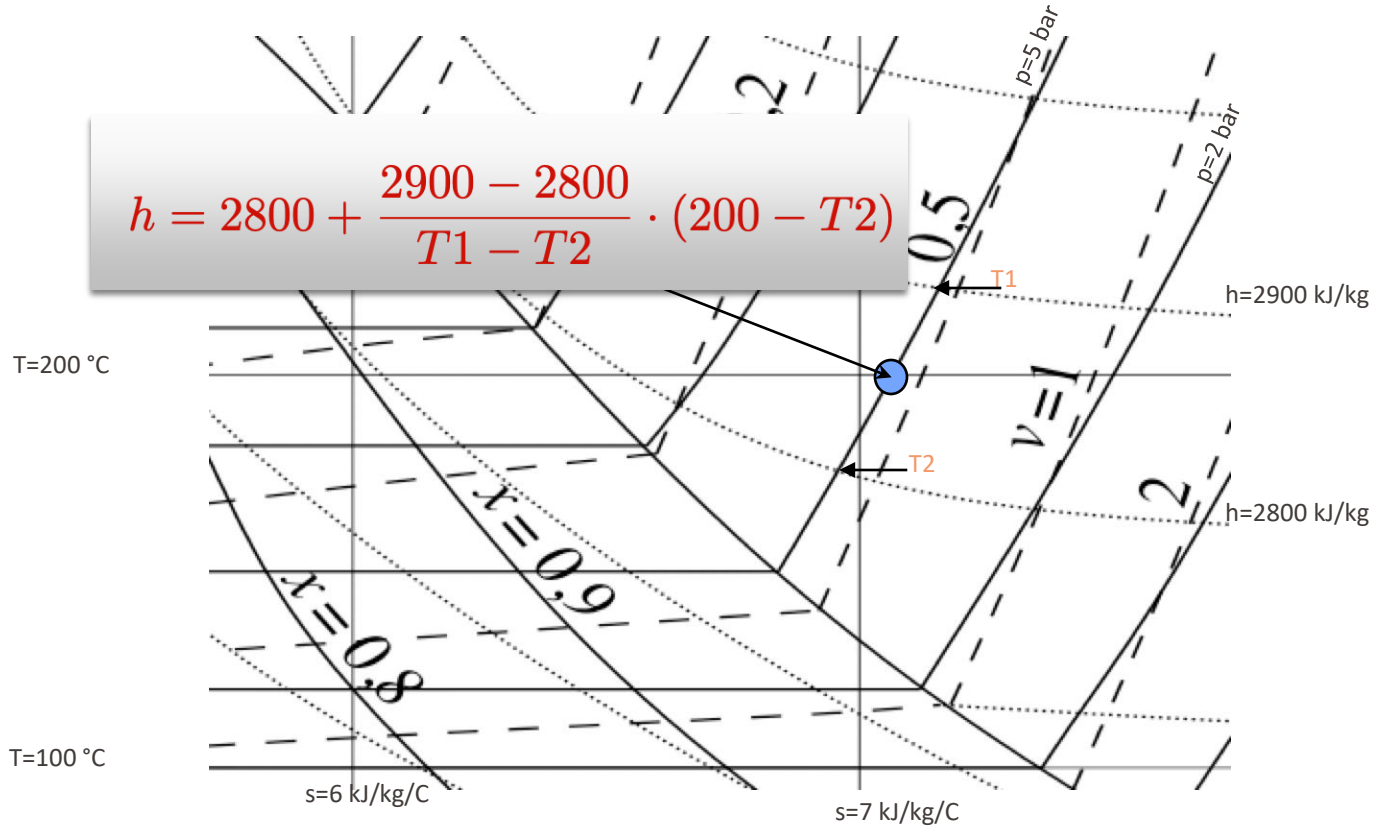
Conversion from liquid to gas state



Thermodynamic state : interpolation between 2 intersections on the same line



Thermodynamic state : interpolation between 2 intersections on the same line



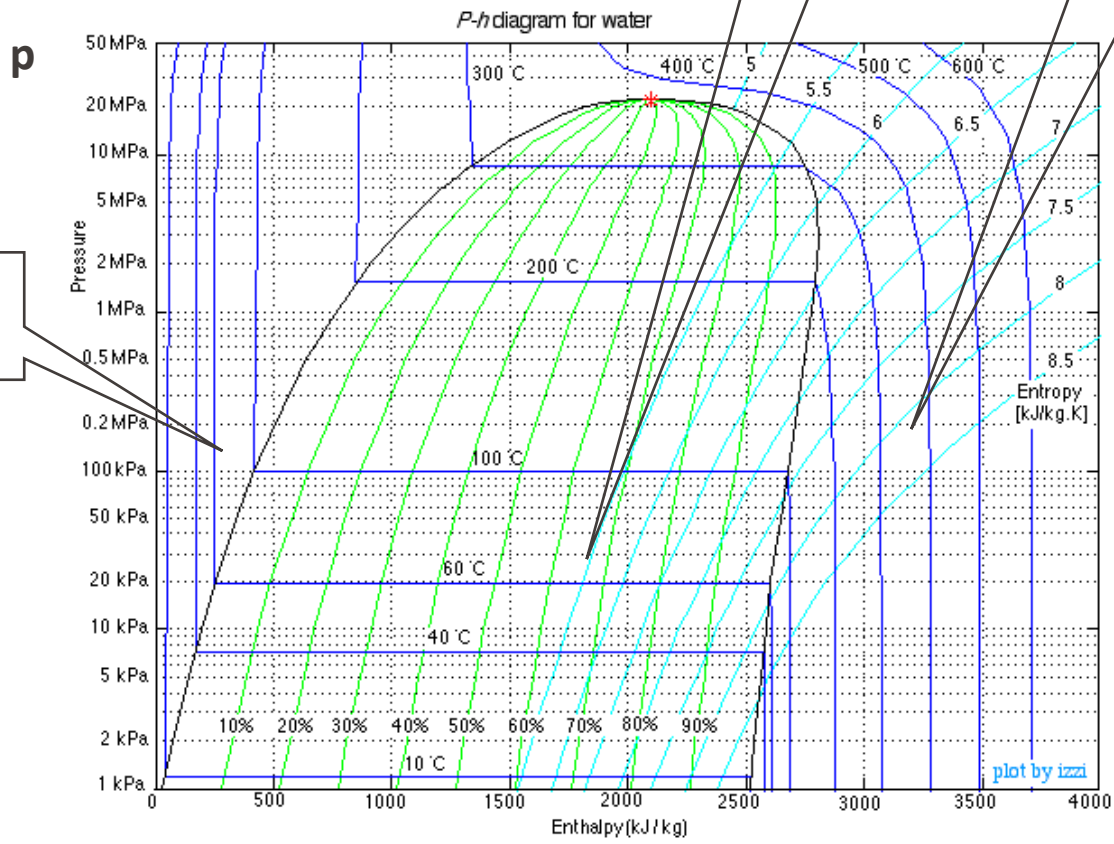
Thermodynamic diagrams

- p-h diagram

LIQUID+
GAS

GAS

LIQUID



h [kJ/kg]

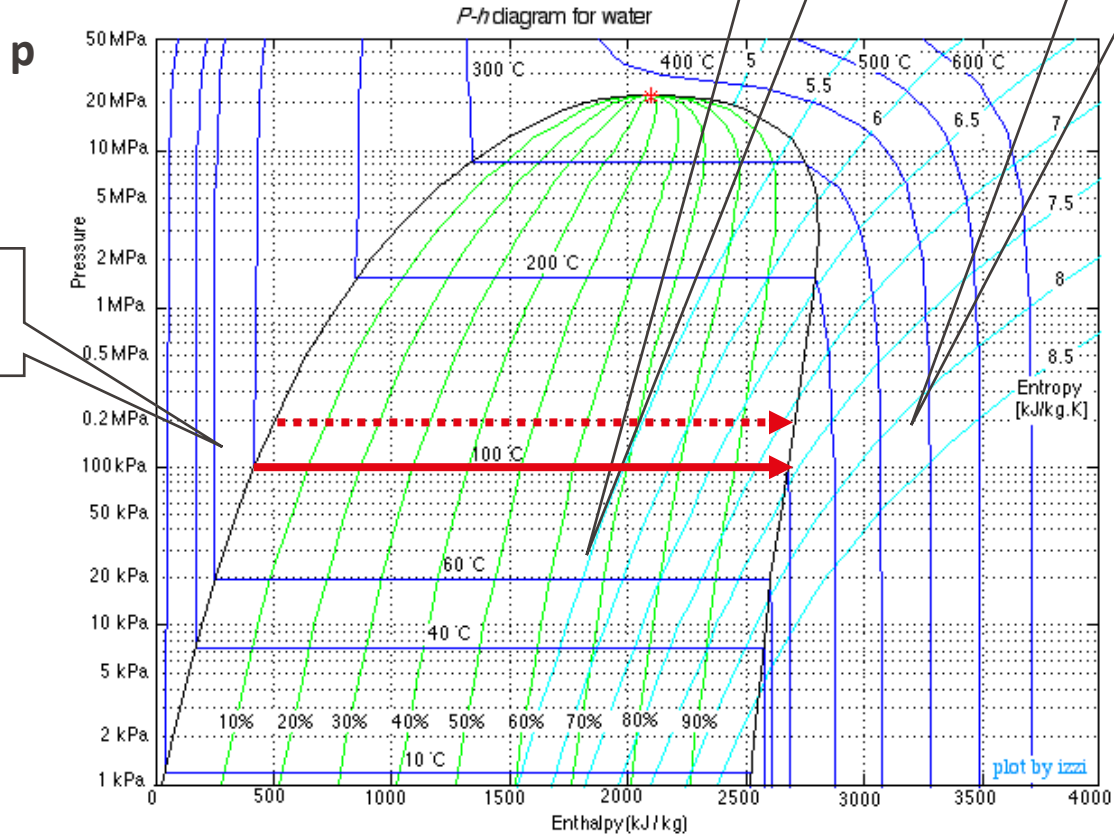
Thermodynamic diagrams

- Pressure cooker effect

LIQUID+
GAS

GAS

LIQUID



h [kJ/kg]



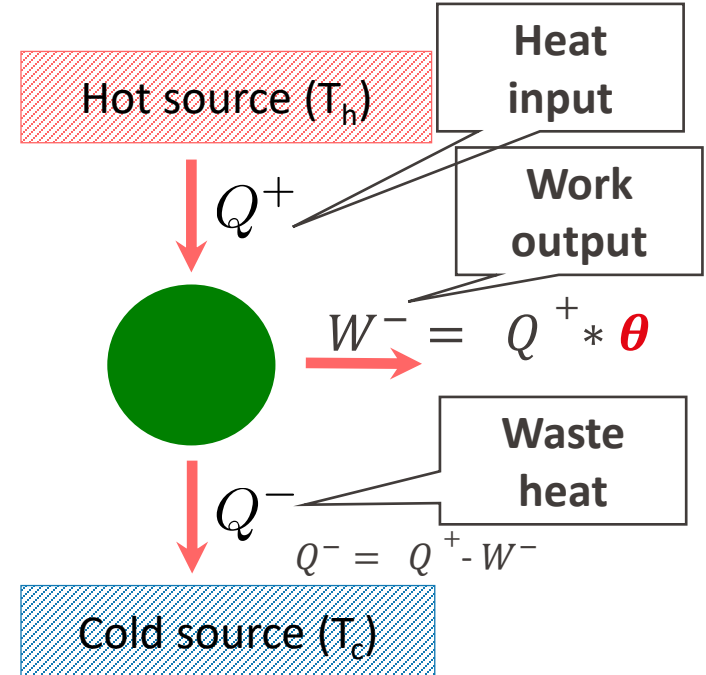
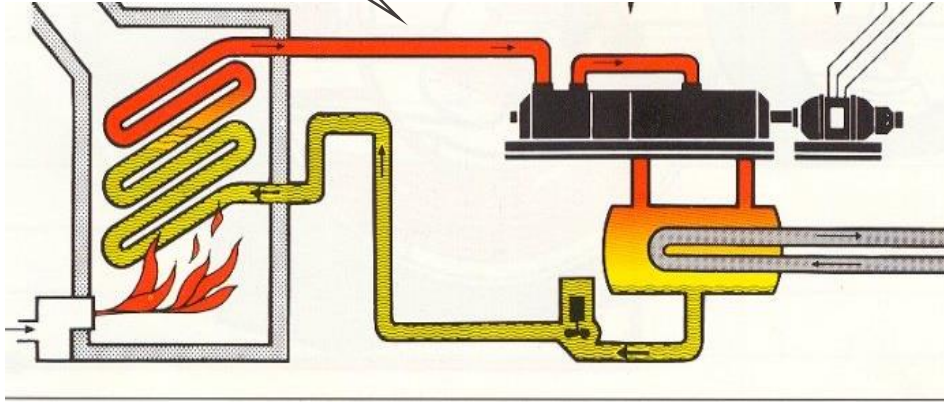
Carnot cycle – the ideal case?

