Heat to Electricity: Rankine cycles

François Marechal

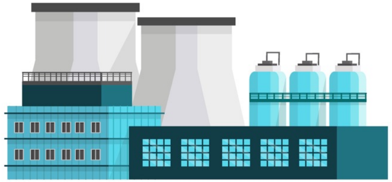
EPFL

Lausanne – 30/09/2024

École
polytechnique
fédérale
de Lausanne

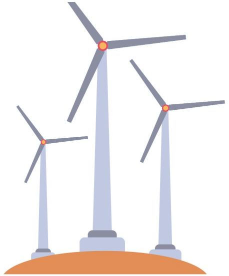
Introduction

– How do we produce electricity today?



HEAT → Heat engine 74% → ELECTRICITY

Chemical / Nuclear energy (Biomass, Coal, etc.)



MECHANICAL → Dams, windmills (turbines) 21% → ELECTRICITY

Kinetic / Potential energy (Wind, Hydro)

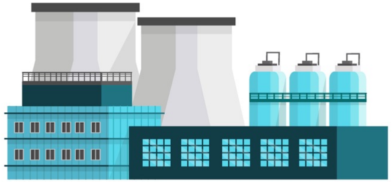
LIGHT → Photovoltaics 5% → ELECTRICITY

Solar radiation (Light)

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Introduction

– How do we produce electricity today?

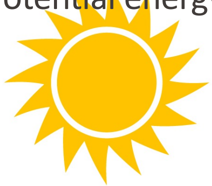


HEAT → HEAT ENGINE 74% → ELECTRICITY

Chemical / Nuclear energy (Biomass, Coal, etc.)

MECHANICAL → Dams, windmills (turbines) → ELECTRICITY

Kinetic / Potential energy (Wind, Hydro)



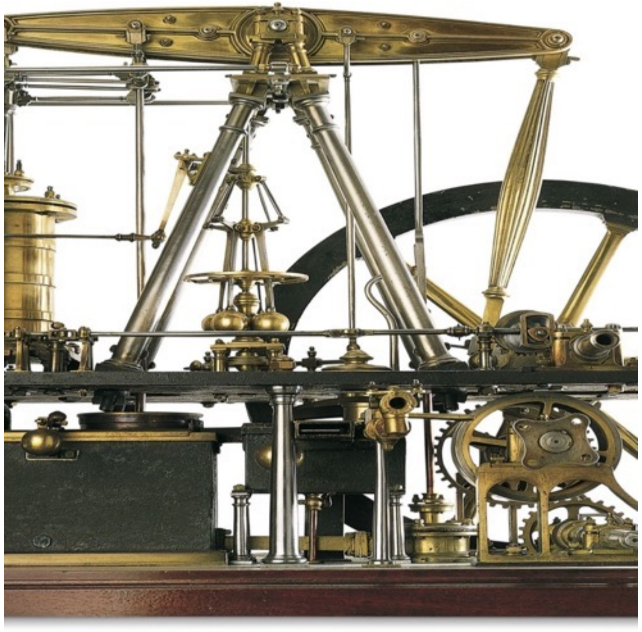
LIGHT → Photovoltaics → ELECTRICITY

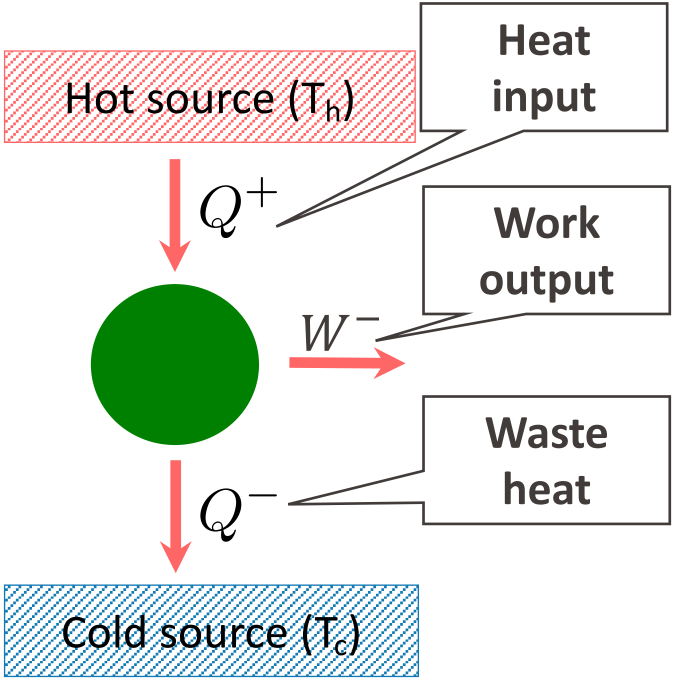
Solar radiation (Light)