Carnot cycle

- The only limit is Carnot

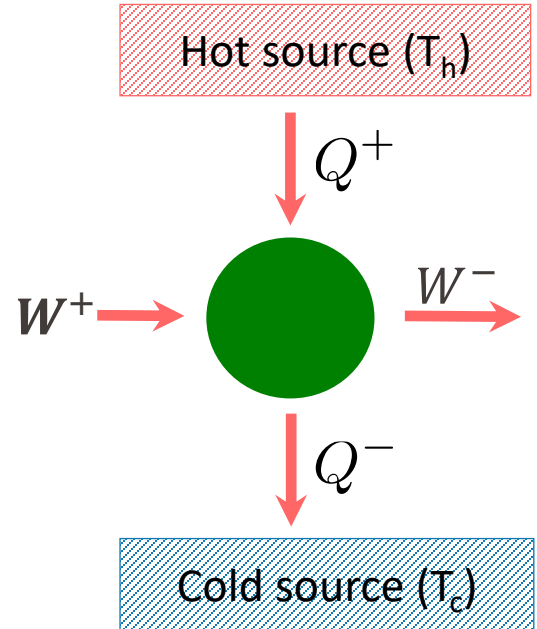
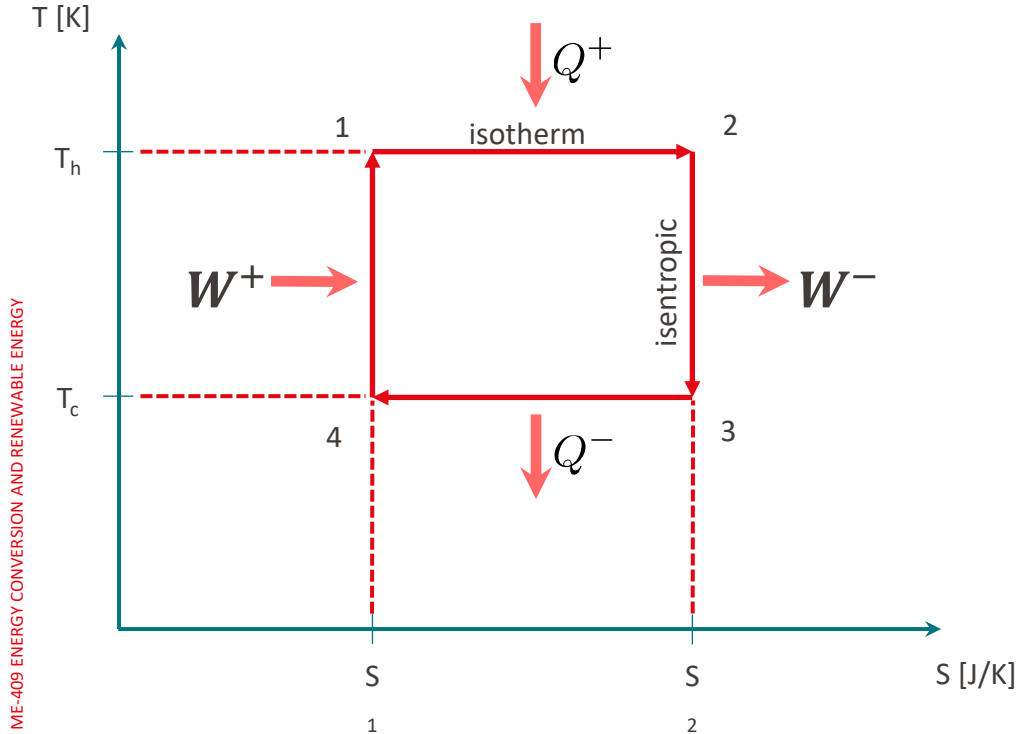
$$\theta = 1 - \frac{T_c}{T_h}$$

Temperatures in K



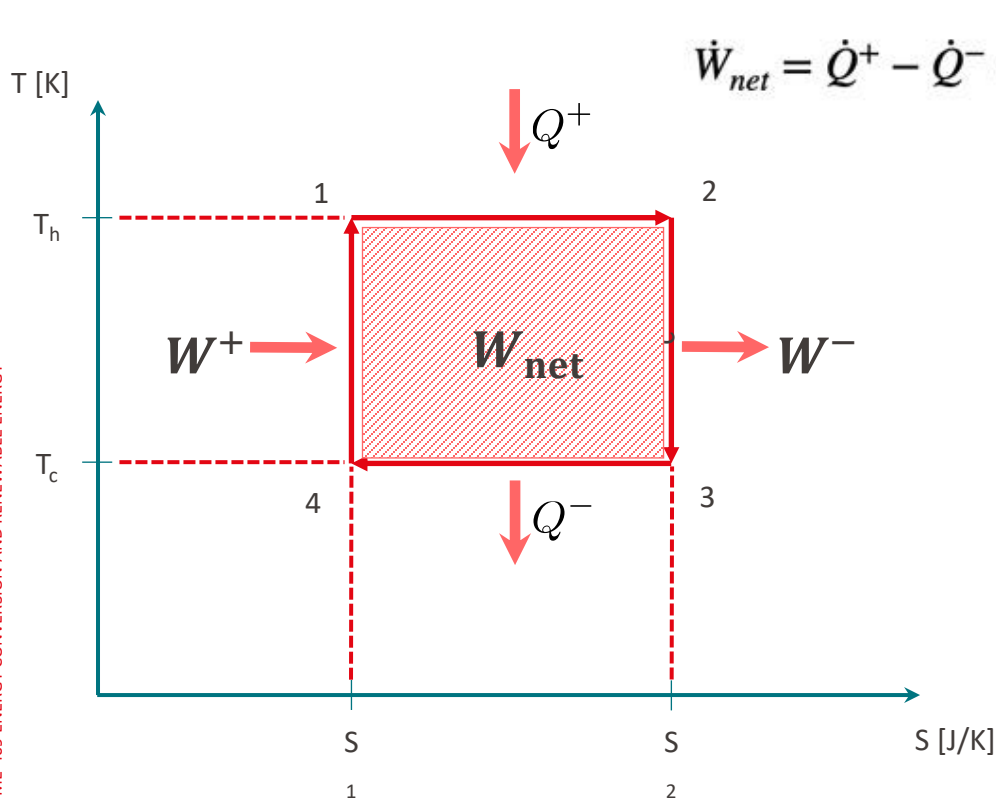
Carnot cycle

- Thermodynamic diagram

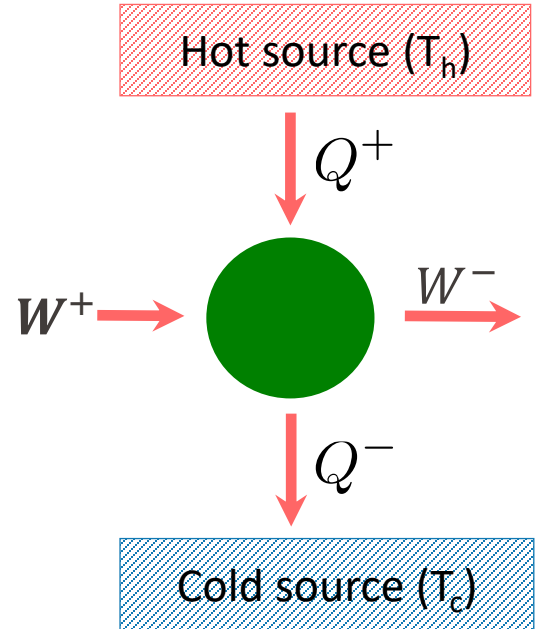


Carnot cycle

- Thermodynamic diagram

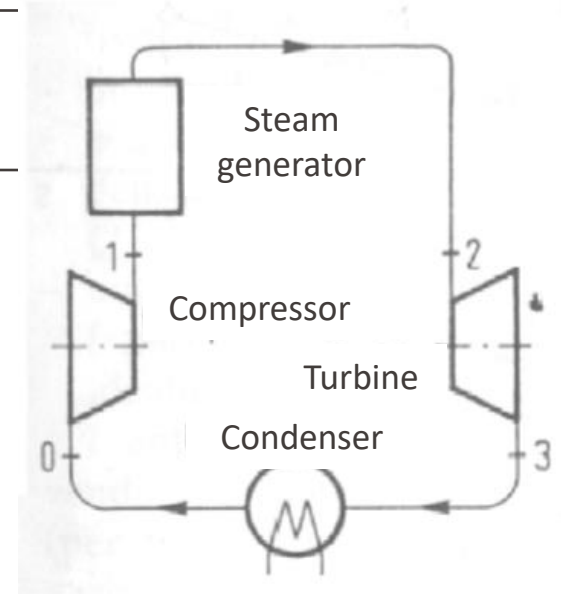
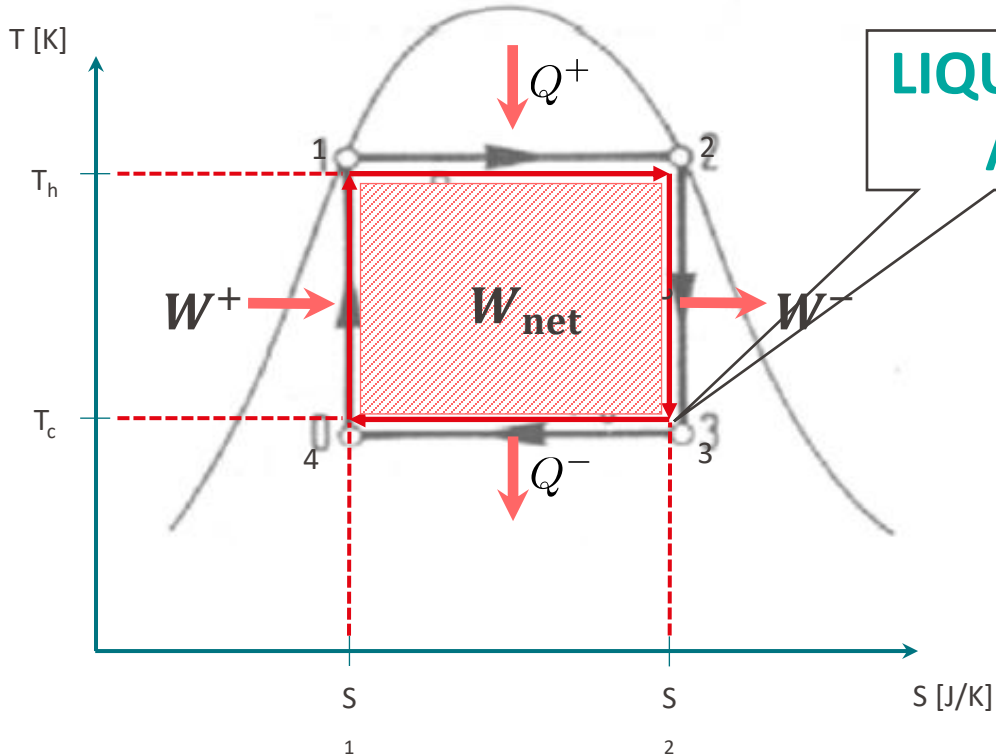


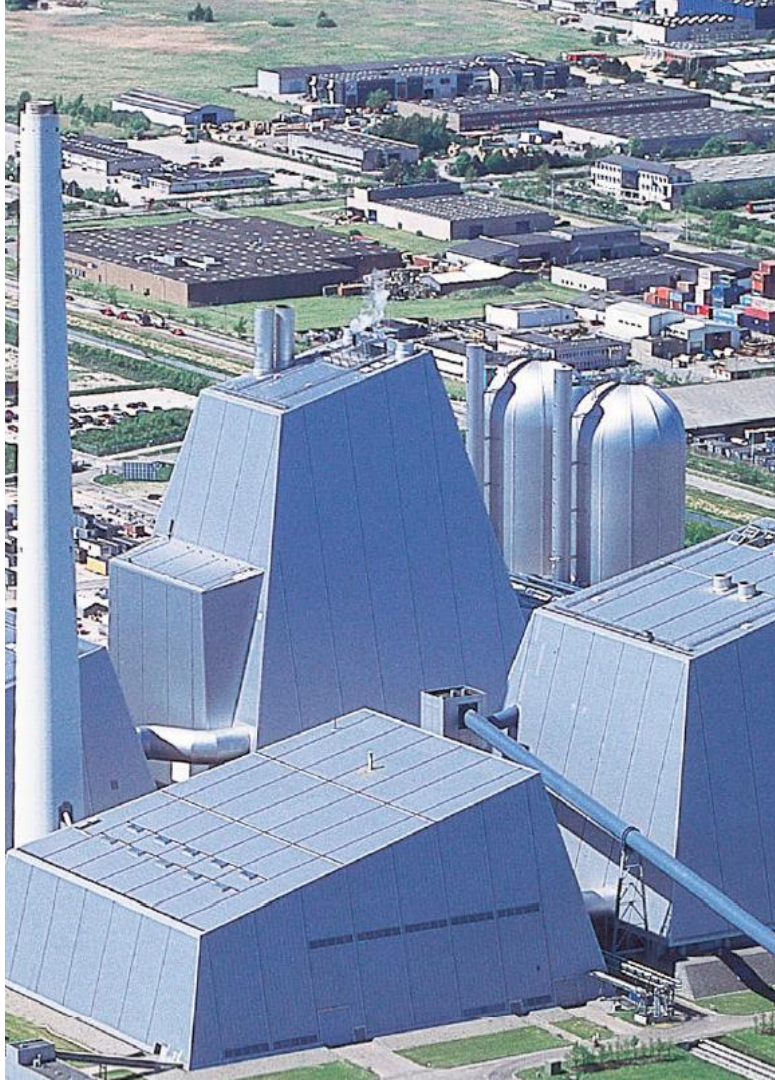
$$\dot{W}_{net} = \dot{Q}^+ - \dot{Q}^- = \int_1^2 T dS - \int_3^4 T dS = T_h \cdot \Delta S_1^2 - T_c \Delta S_4^3$$



Carnot cycle

- Applied to water

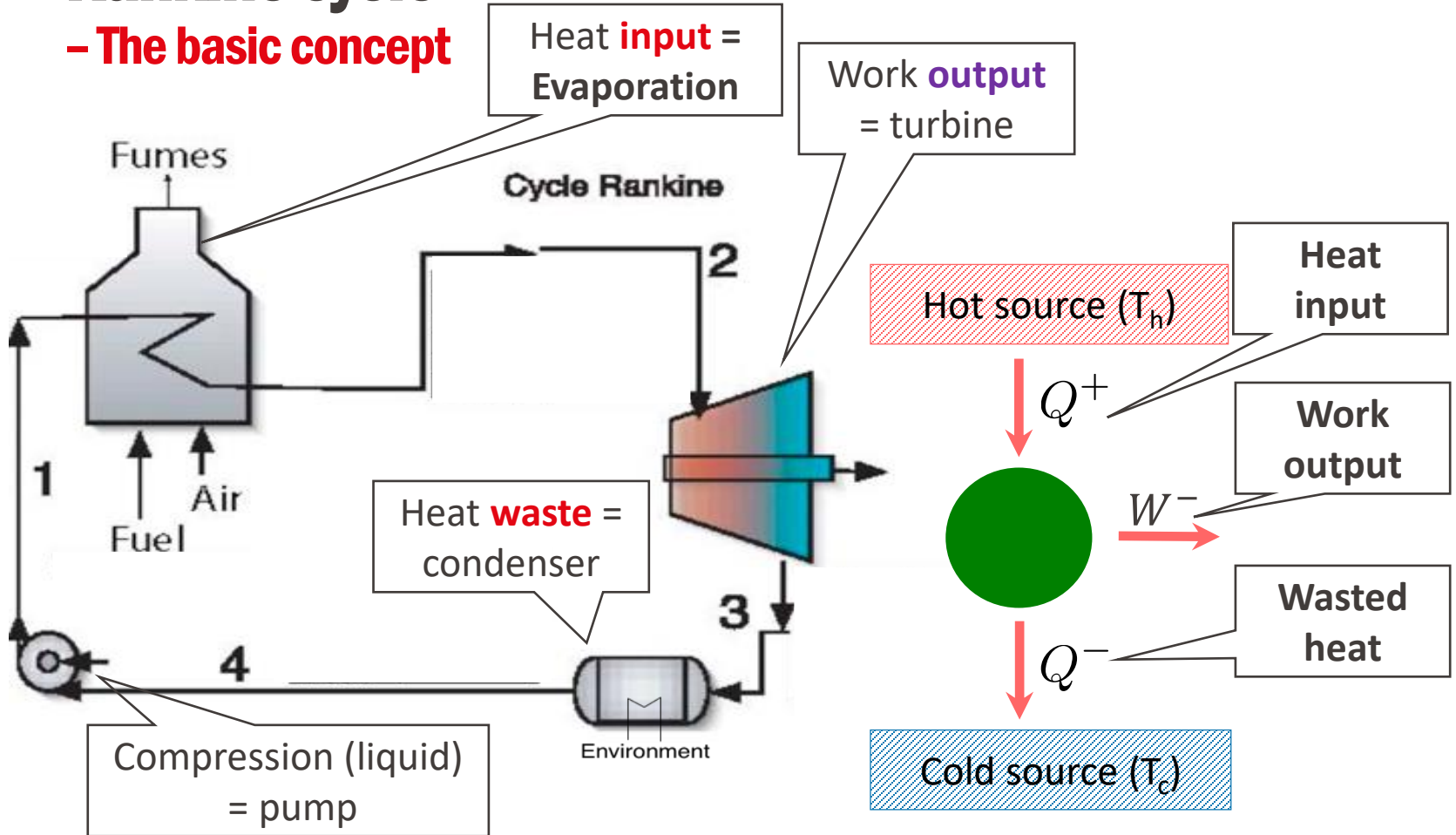




Rankine cycle – the basic concept

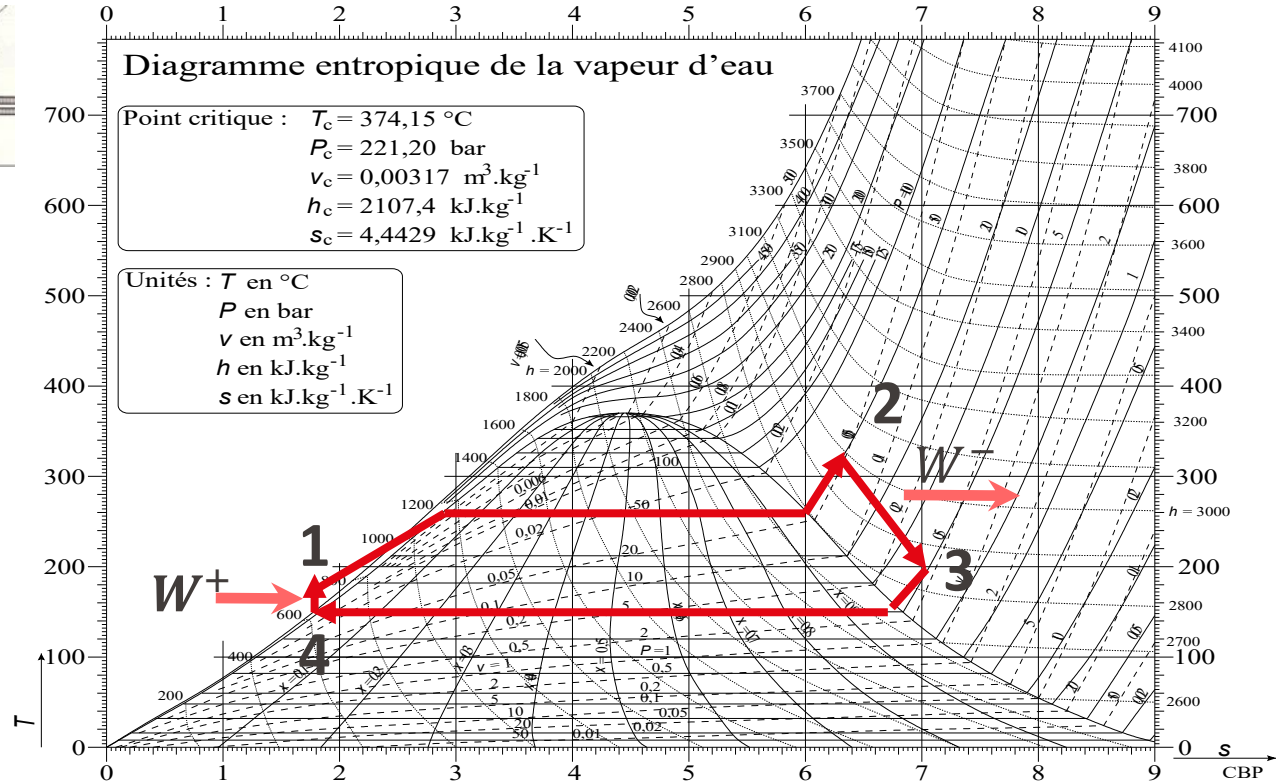
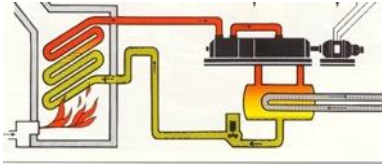
Rankine cycle

- The basic concept



Rankine cycle

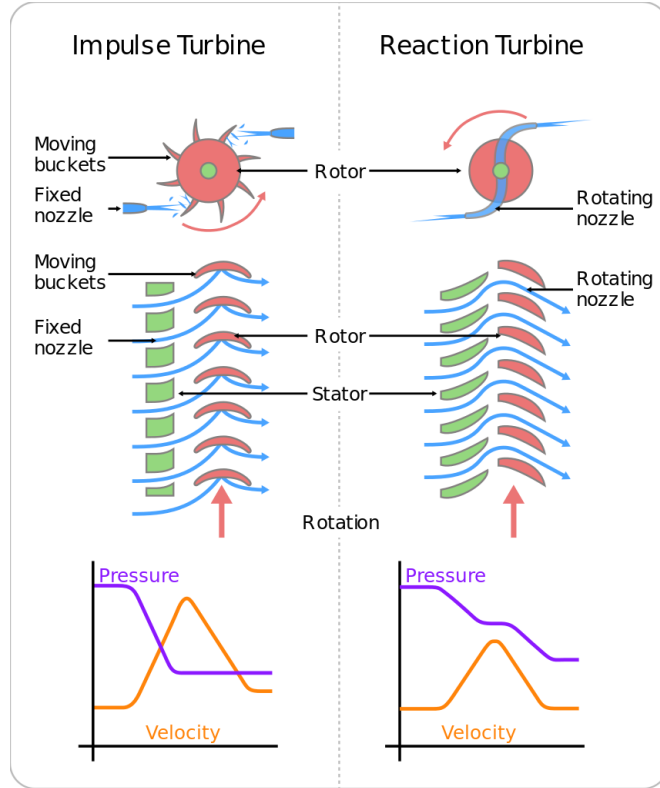
- The four steps of a Rankine cycle



Turbine : Transforming pressure into kinetic energy and kinetic energy into work

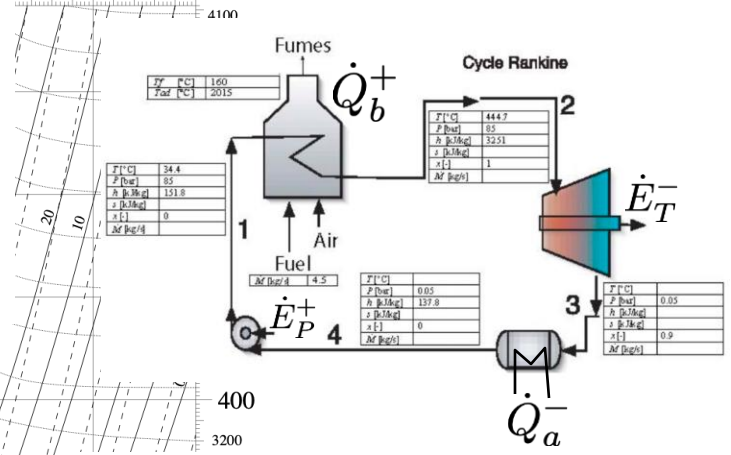
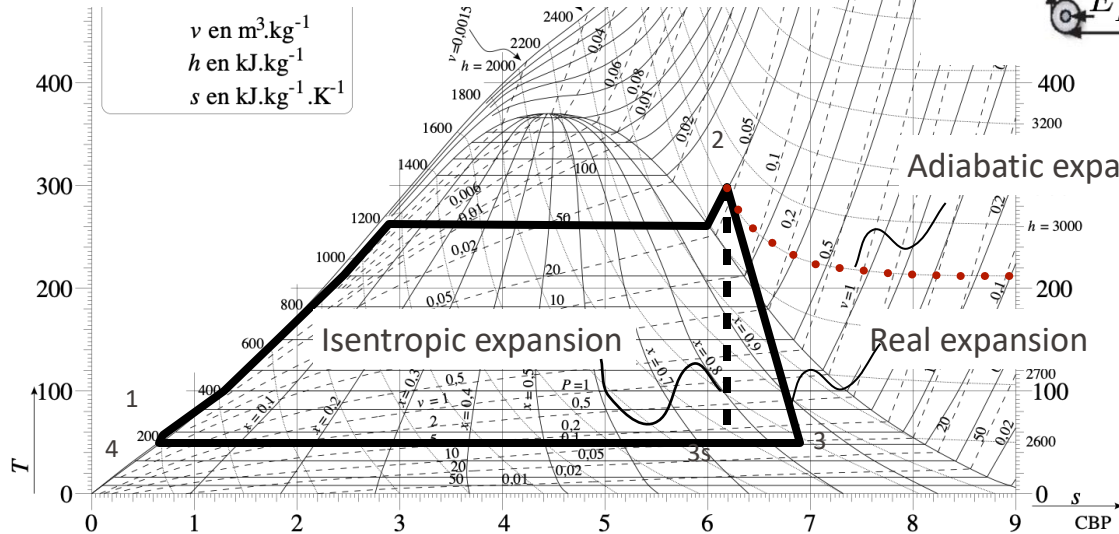


$$\dot{W} = \dot{m}\Delta h = \dot{m}\left(\frac{V_1^2}{2} - \frac{V_2^2}{2}\right)$$



Rankine cycle in the T-S diagram

Isentropic expansion corresponds to the maximum mechanical work that can be produced by the expansion (no loss by friction or leakage)

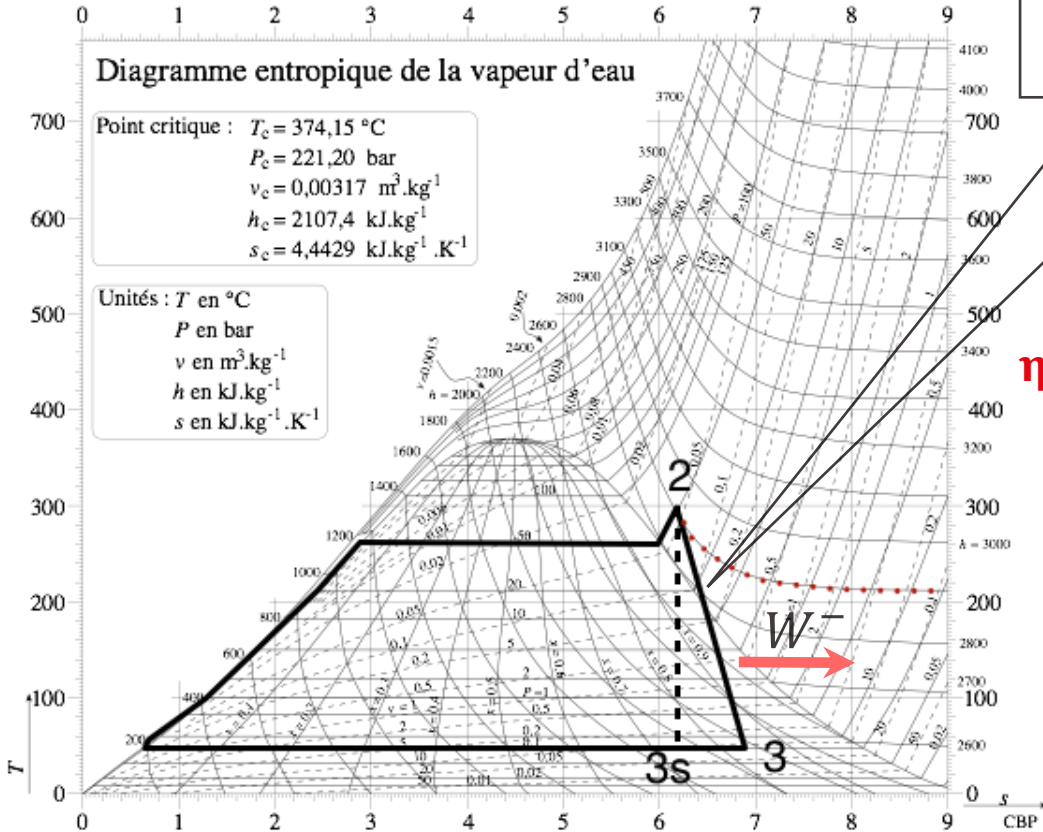


Adiabatic expansion (valve)

Real expansion

Rankine cycle

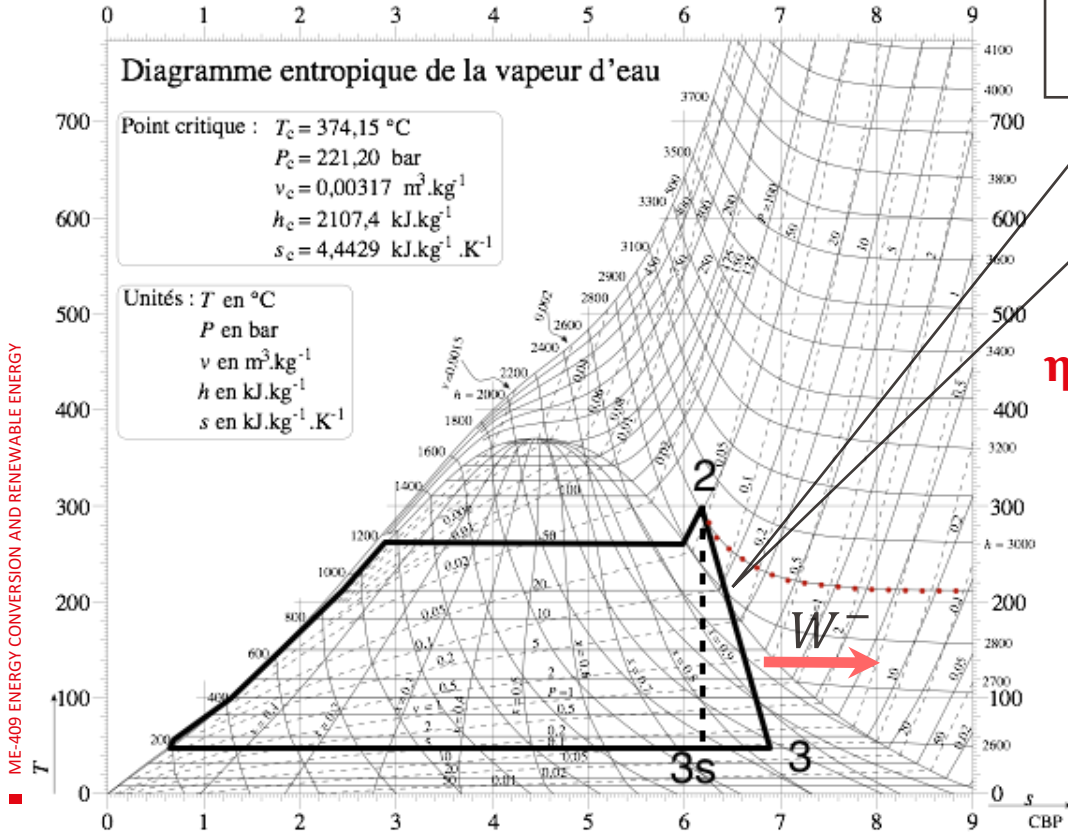
- Turbine efficiency (η_t)