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Introduction
– Heat engines

- Conversion of **heat to work (electrical, mechanical)**

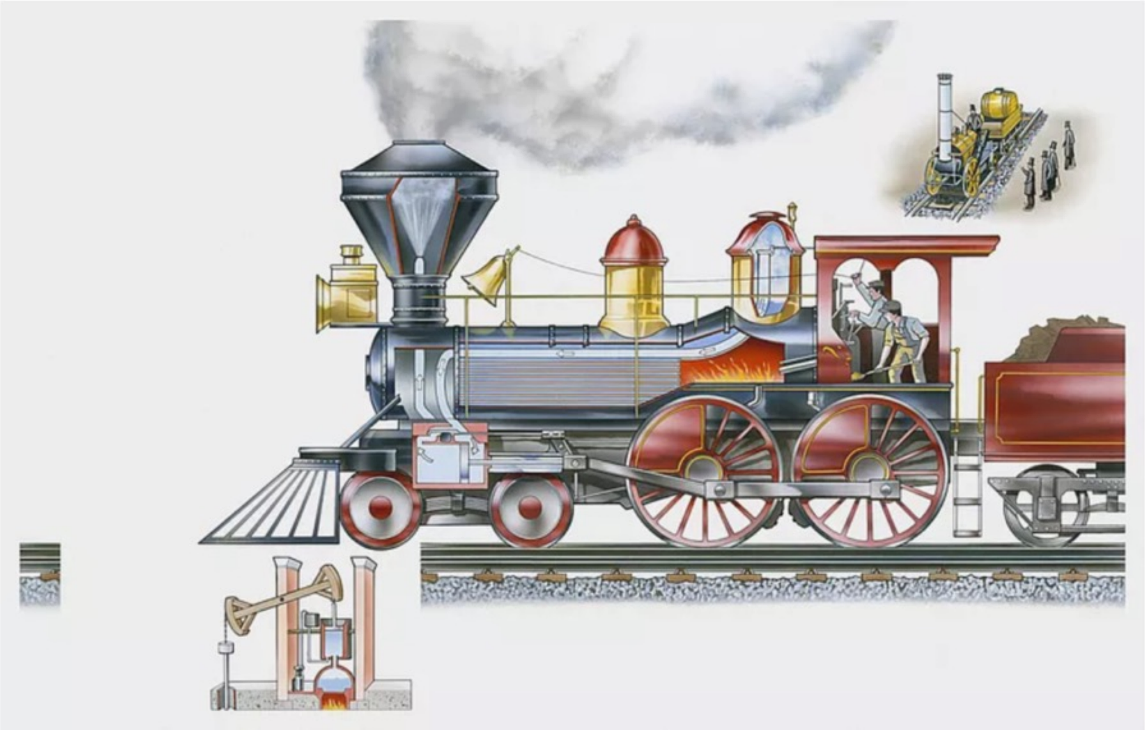




Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Introduction

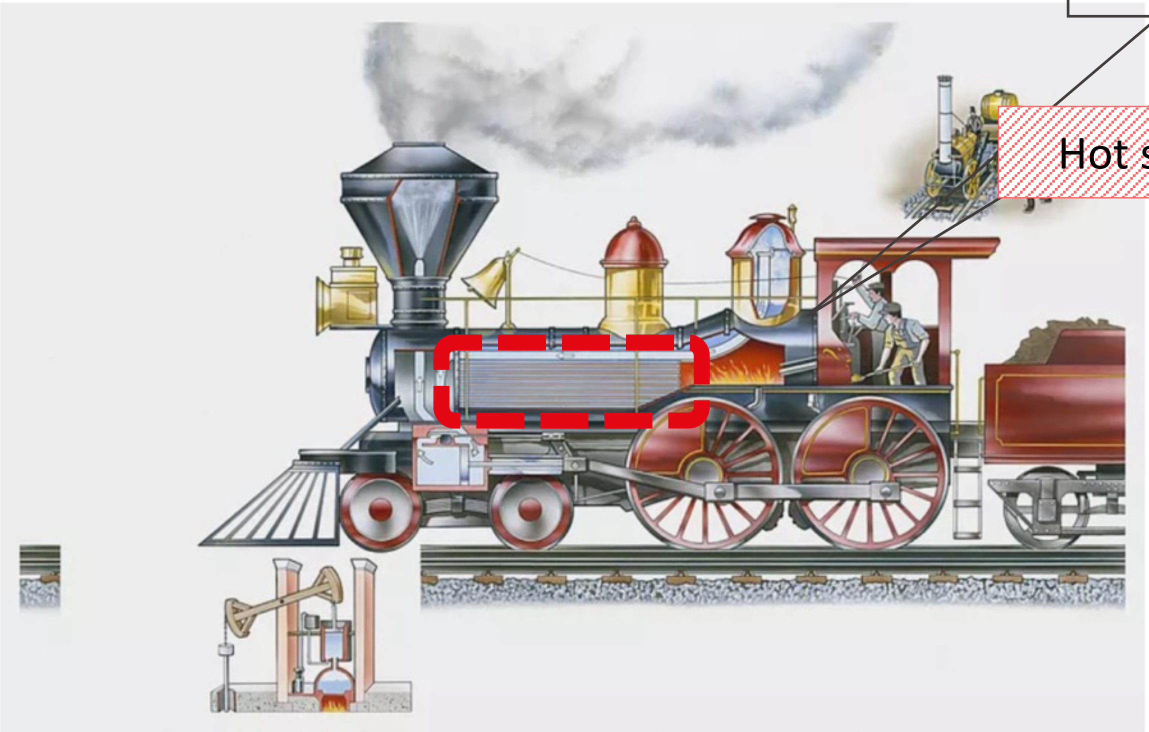
– The example of the steam train



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Introduction

– The example of the steam train



Steam generation
Heat **input** = boiler

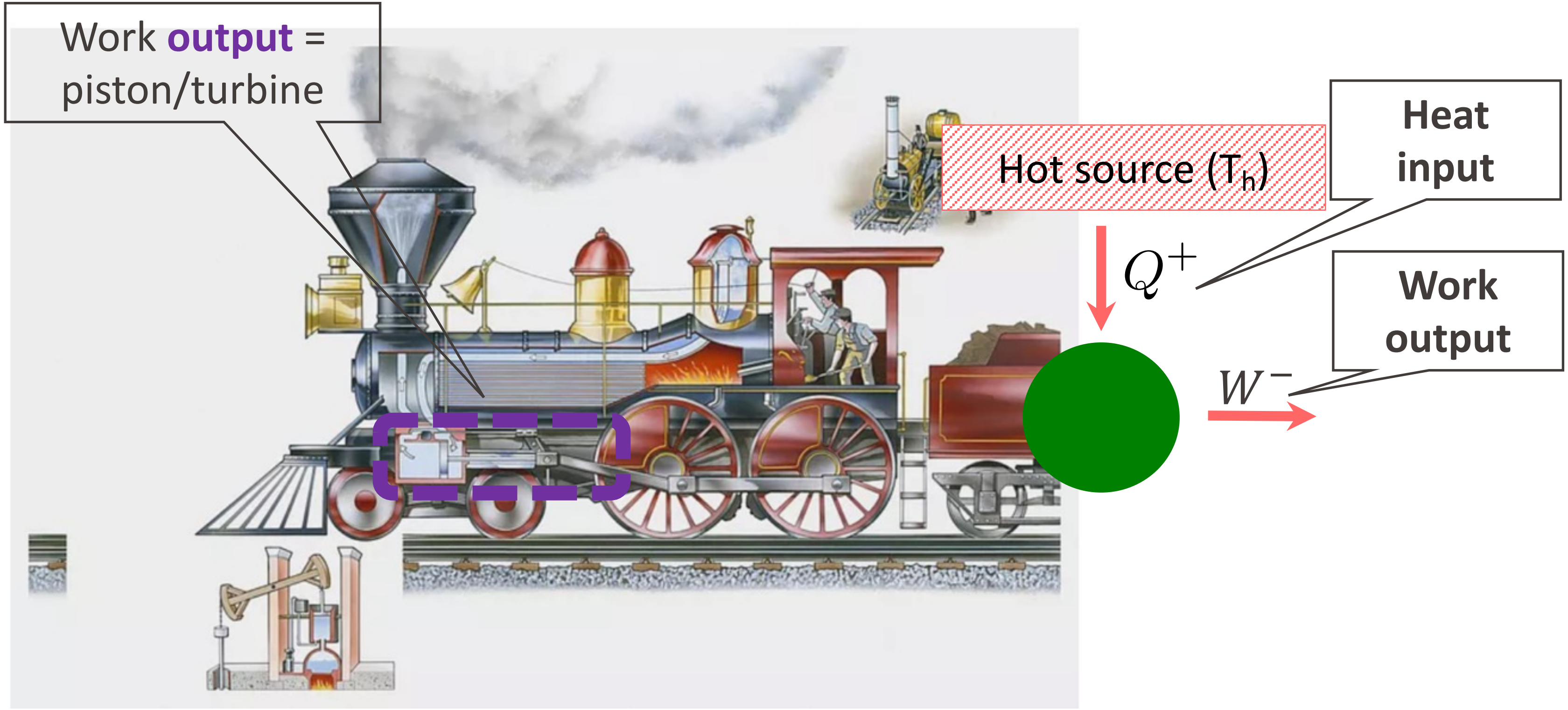
Hot source (T_h)

Q^+

Heat input

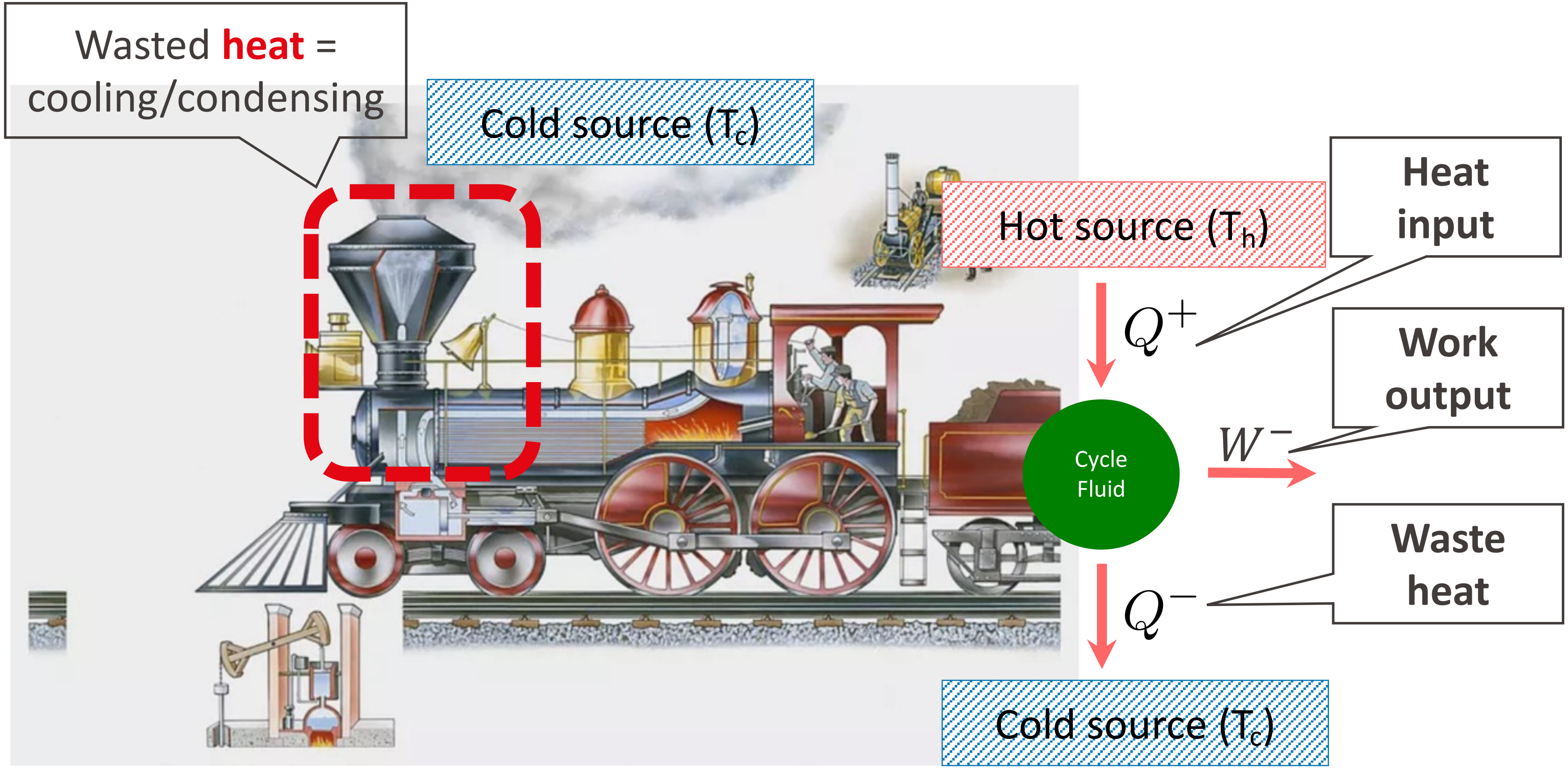
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Introduction
– The basic concept



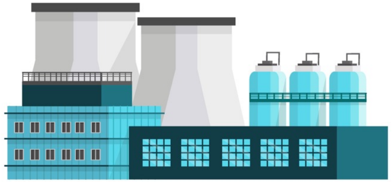
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Introduction
– The basic concept



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Introduction
– How do we produce electricity today?



Chemical / Nuclear energy (Biomass, Coal, etc.)

HEAT

HEAT ENGINE

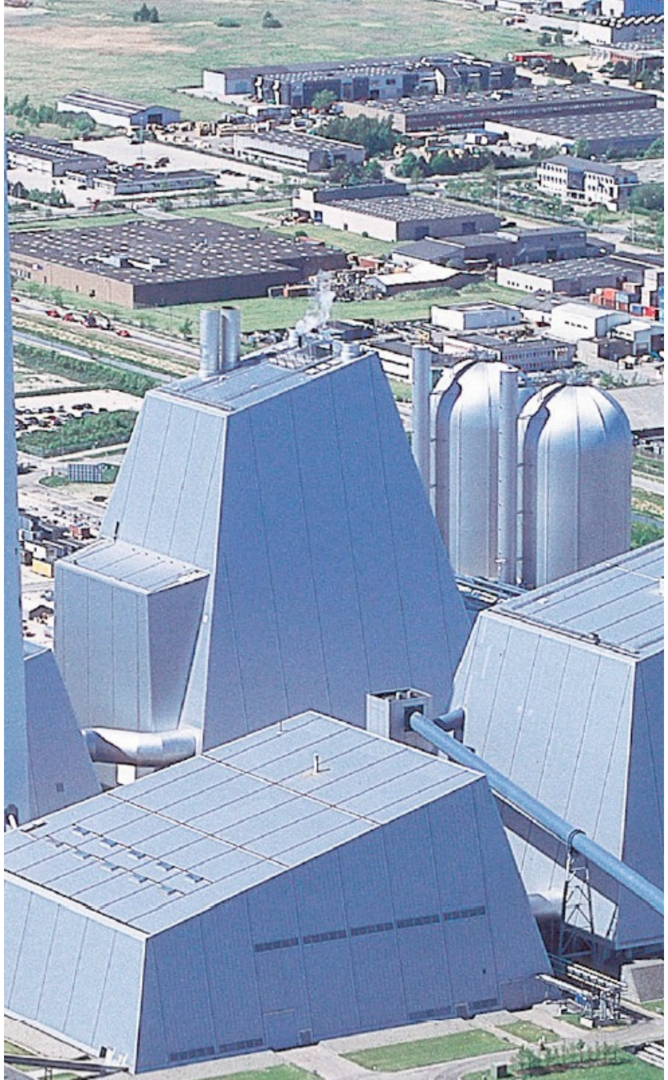
ELECTRICITY

The **Rankine** cycle

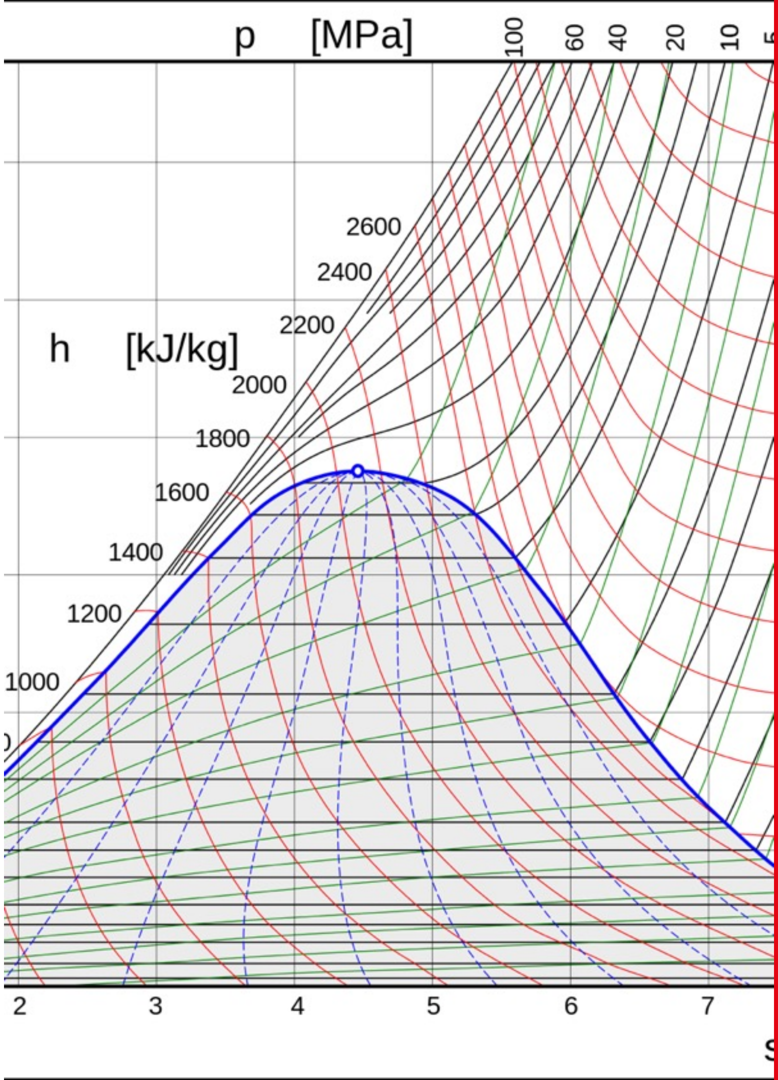
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Goals

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



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch



Working Fluid Thermodynamic diagrams

State variables

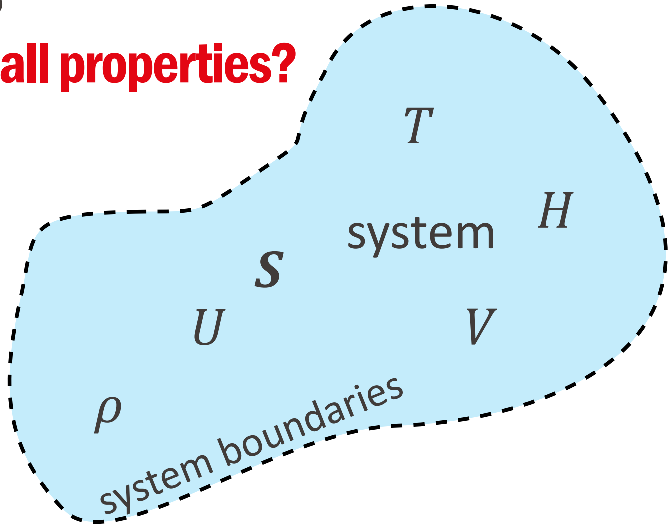
Temperature-entropy (T-s)

Pressure-enthalpy (p-h)

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

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
  - …

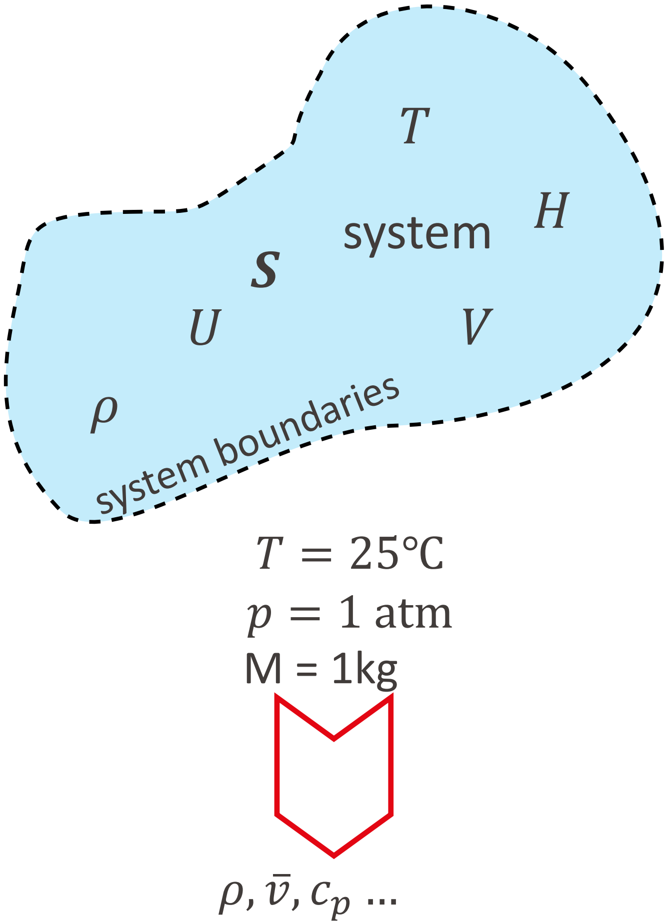
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Thermodynamic diagrams
– The degrees fo 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



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Thermodynamic diagrams

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

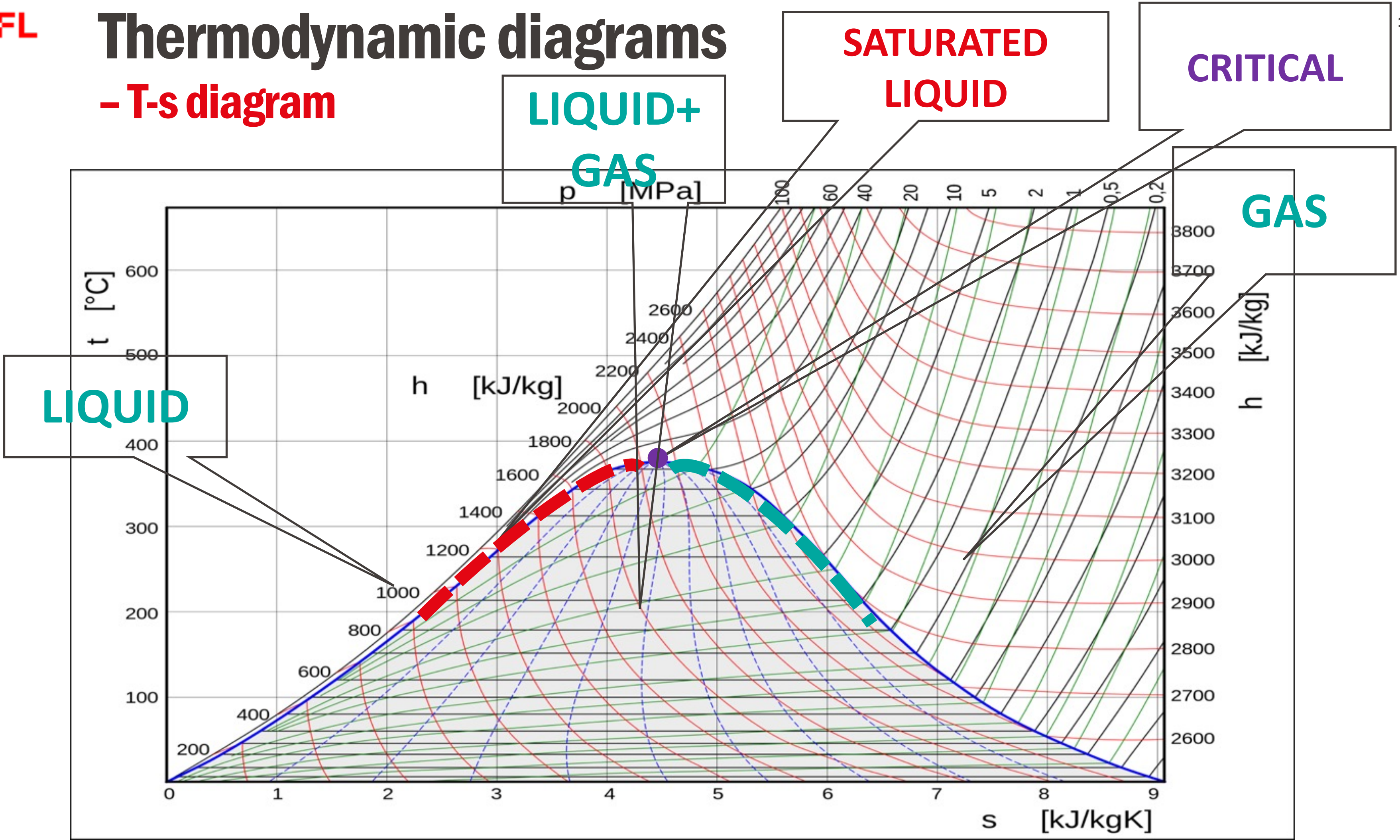
p	T	v gas	h gas	s gas
Bar	Deg. C	m^3/kg	kJ/kg	kJ/(kg K)
40	200	0.0323	2476.9	5.4111
40	250	0.0497	2799.5	6.0669
40	300	0.0588	2960.3	6.3611
40	350	0.0664	3092.1	6.5817
40	400	0.0734	3213.2	6.7687
40	450	0.0800	3329.9	6.9360
40	500	0.0864	3444.9	7.0897
40	550	0.0927	3559.4	7.2333
40	600	0.0988	3674.1	7.3686
50	200	0.0012	853.6	2.3253
50	250	0.0366	2729.1	5.8507
50	300	0.0453	2924.2	6.2081
50	350	0.0519	3068.1	6.4490
50	400	0.0578	3195.3	6.6456
50	450	0.0633	3315.8	6.8183
50	500	0.0686	3433.4	6.9756

p	T	v gas	h gas	s gas
Bar	Deg. C	m^3/kg	kJ/kg	kJ/(kg K)
90	200	0.0011	855.3	2.3192
90	250	0.0012	1085.1	2.7807
90	300	0.0199	2719.4	5.6380
90	350	0.0258	2956.2	6.0359
90	400	0.0299	3117.4	6.2850
90	450	0.0335	3256.3	6.4841
90	500	0.0368	3385.7	6.6572
90	550	0.0399	3510.7	6.8139
90	600	0.0428	3633.4	6.9586
100	200	0.0011	855.7	2.3177
100	250	0.0012	1085.1	2.7784
100	300	0.0161	2631.2	5.4527
100	350	0.0224	2923.1	5.9440
100	400	0.0264	3096.1	6.2117
100	450	0.0297	3240.5	6.4186
100	500	0.0328	3373.3	6.5963