(1) Higher turbine efficiency

$$\eta_t = \frac{\text{what is produced}}{\text{what would ideally be produced}}$$

Rankine cycle



(1) Higher turbine efficiency

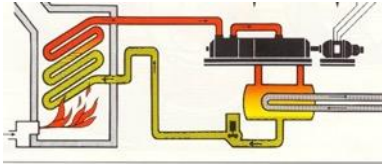
what is produced

$$\eta_t = \frac{\text{what would ideally be produced}}{h_2(T_2, P_2) - h_3(T_3, P_3, x_3)}$$

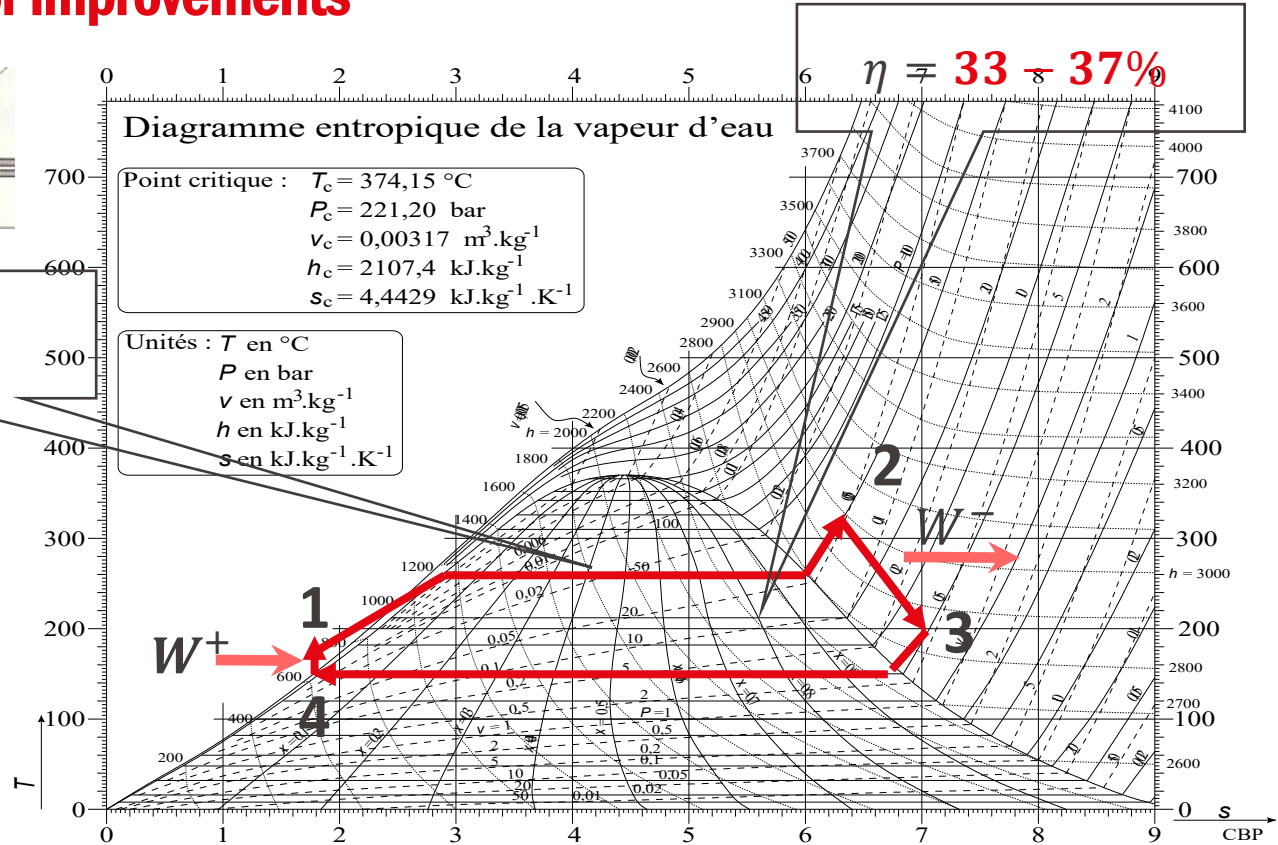
$$h_2(T_2, P_2) - h_{is}(s_2(T_2, P_2), P_3)$$

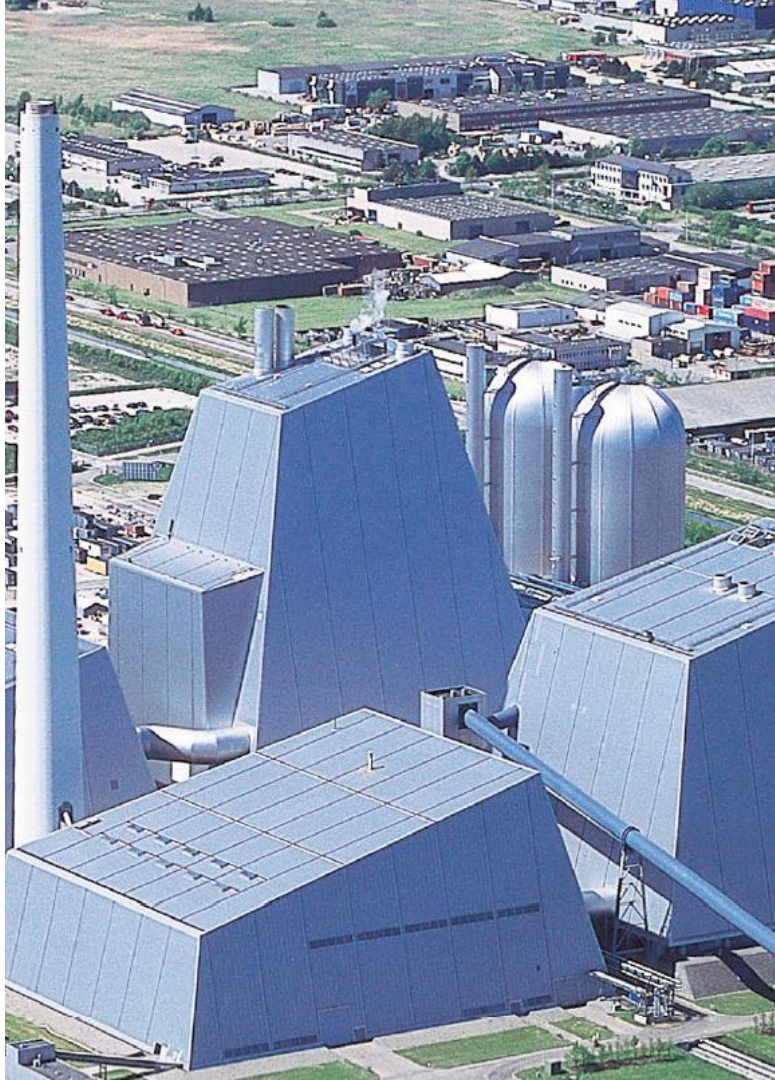
Rankine cycle

- Needs for improvements



$\theta = 52\%$

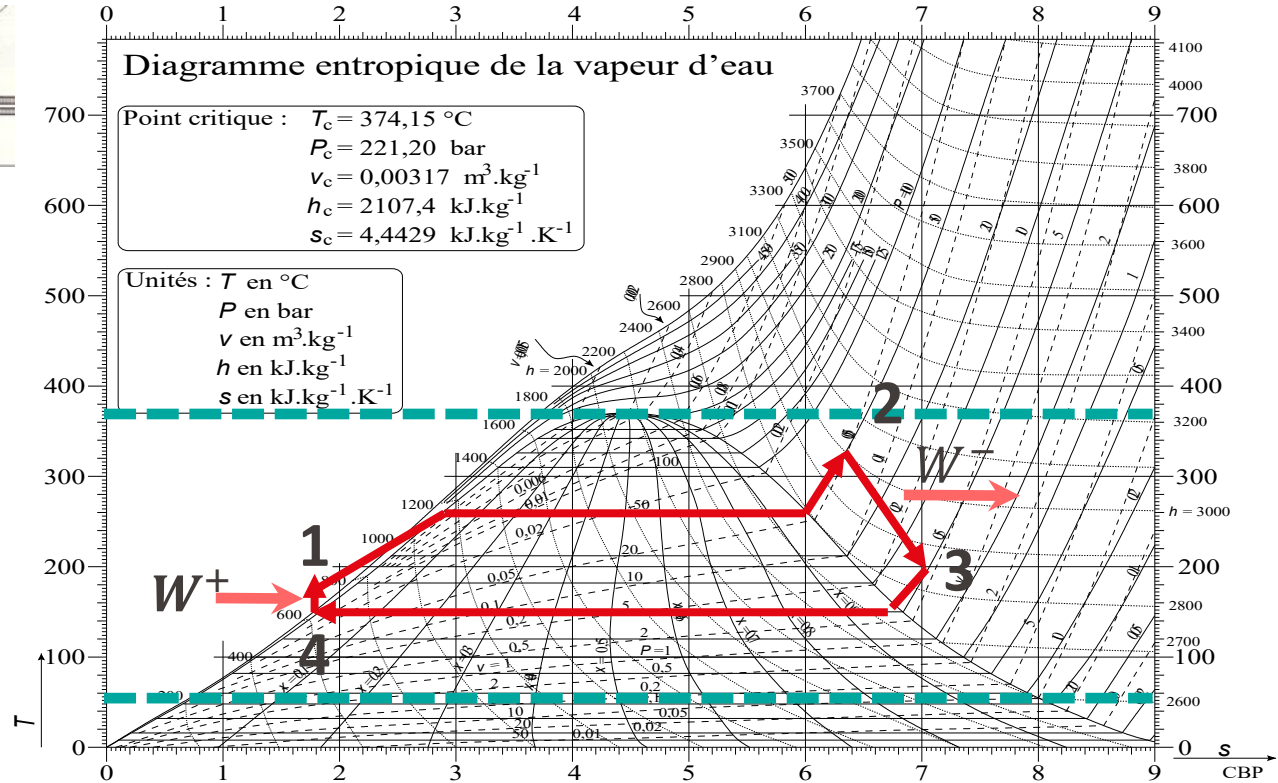
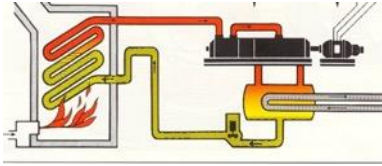