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

EPFL

Thermodynamic diagrams
– T-s diagram

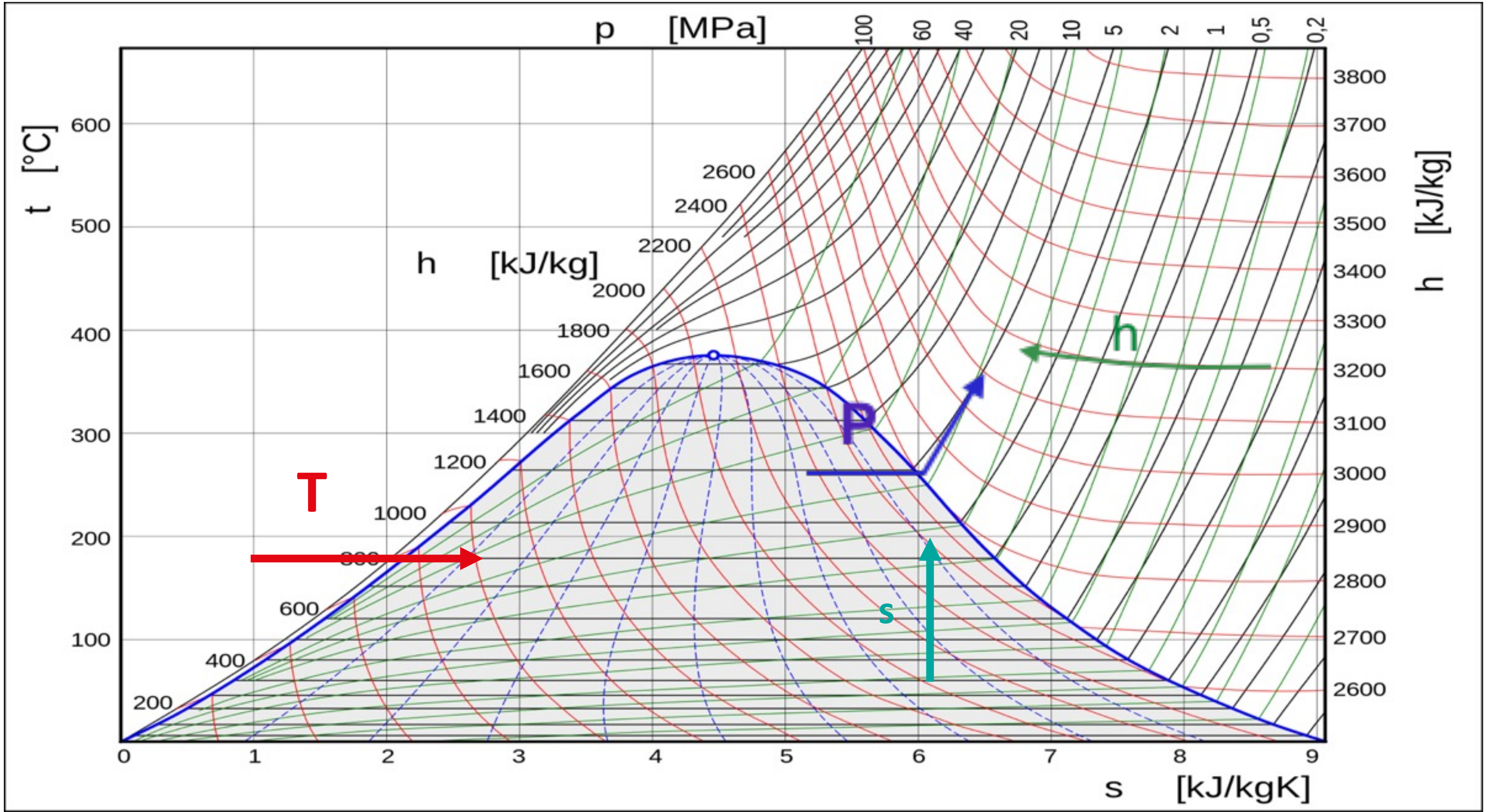


Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Thermodynamic diagrams

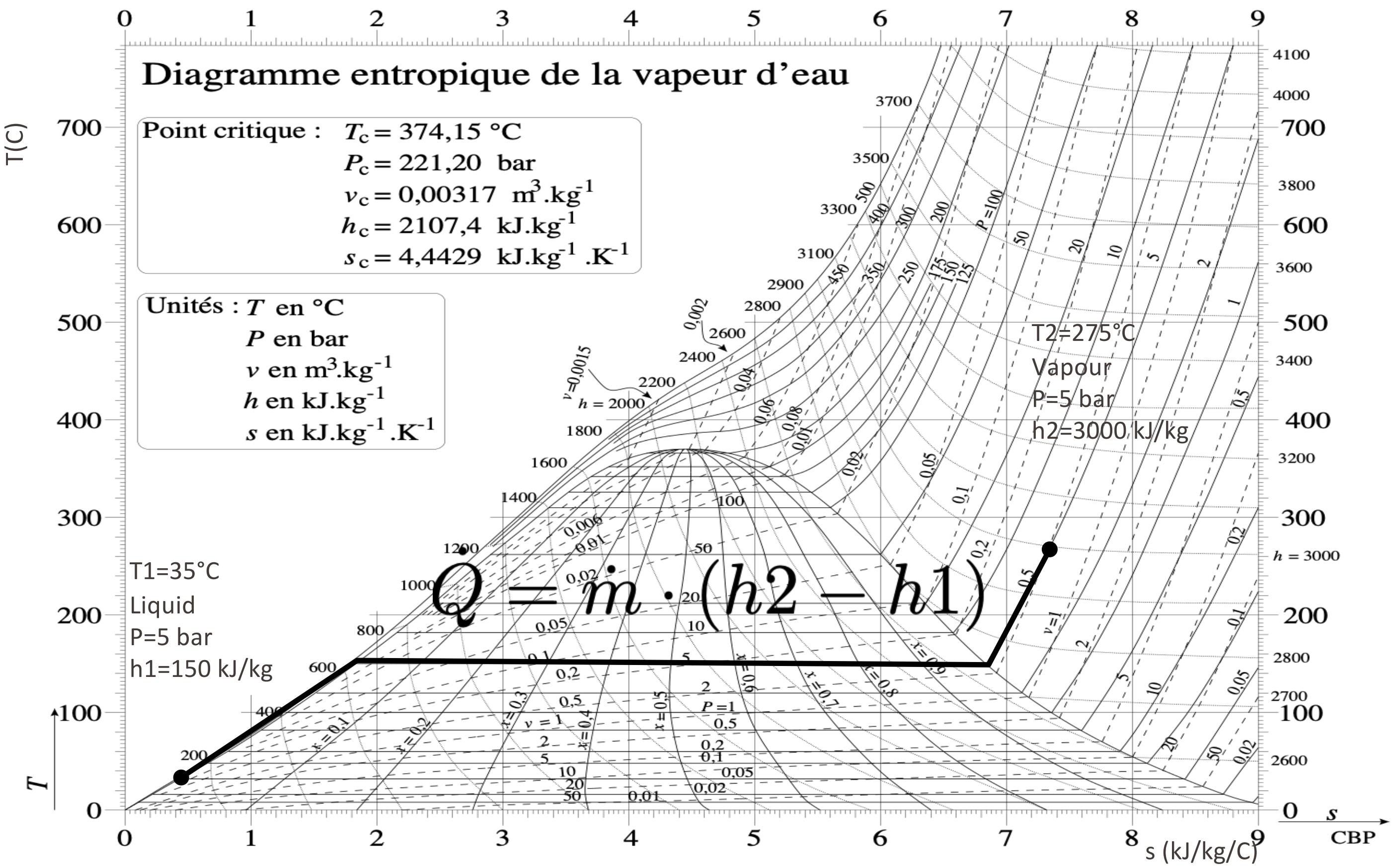
– T-s diagram

P : isobars
h : iso enthalpy
V : isochore



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Conversion from liquid to gas state

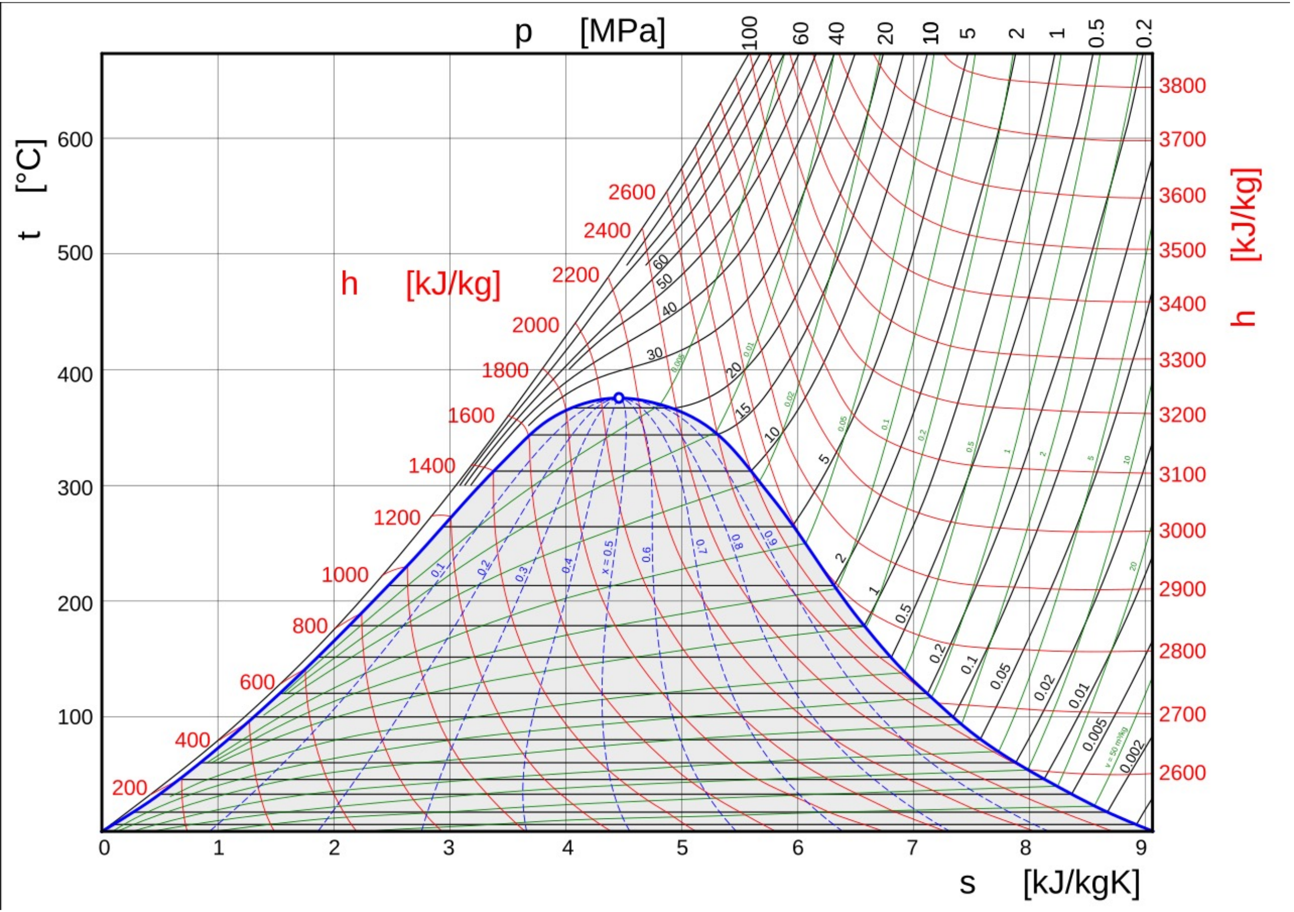


Group Question (2-3 pp., 5.-10 mins)

- Determine the **states** (liquid, vapour, liquid-vapour) **and** specific enthalpies (h, kJ/kg) for the following points, using the T-s diagram of water
  - Point 1 : 35°C and 85 bar (8.5 MPa)
  - Point 2 : 445°C and 85 bar
  - Point 3 : 0.05 bar and 90% liquid (liquid-vapour region)
  - Point 4 : 0.05 bar and saturated liquid (0% vapour on the liquid-vapour region)

  Interpolate if necessary
- If time allows, calculate the **variation in enthalpy** (kJ/kg) for each transformation - what happens in each process ?
  - Point 1 to point 2
  - Point 2 to point 3
  - Point 3 to point 4
  - Point 4 to point 1
- Answer at: https://app.wooclap.com/ME409/questionnaires/66fa5c941f1e87c8a486ff9c

Group Question



You can as well use:
https://www.wolframalpha.com

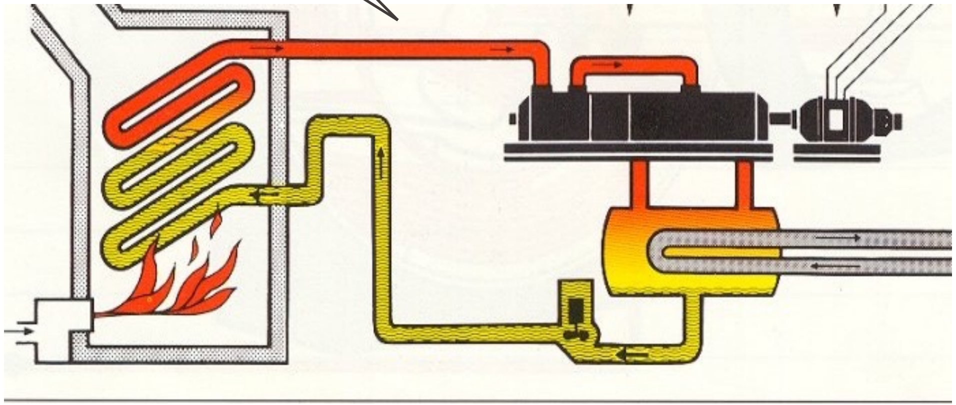
Ask for example :
“enthalpy of water at 5 bar and 15 degrees celsius

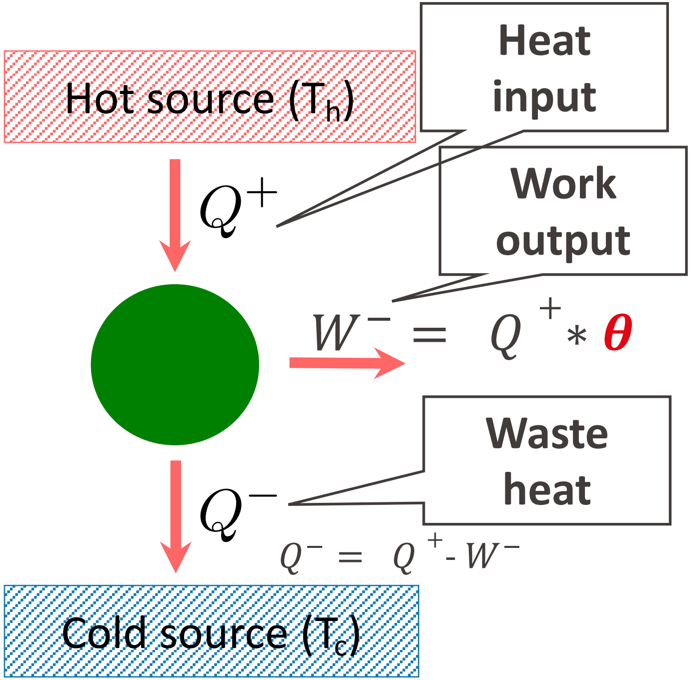
Carnot cycle – the ideal case?

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Carnot cycle
– The only limit is Carnot

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

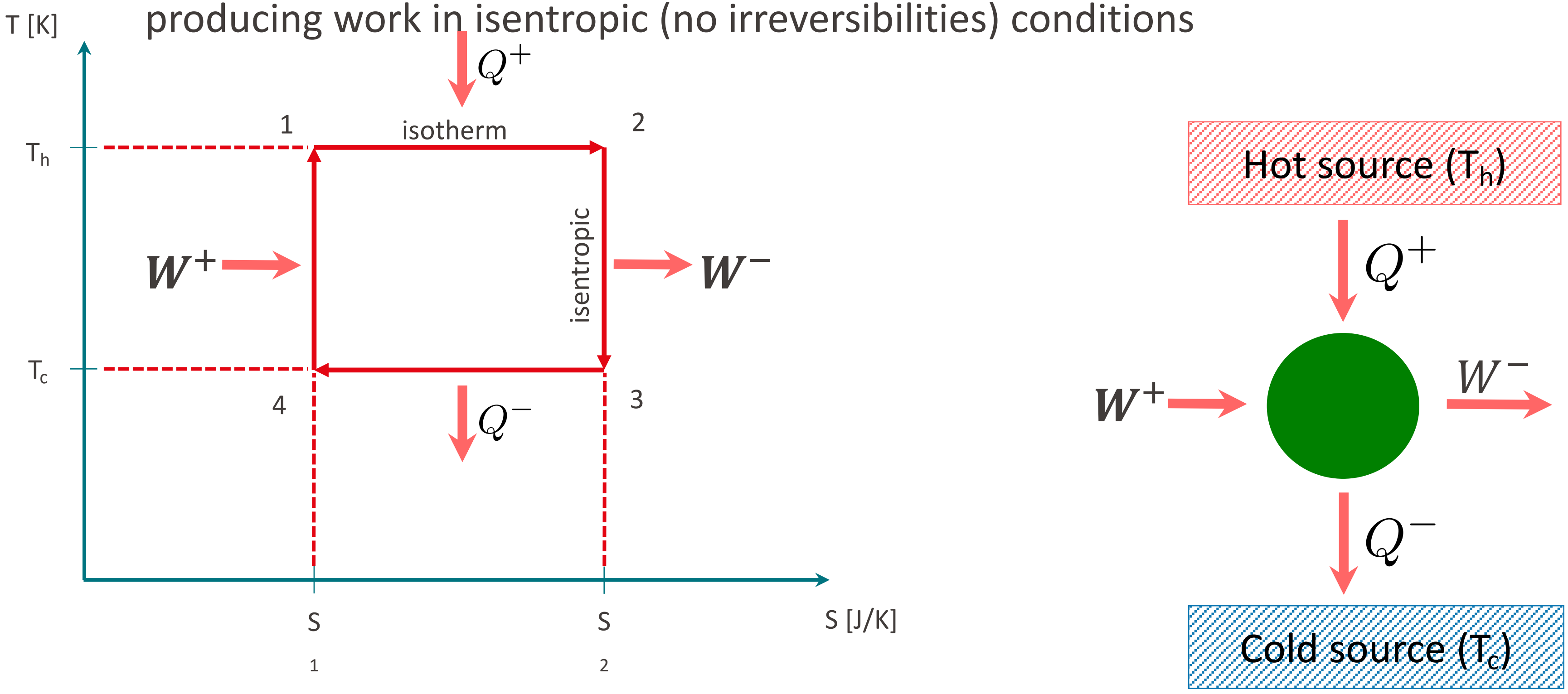




Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Carnot cycle
– Thermodynamic diagram

- The Carnot cycle : getting and removing heat at constant temperature, producing work in isentropic (no irreversibilities) conditions



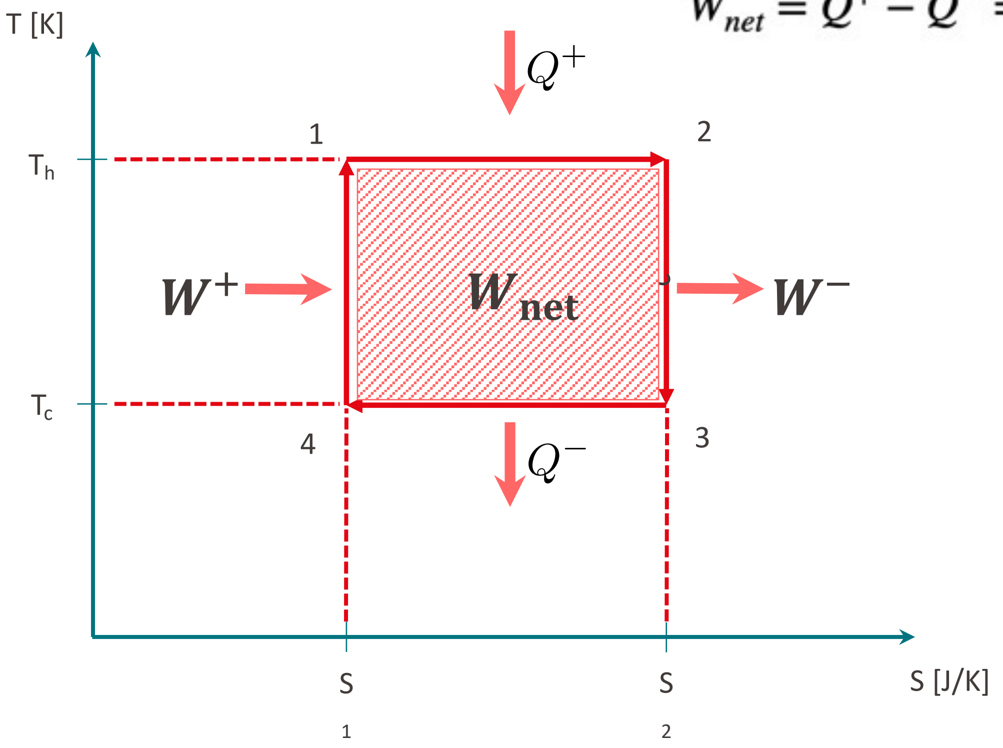
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