Rankine cycle - Increasing the efficiency

Rankine cycle

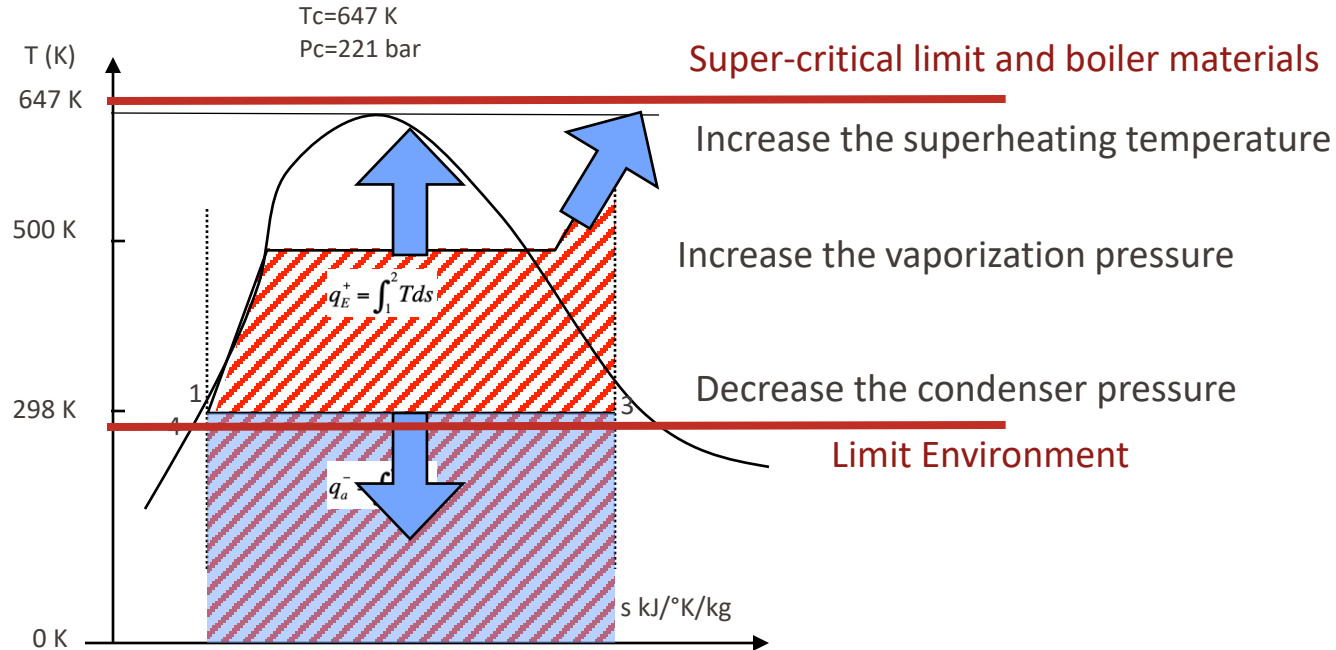
- Limits



Increase the efficiency

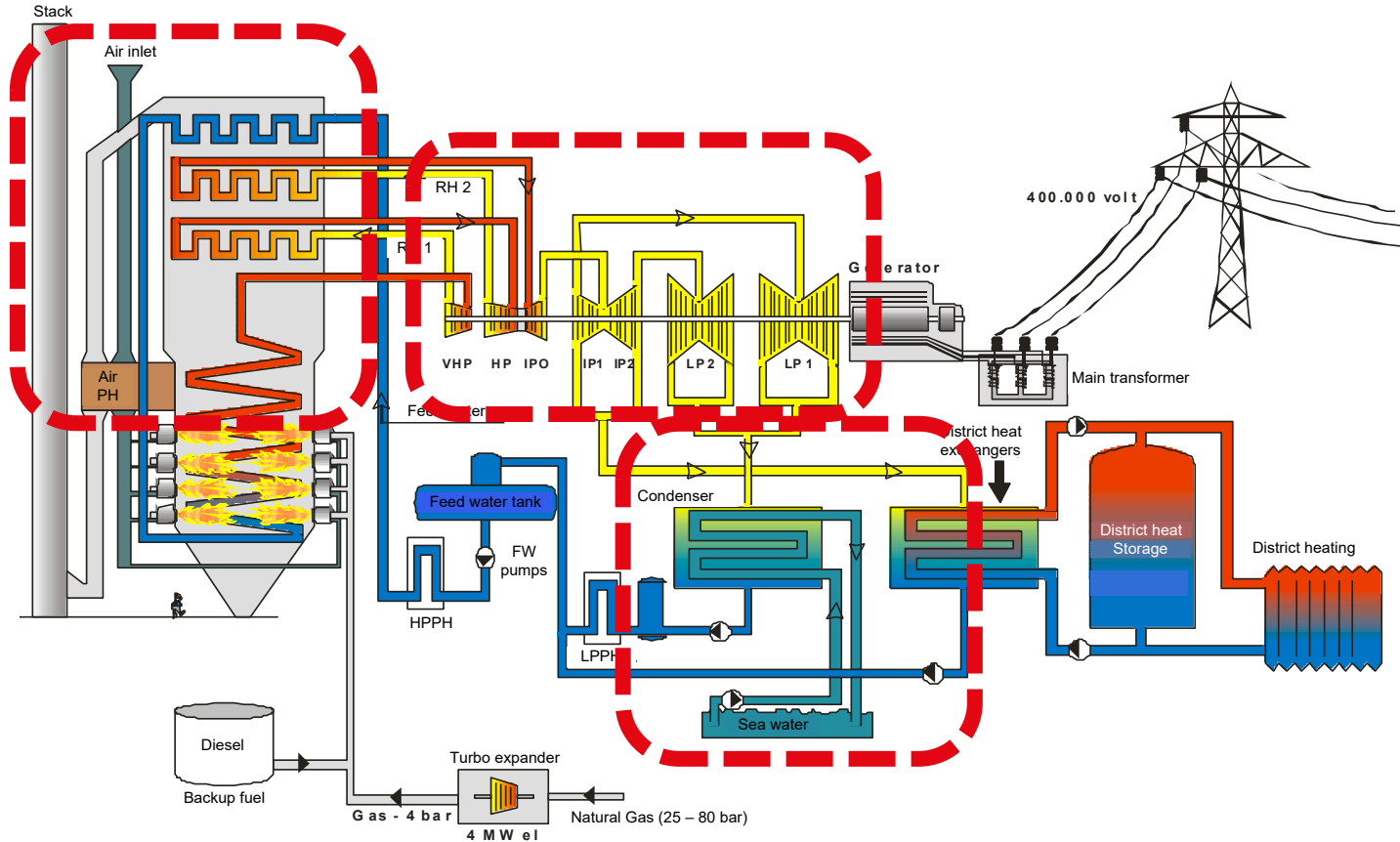
$$e = q_E^+ - q_a^- = \int_1^2 T ds - \int_3^4 T ds$$

Maximise area between the 2 isobars



Rankine cycle

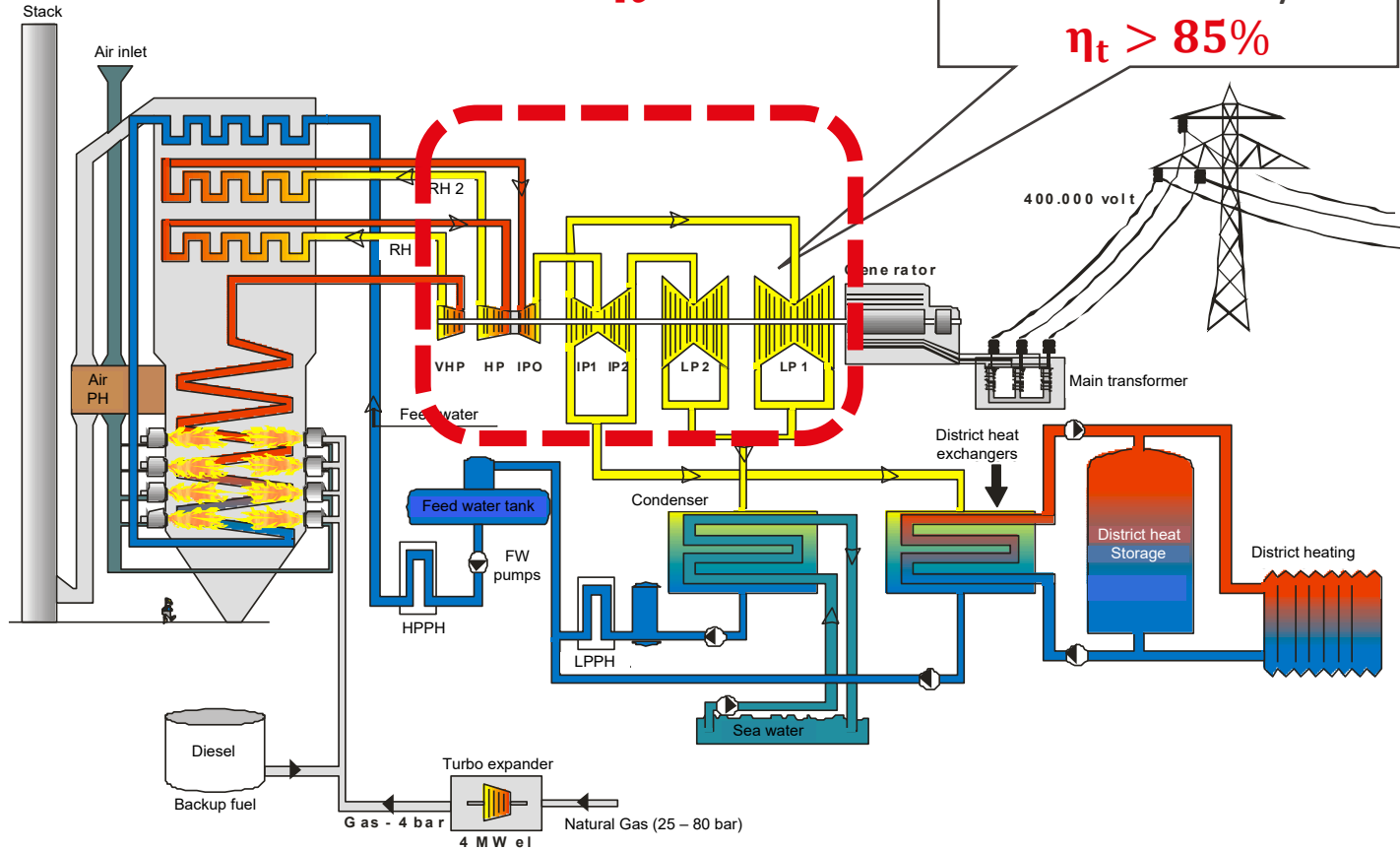
- A state-of-the-art concept



Rankine cycle

- Improvement (1) - Turbine (η_t)

(1) Higher turbine efficiency
 $\eta_t > 85\%$

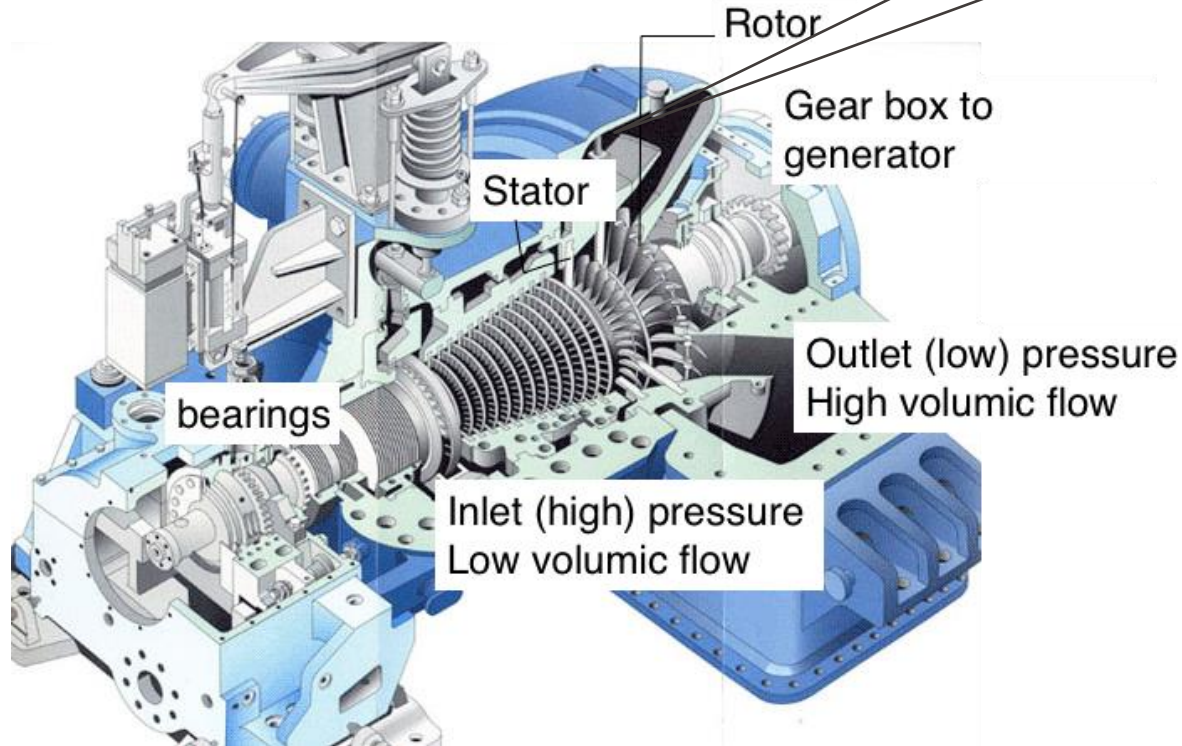


Rankine cycle

- Improvement (1) - Turbine (η_t)

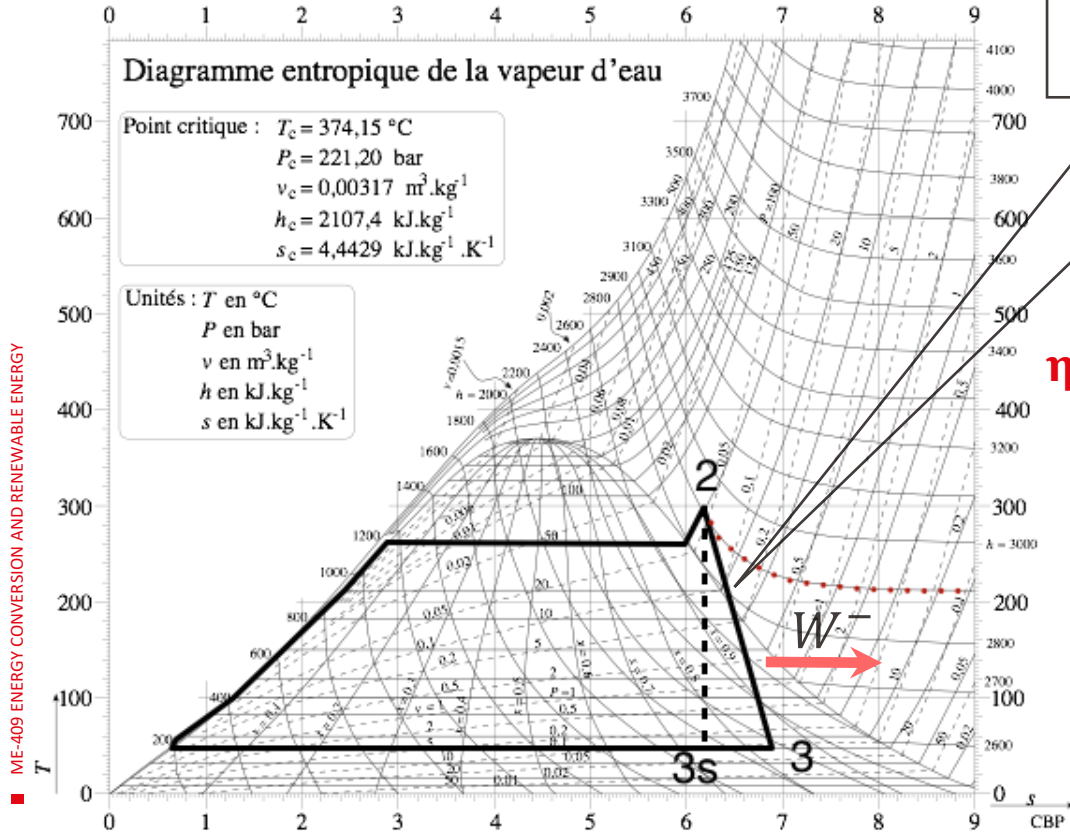
(1) Higher turbine efficiency

$$\eta_t > 85\%$$



Rankine cycle

- Improvement (1) - Turbine (η_t)

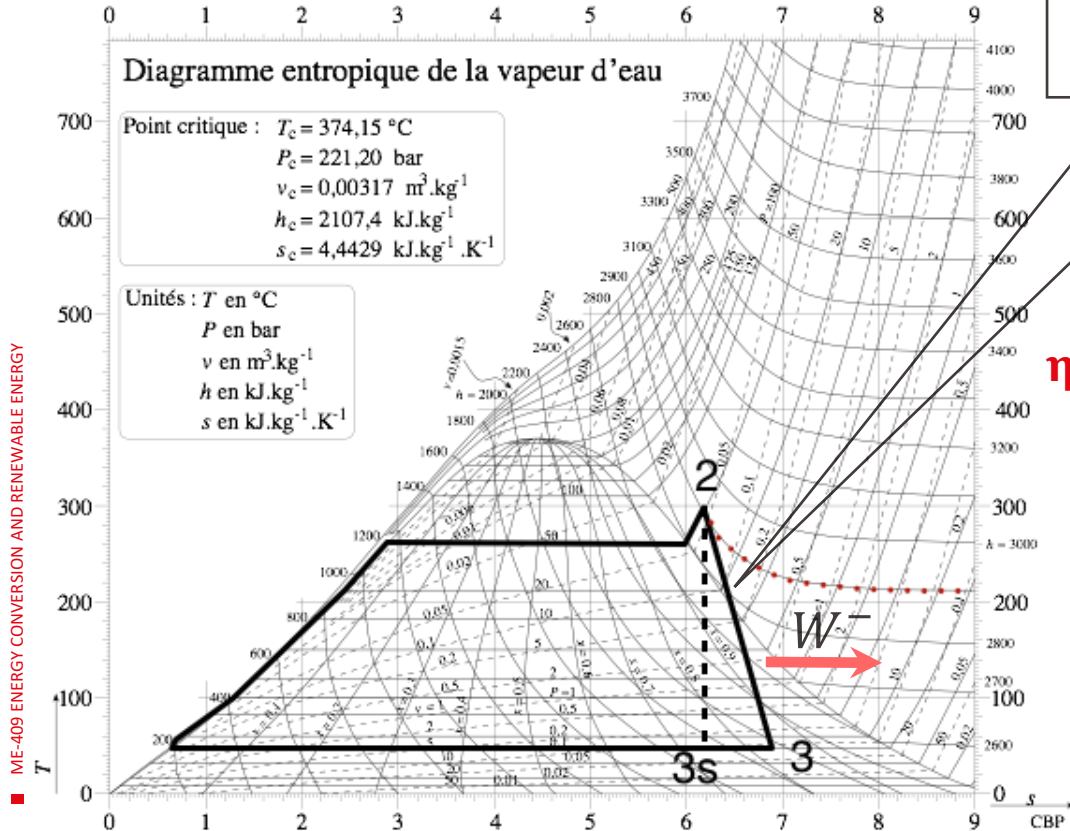


(1) Higher turbine efficiency

$$\eta_t = \frac{\text{what is produced}}{\text{what would ideally be produced}}$$

Rankine cycle

- Improvement (1) - Turbine (η_t)



(1) Higher turbine efficiency

what is produced

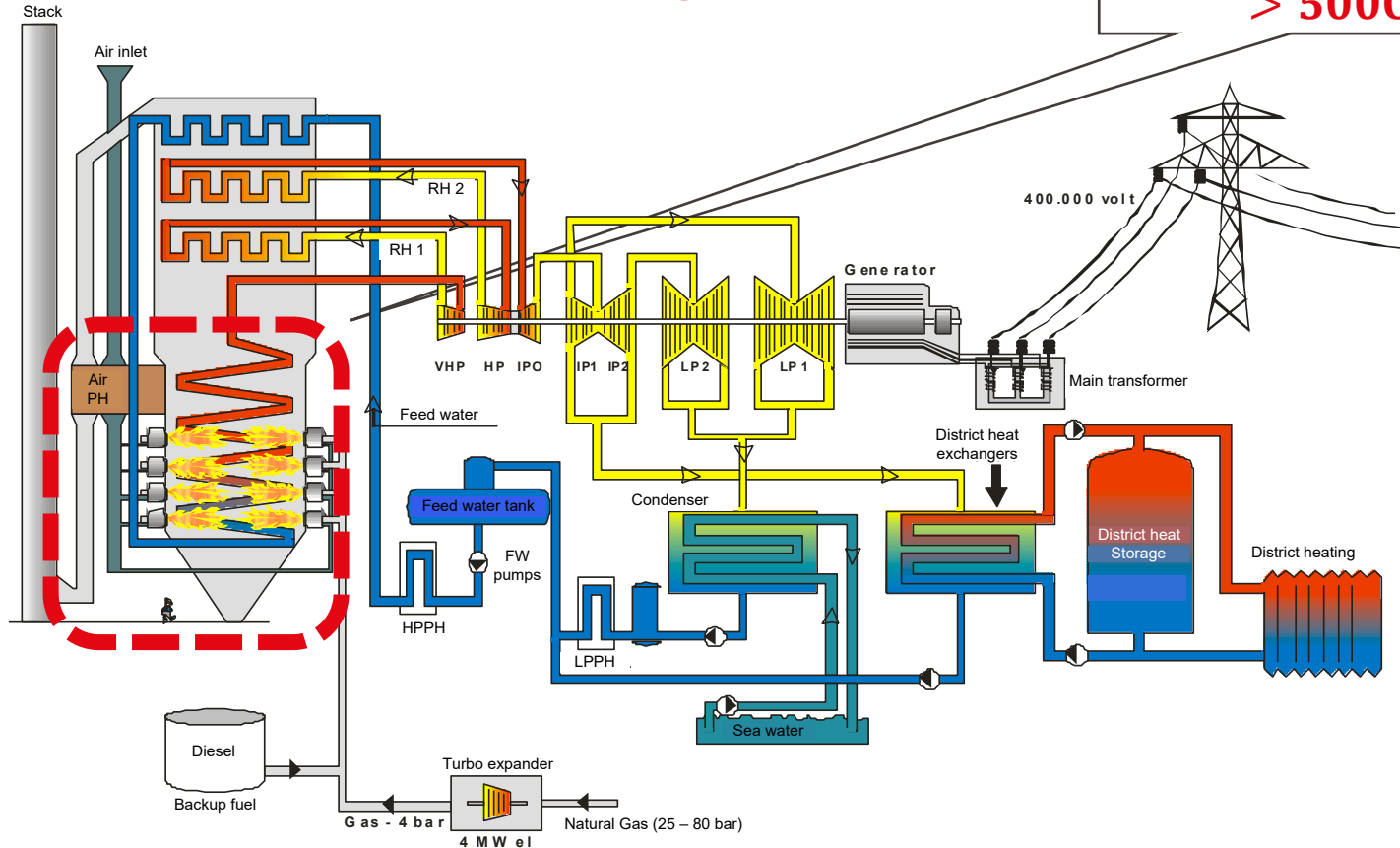
$$\eta_t = \frac{\text{what is produced}}{\text{what would ideally be produced}}$$

$$\eta_t = \frac{h_2(T_2, P_2) - h_3(T_3, P_3, x_3)}{h_2(T_2, P_2) - h_{is}(s_2(T_2, P_2), P_3)}$$