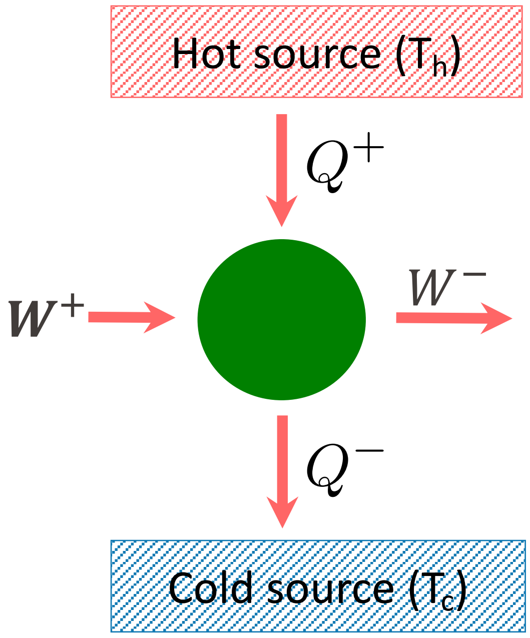
EPFL

Carnot cycle

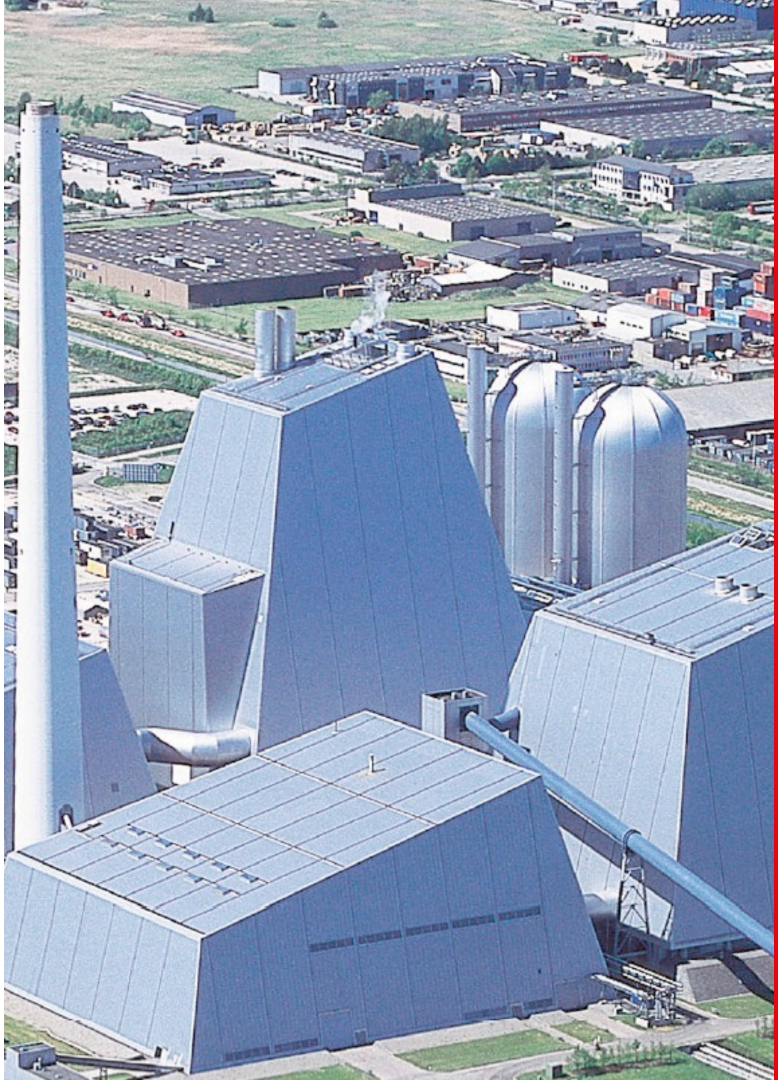
– Thermodynamic diagram

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





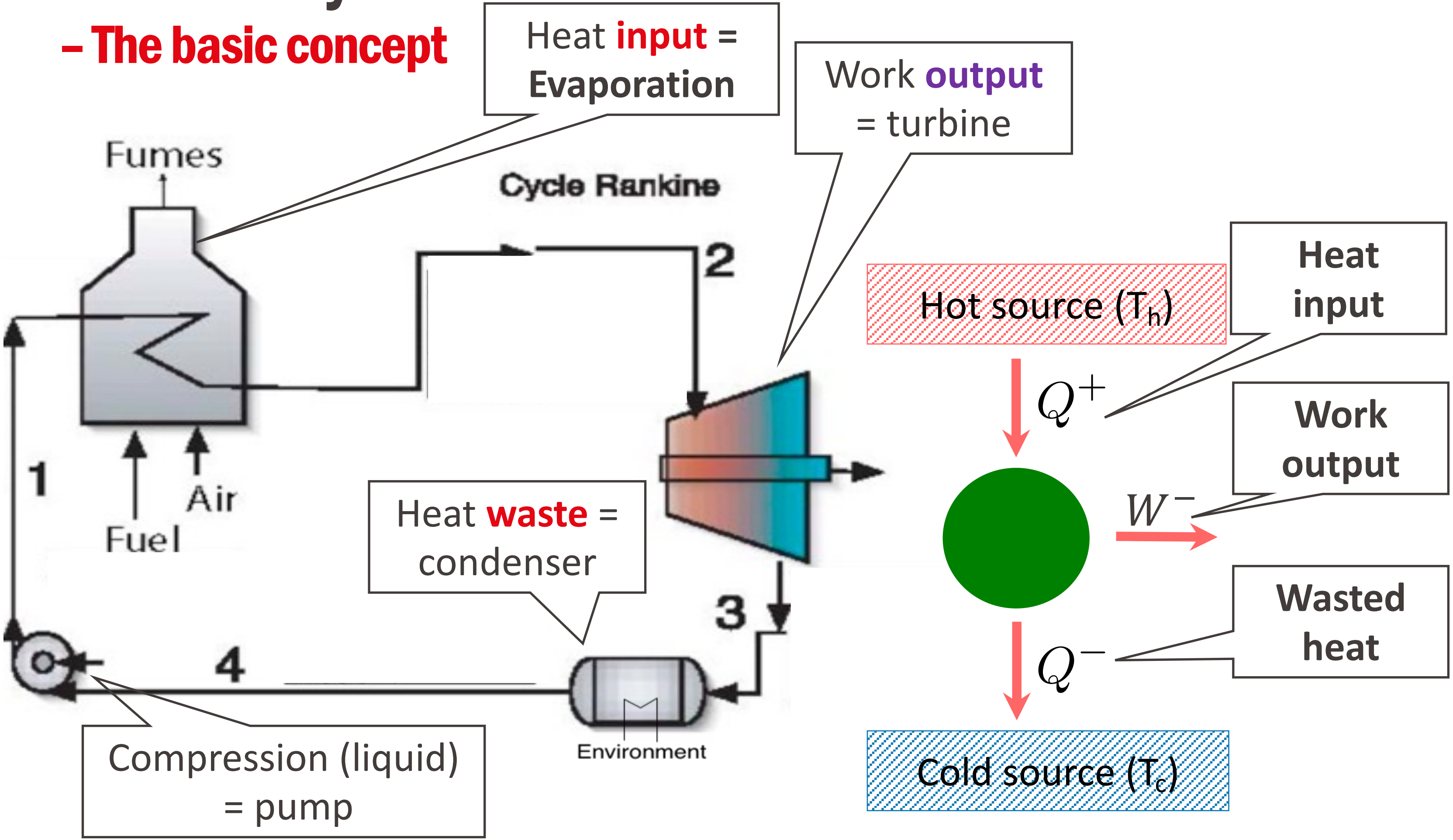
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch



Rankine cycle – the basic concept

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

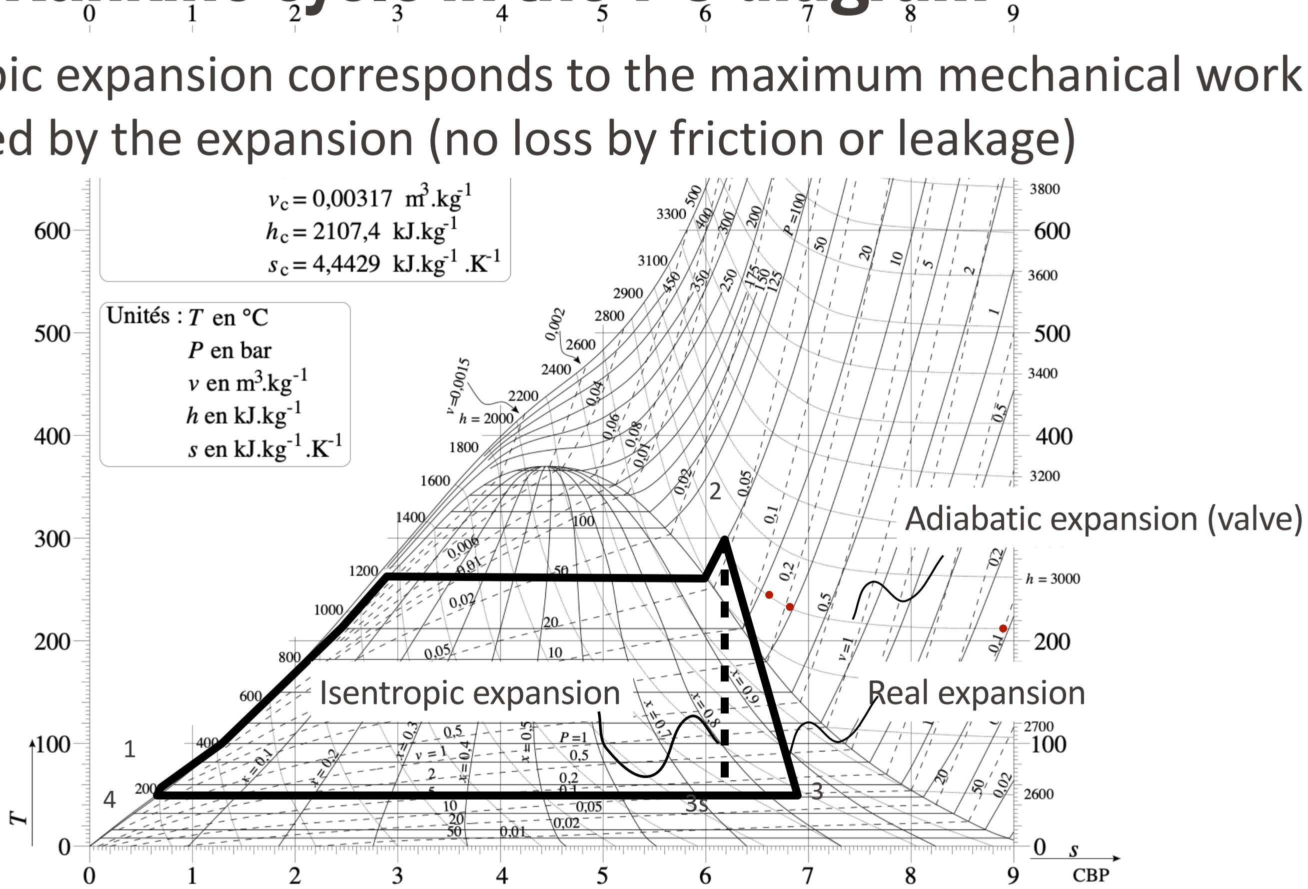
Rankine cycle
– The basic concept



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle in the T-S diagram

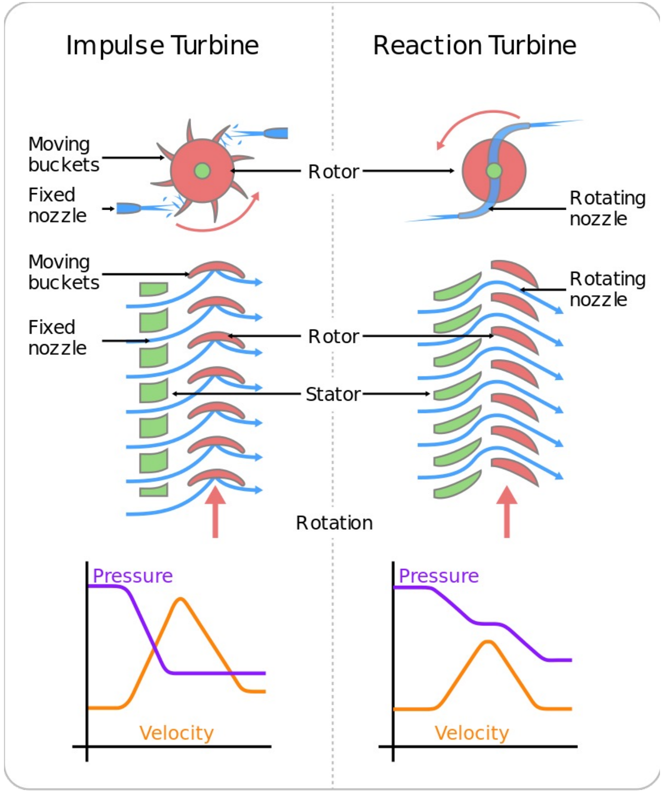
Isentropic expansion corresponds to the maximum mechanical work that can be produced by the expansion (no loss by friction or leakage)



Rankine cycle

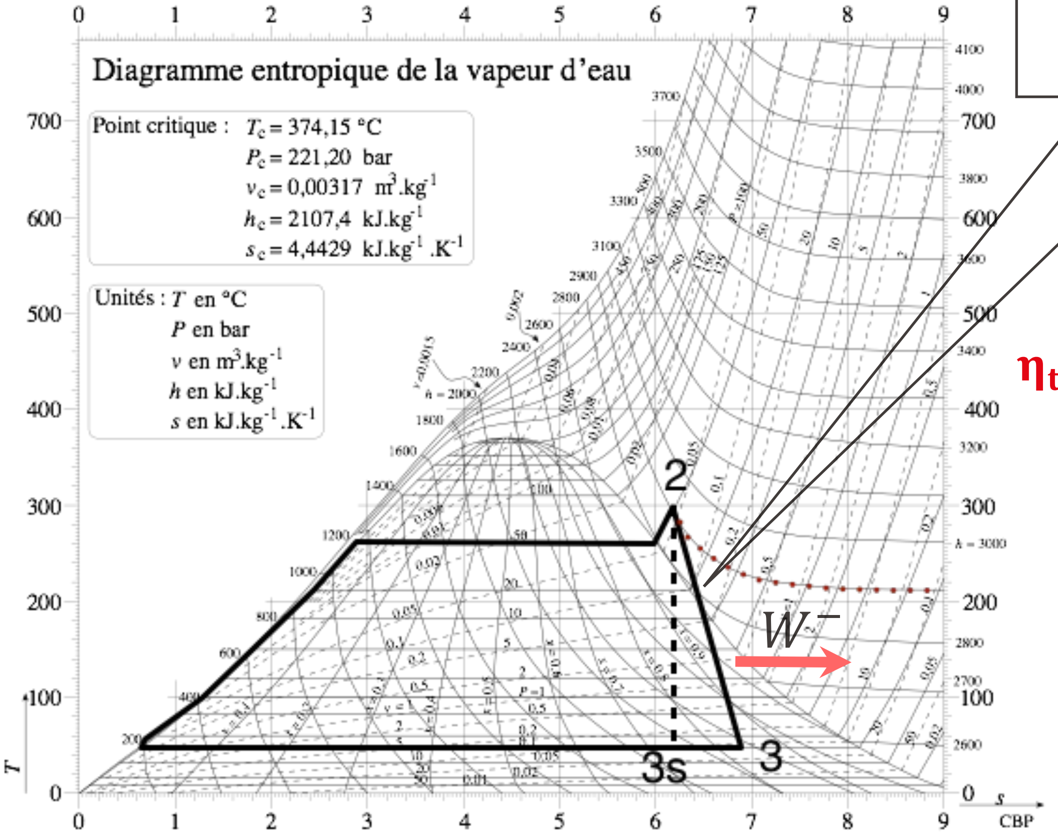
– Turbine : Transforming pressure into kinetic energy and kinetic energy into work

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



Rankine cycle

– Turbine efficiency (η_t)