Rankine cycle

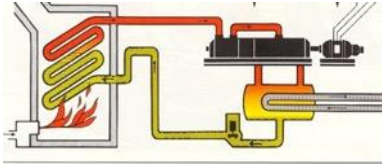
- Improvement (2) - Superheating

(2) Higher boiler temperatures
> 500C

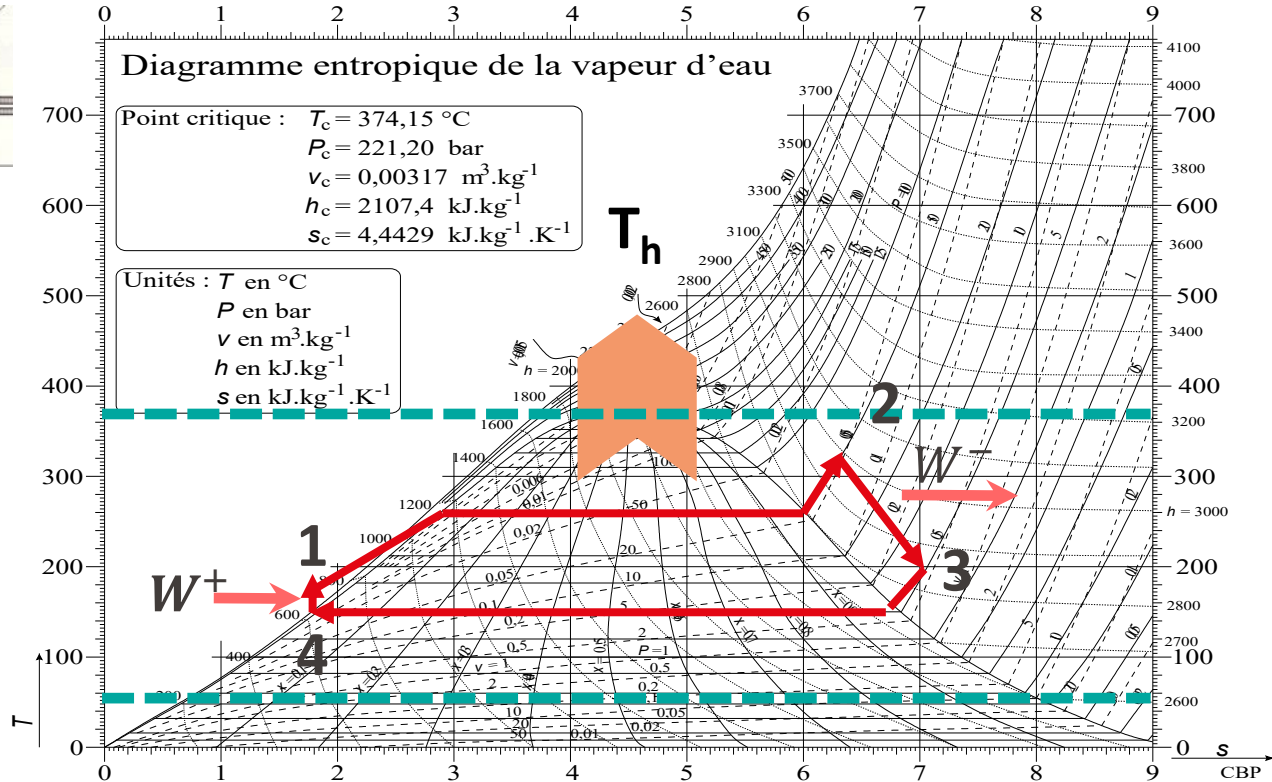


Rankine cycle

- Improvement (2) - Superheating



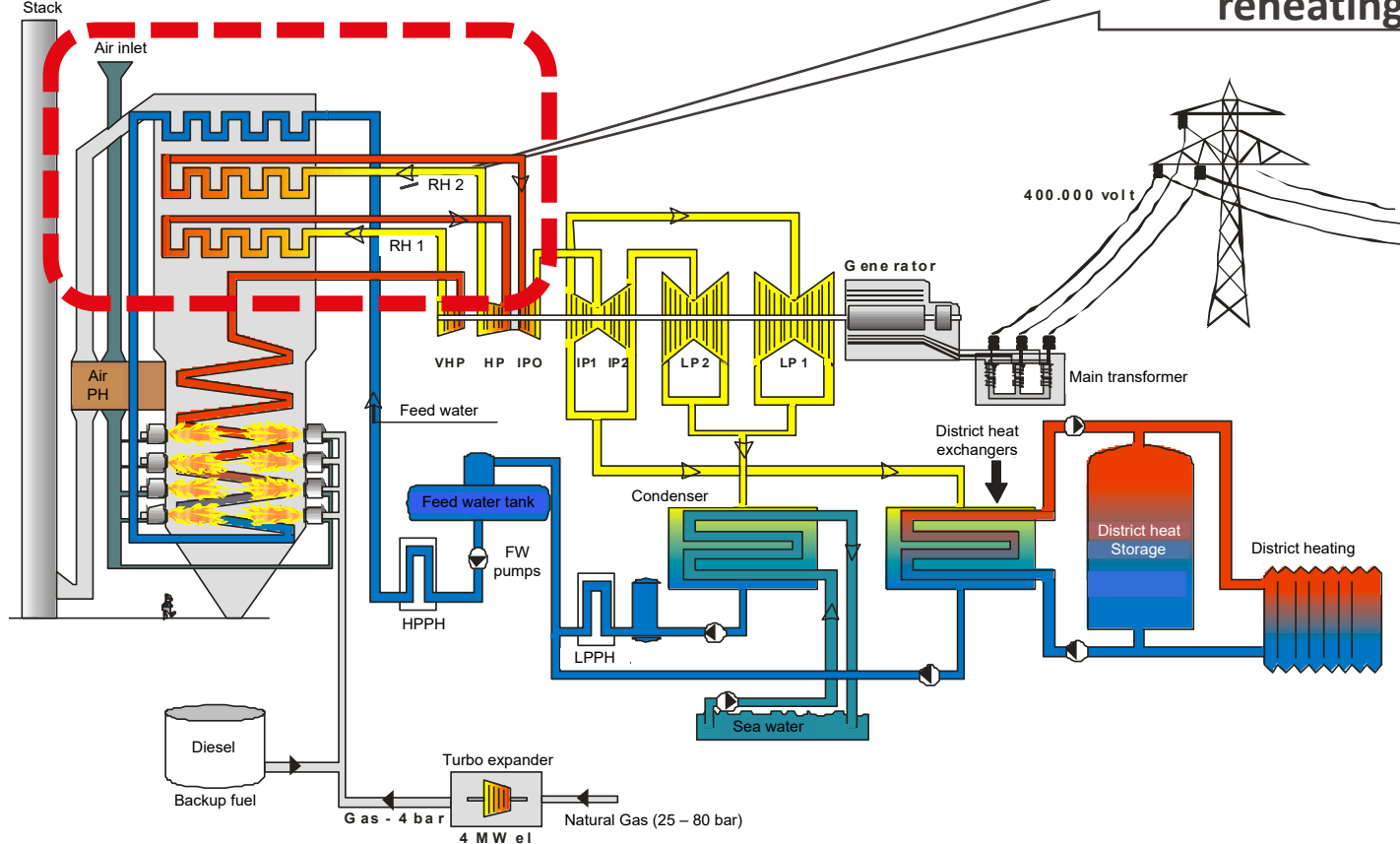
$$\theta = 1 - \frac{T_c}{T_h}$$



Rankine cycle

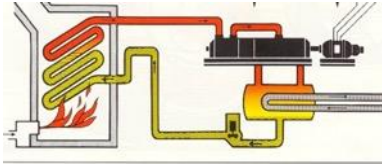
- Improvement (3) - Reheating

(3) Double reheating

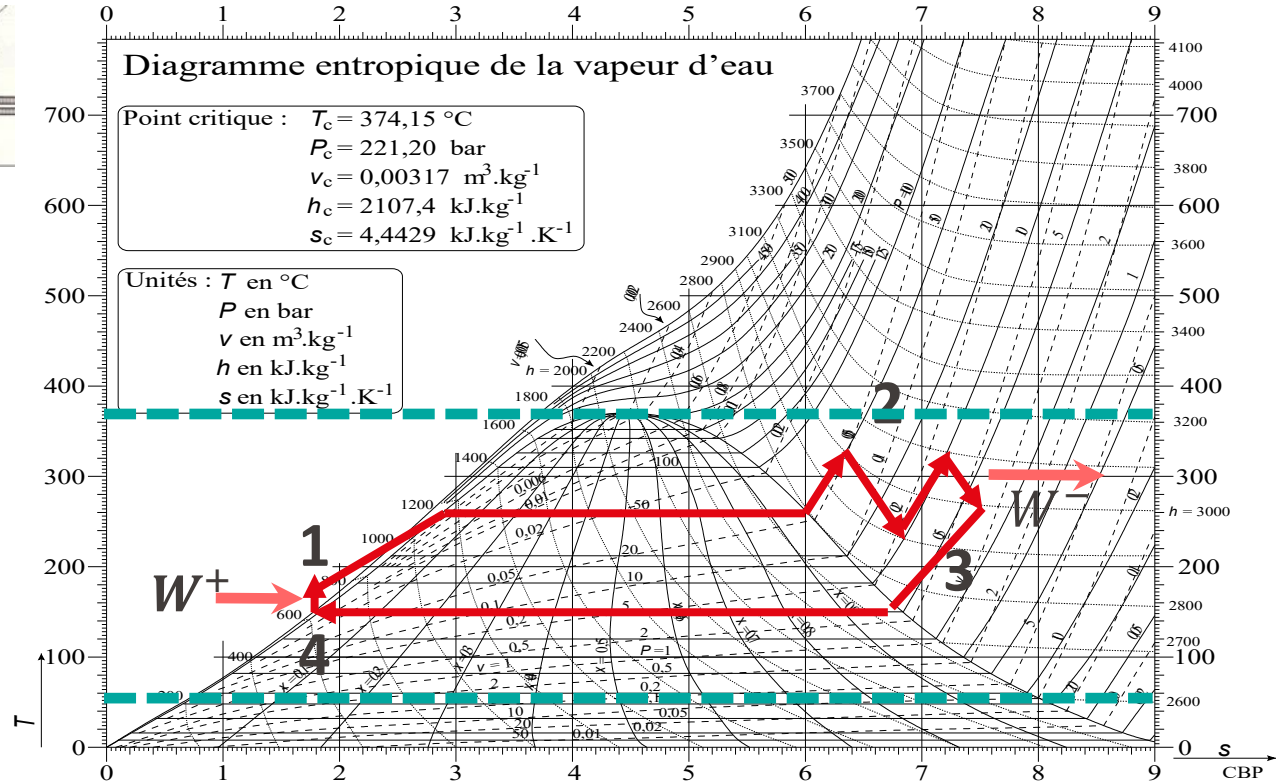


Rankine cycle

- Improvement (3) - Reheating



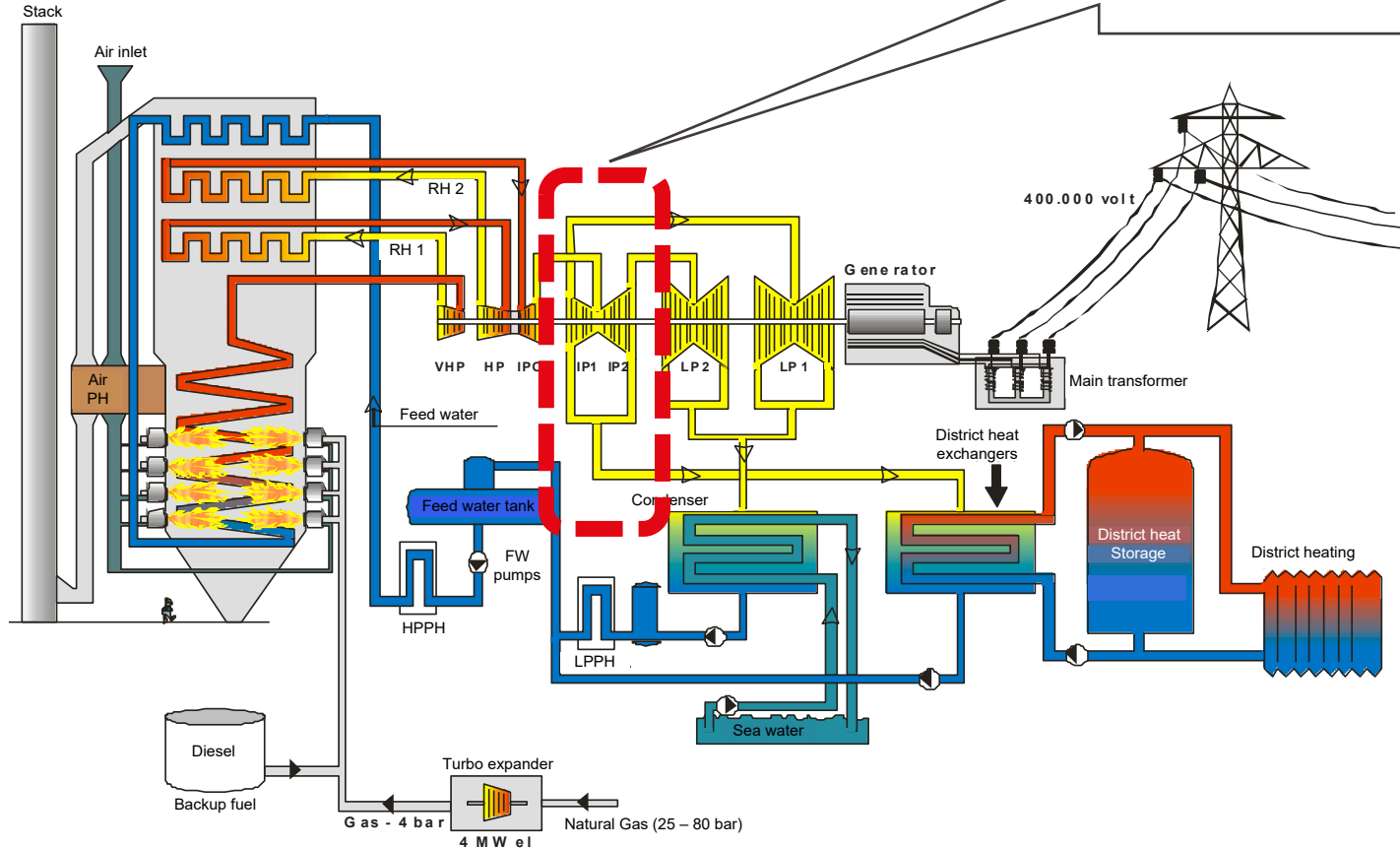
$$\theta = 1 - \frac{T_c}{T_h}$$



Rankine cycle

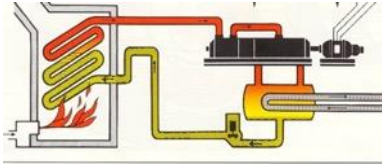
- Improvement (4) - Draw-off

(4) Steam draw-off

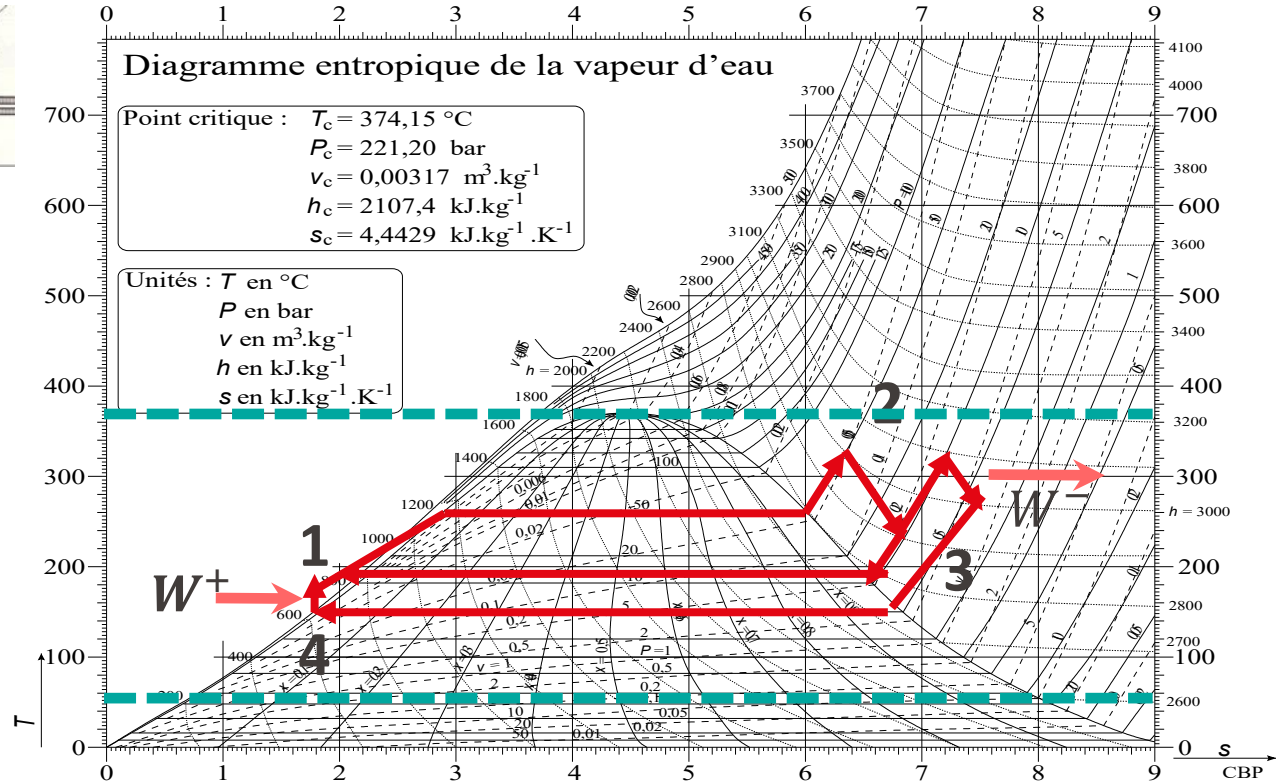


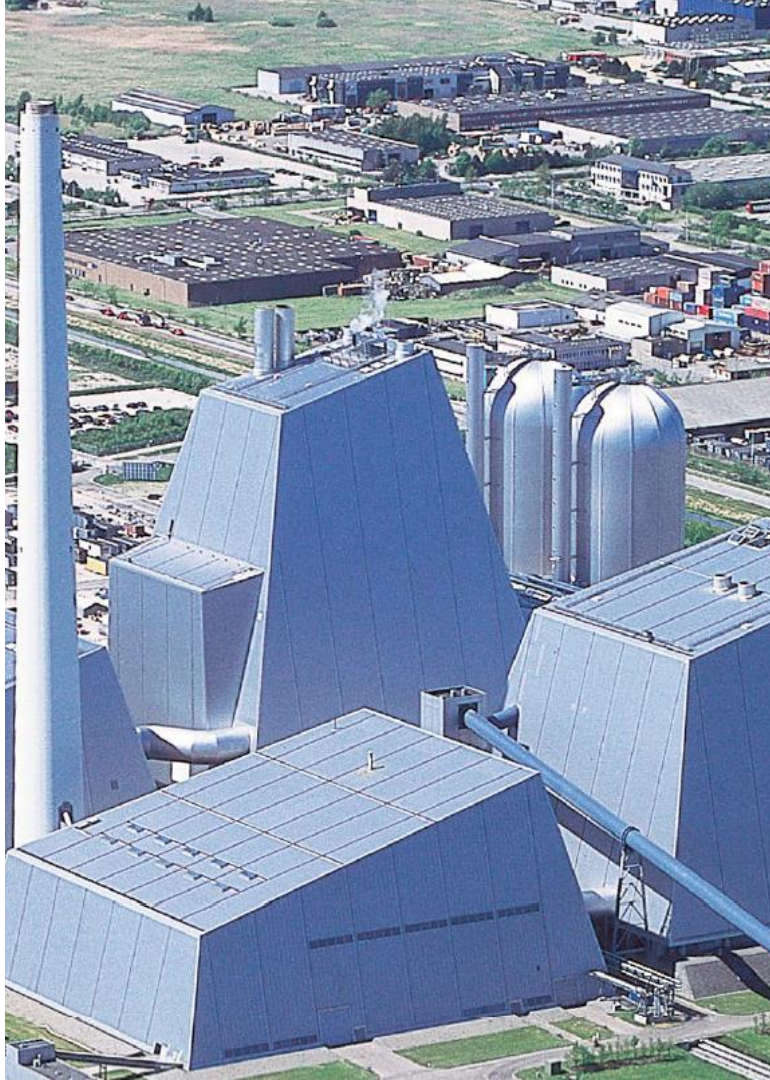
Rankine cycle

- Improvement (4) - Draw-off



$$\theta = 1 - \frac{T_c}{T_h}$$





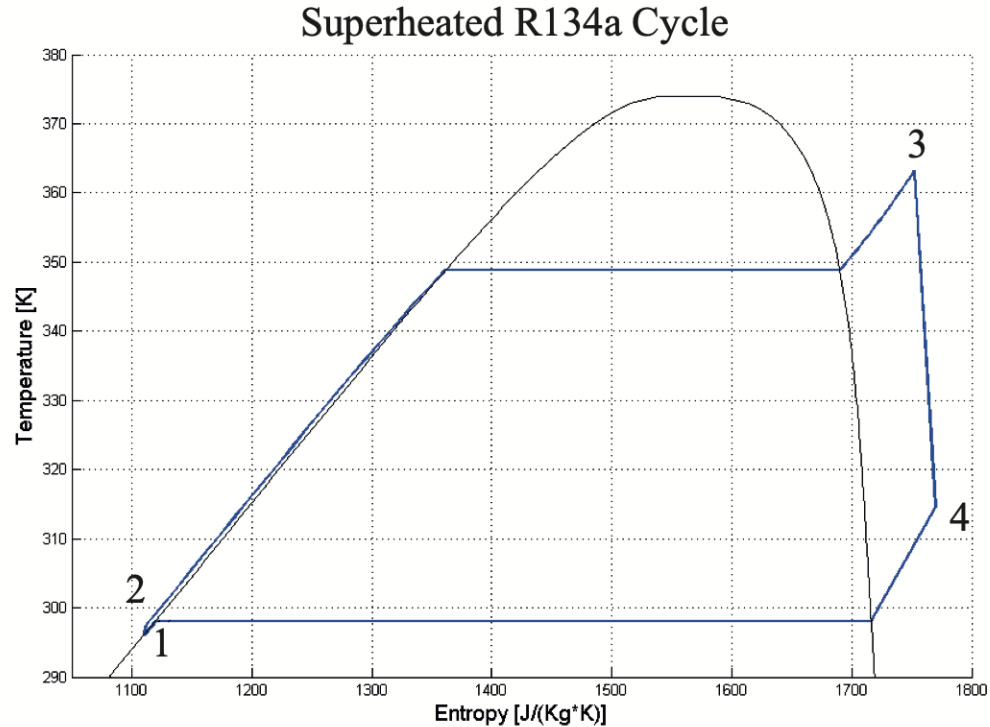
Rankine Cycles Working fluids

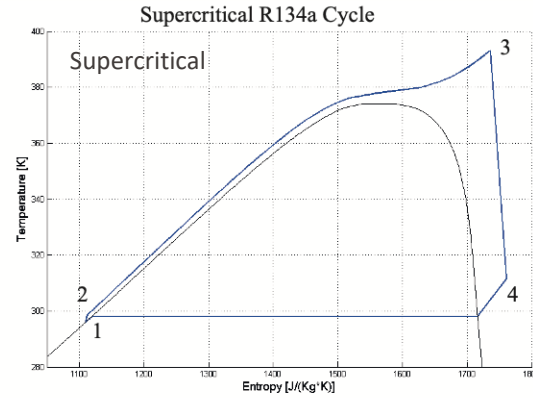
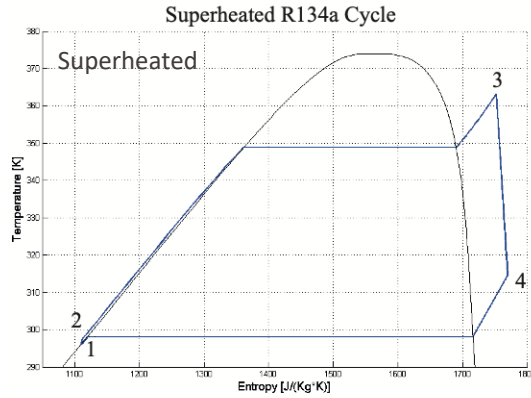
Changing the fluid : Organic Rankine cycles

- When T source is low e.g. below 100°C
 - Difficulty working in sub-atmospheric conditions
 - Difficulty with phase change

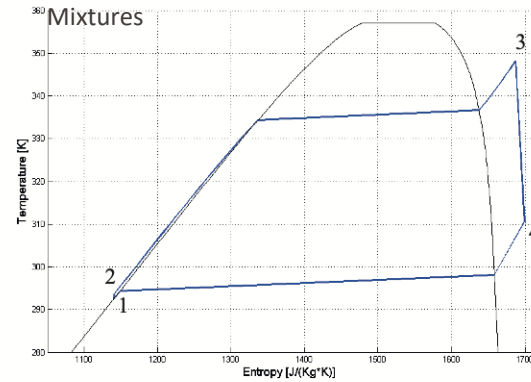
Changing the fluid : Organic Rankine cycles

- Use of refrigerant => evaporation at higher pressure & lower temperature.