(1) Higher **turbine** efficiency

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

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

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

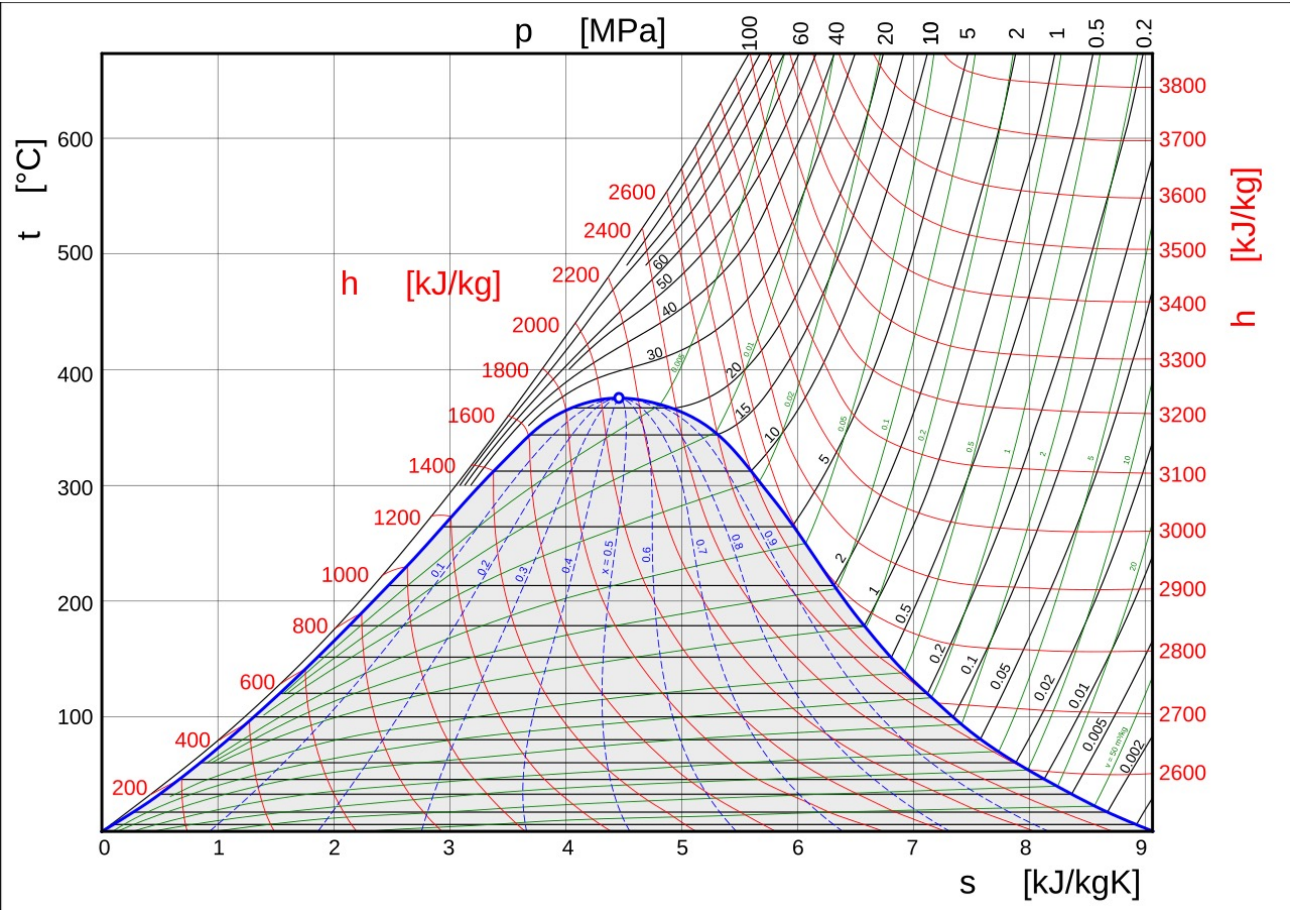
Group Question (2-3 pp., 5.-10 mins)

- Calculate the **variation in enthalpy** (kJ/kg) for each transformation
  - Point 1 to point 2
  - Point 2 to point 3
  - Point 3 to point 4
  - Point 4 to point 1

  (using the data calculated before)

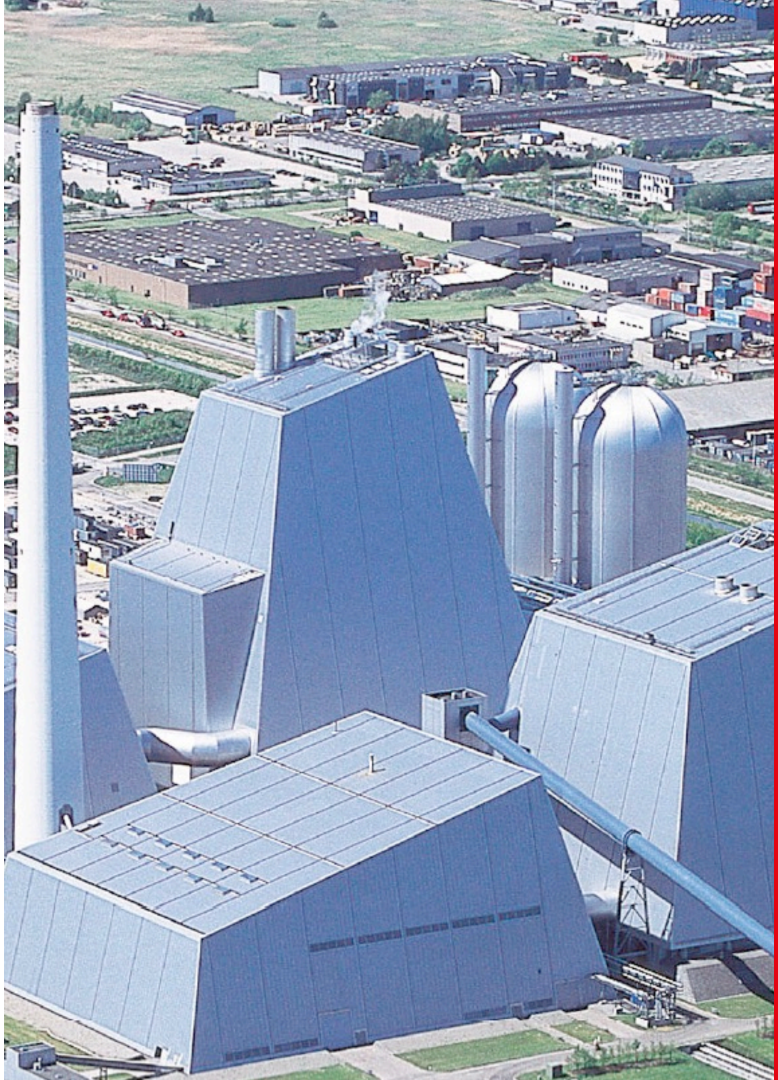
- How much **heat** is injected into the cycle, and how much is lost ? (kJ/kg of steam) How much **work** is produced ?
- What is the **energy efficiency** of this process ?
- Answer at: https://app.wooclap.com/ME409/questionnaires/66fa5c941f1e87c8a486ff9c

Group Question



You can as well use:
https://www.wolframalpha.com

Ask for example :
“enthalpy of water at 5 bar and 15 degrees celsius

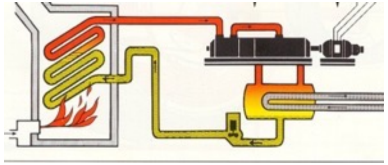


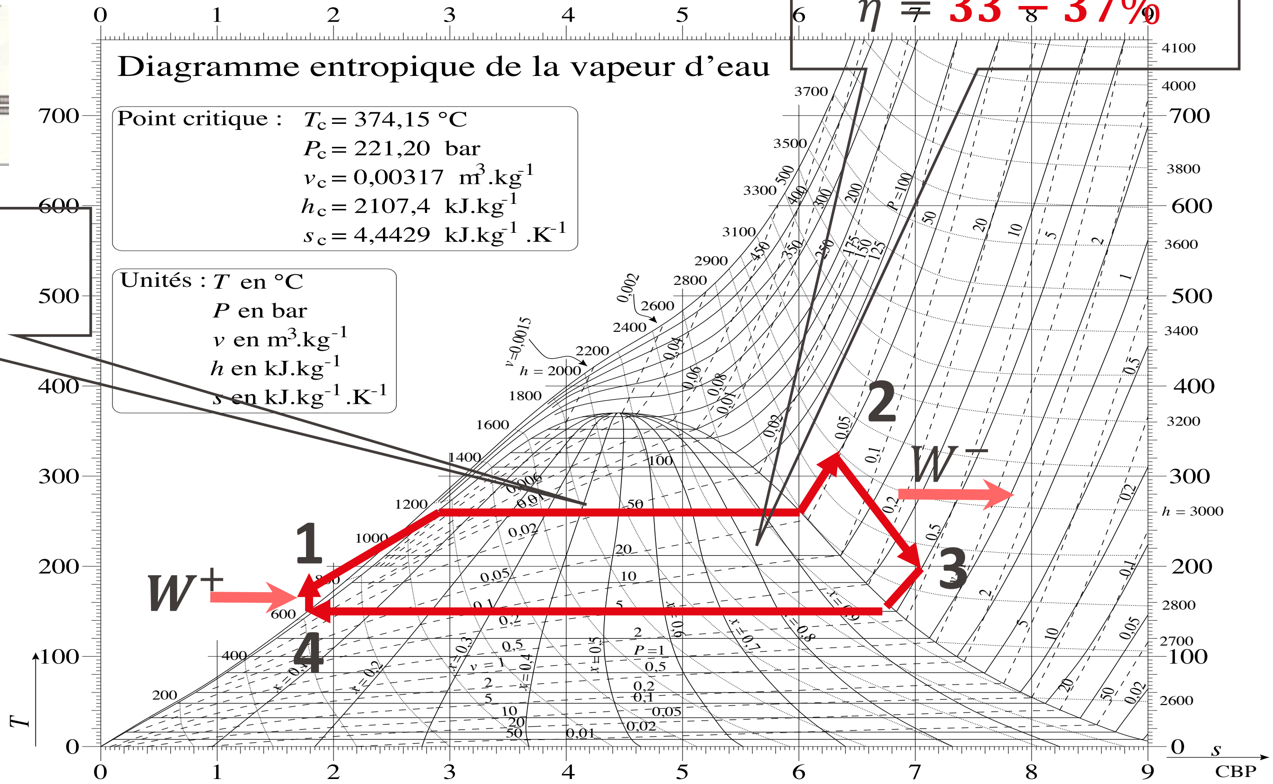
Rankine cycle
- Increasing the efficiency