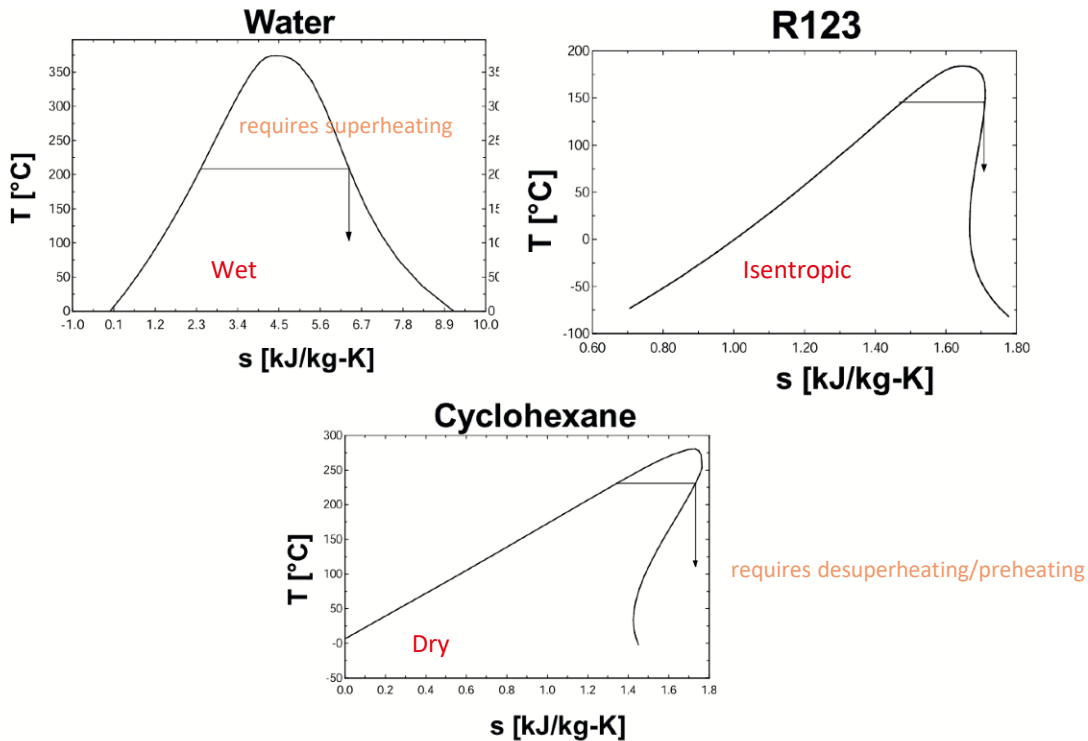


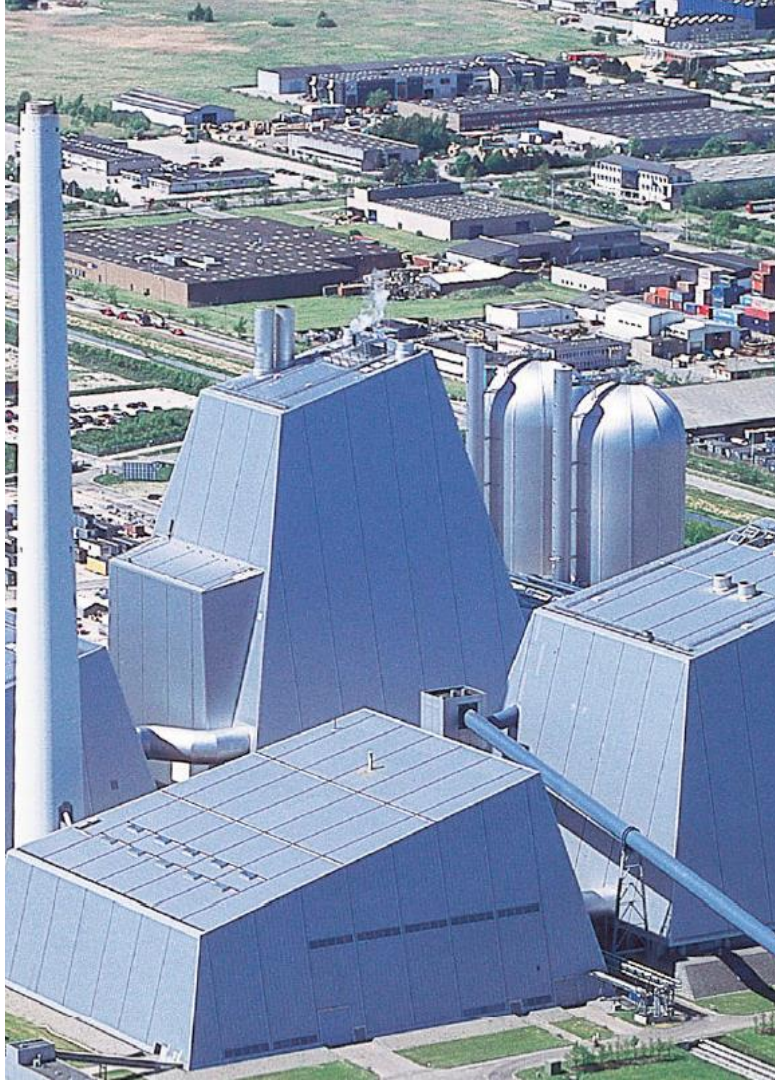


Superheated Mixture of 50% R134a and 50% R125 Cycle



Different types of fluids/different thermodynamic properties



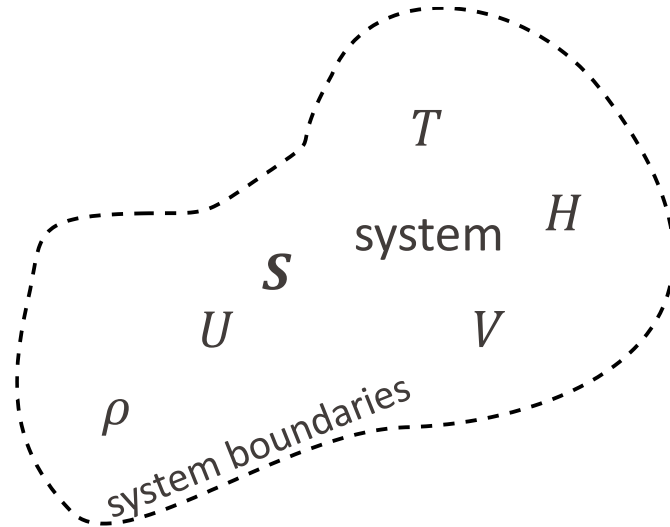


Take-home message

Take-home message

- How many **system properties (F)** do I need to know everything?

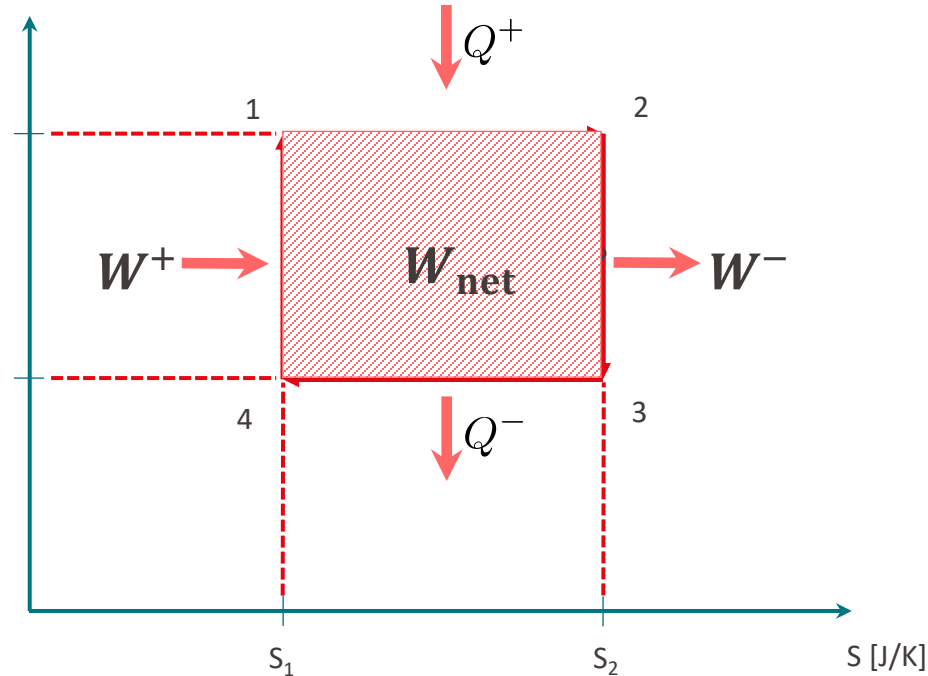
Gibbs' phase rule: **F** = C+2



Take-home message

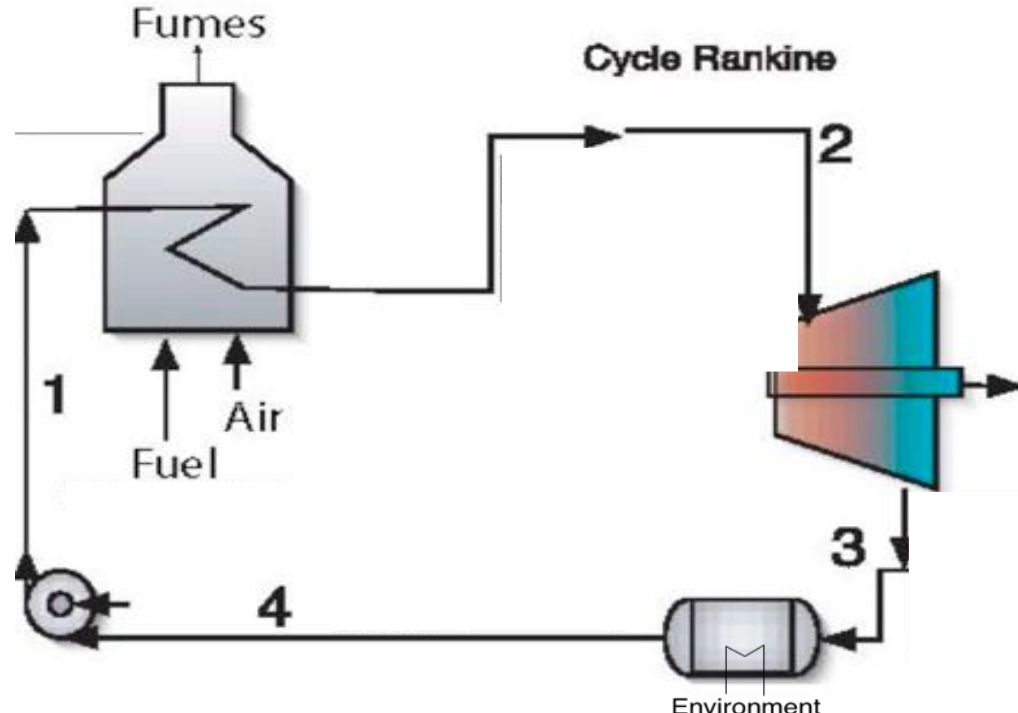
- What is the **ideal thermodynamic cycle** and efficiency? **Carnot cycle**

$$\theta = 1 - \frac{T_c}{T_h}$$

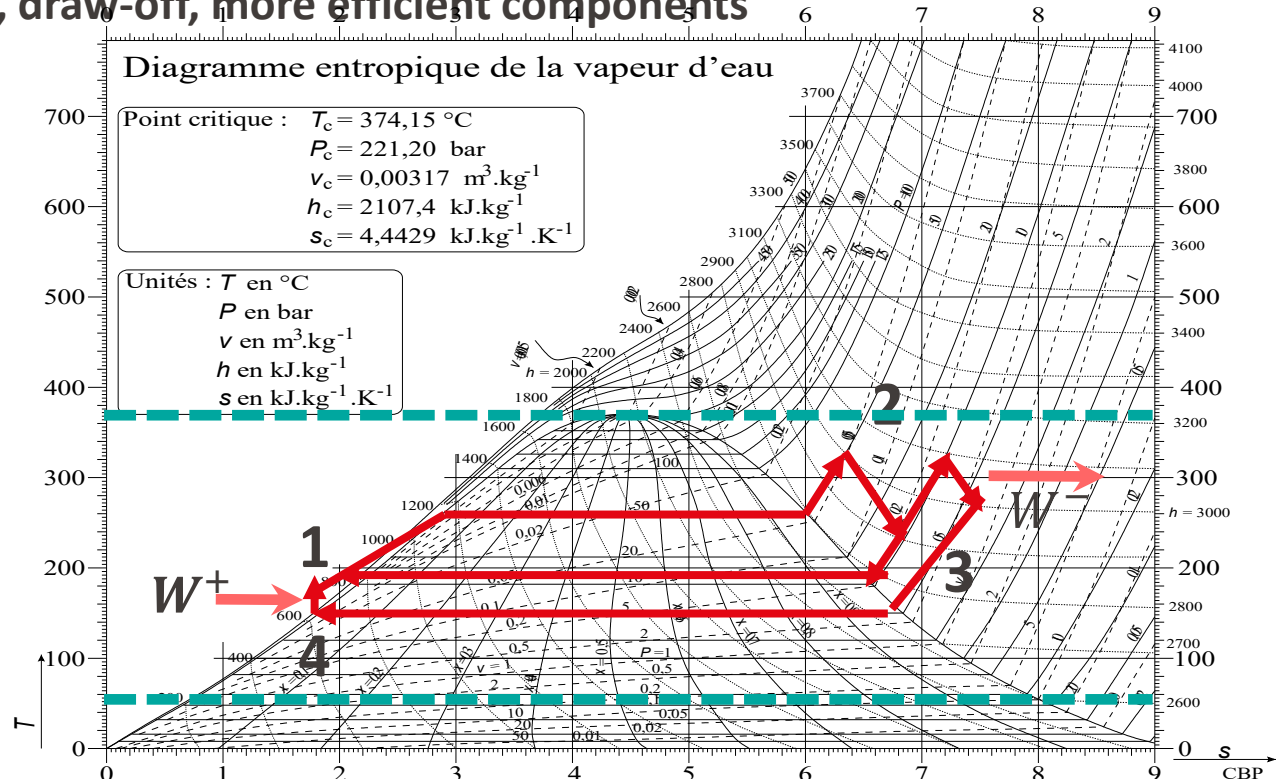


Take-home message

- Which process is **most used** in power plants? Rankine cycle



- How can we improve the efficiency of Rankine cycles? **Superheating, reheating, draw-off, more efficient components**





Questions?