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle

– Needs for improvements





$\theta = 52\%$

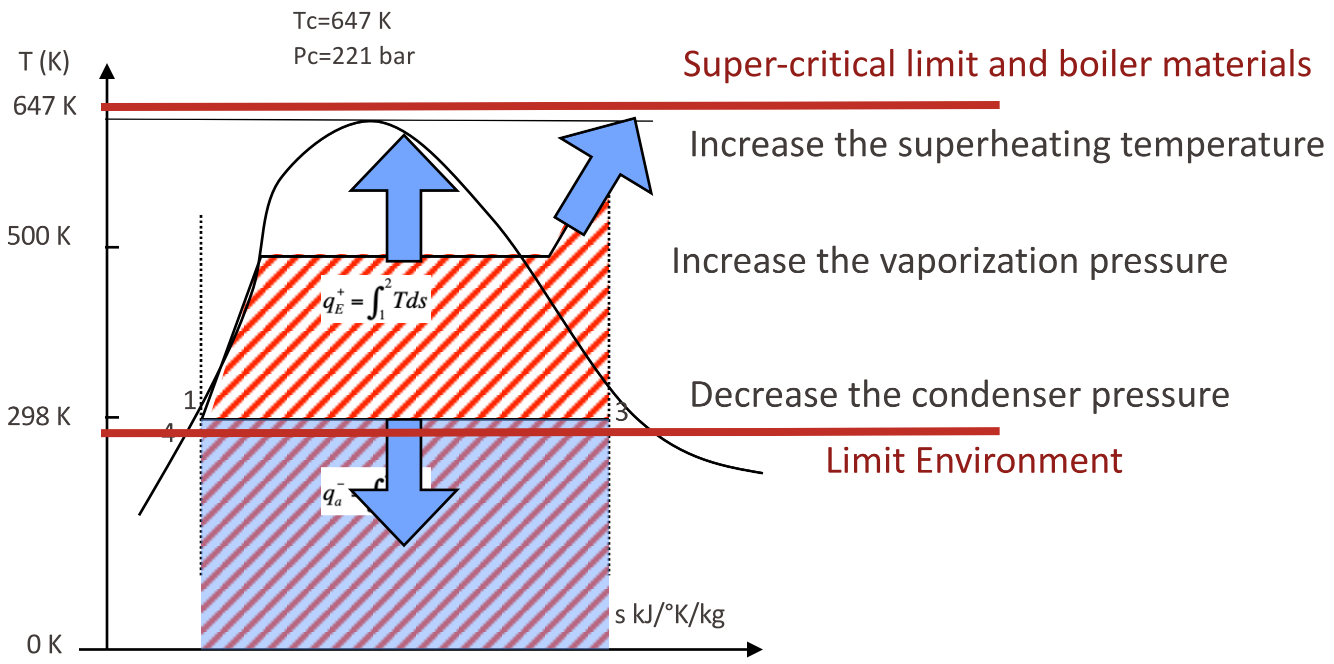
$\eta = 33 - 37\%$

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

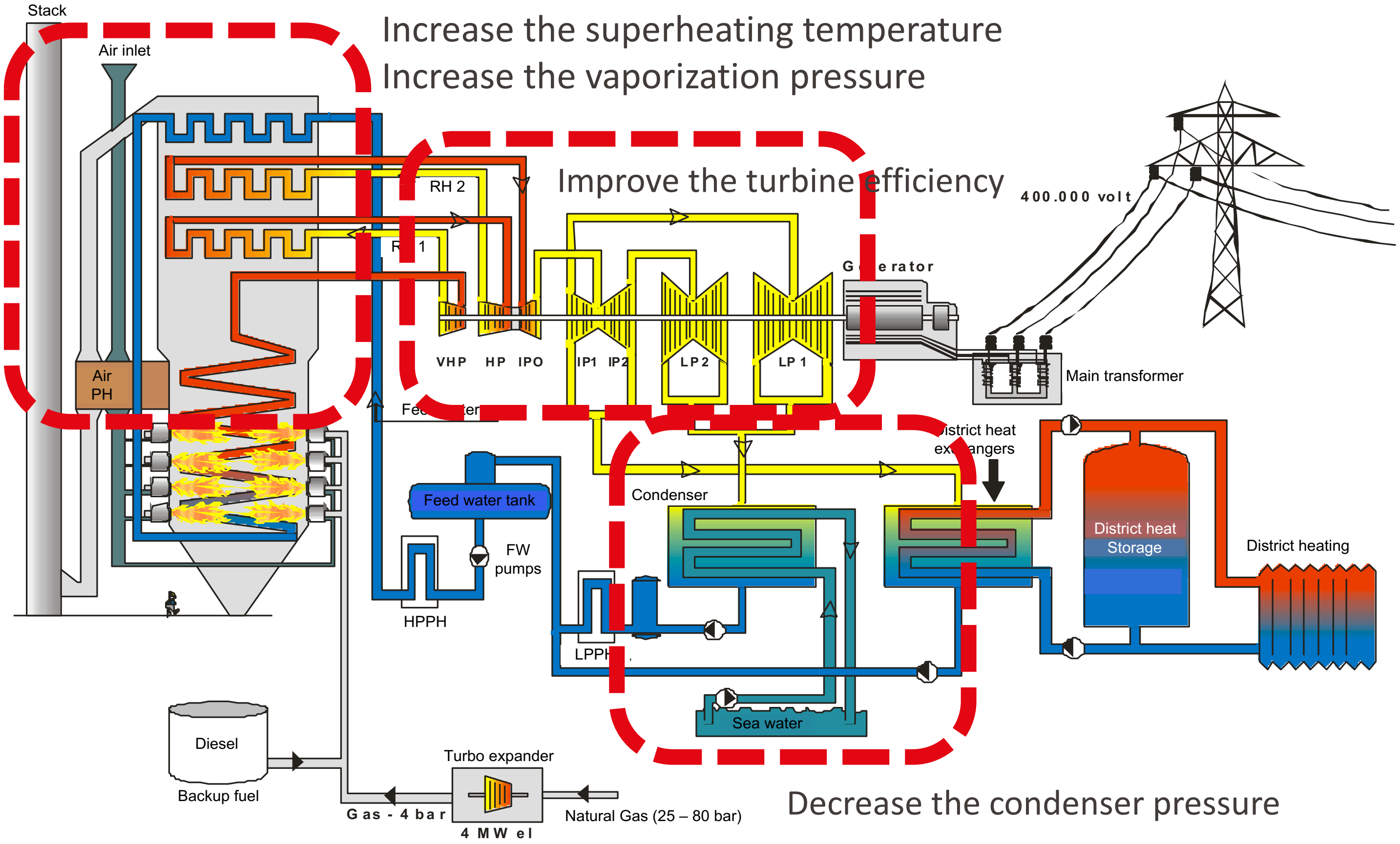
Increase the efficiency

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

Maximise area between the 2 isobars



Rankine cycle
– A state-of-the-art concept



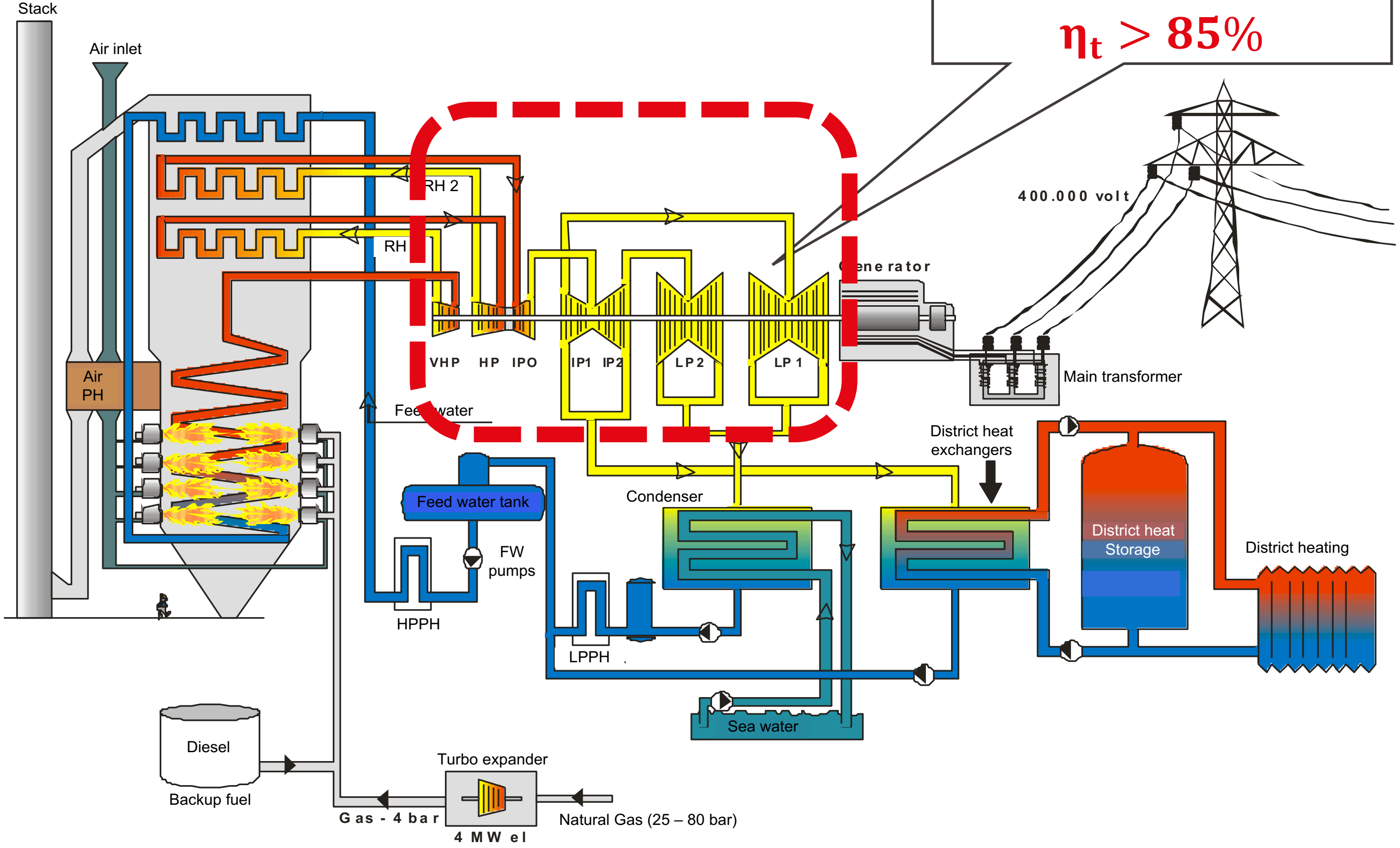
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle

– Improvement (1) – Turbine (η_t)

(1) Higher **turbine** efficiency

$\eta_t > 85\%$

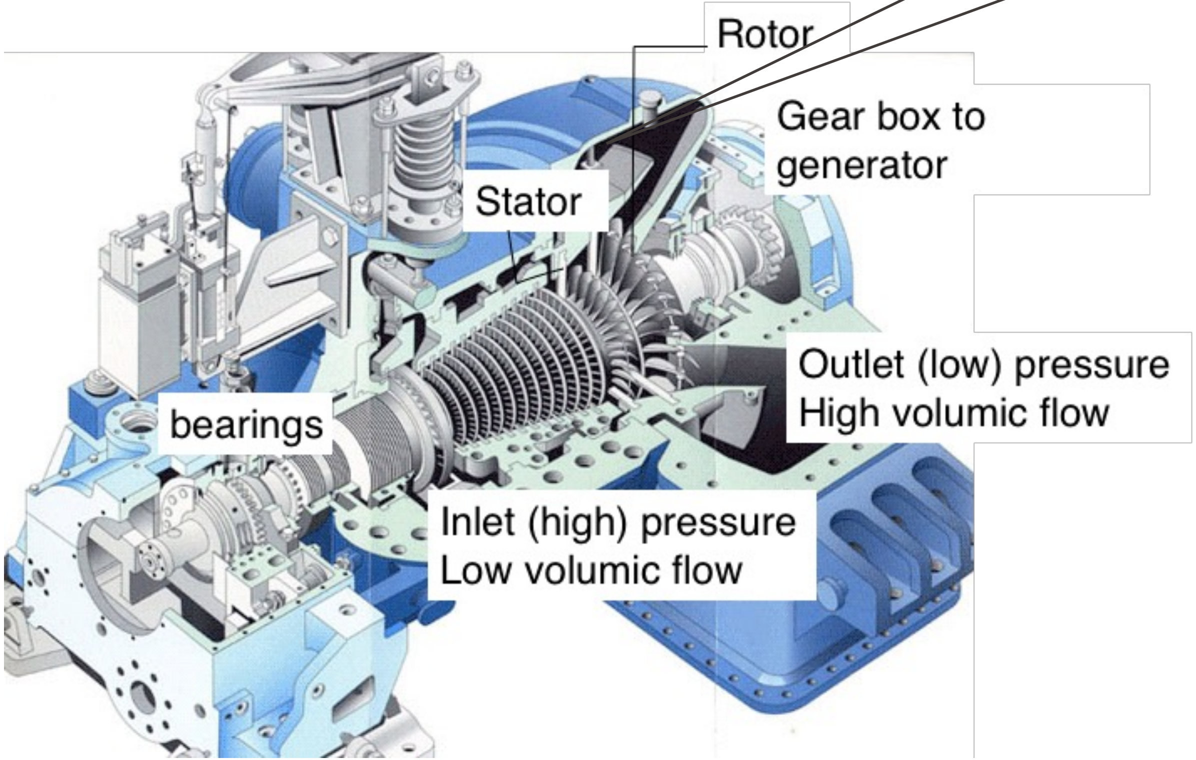


Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle
– Improvement (1) – Turbine (η_t)

(1) Higher **turbine** efficiency

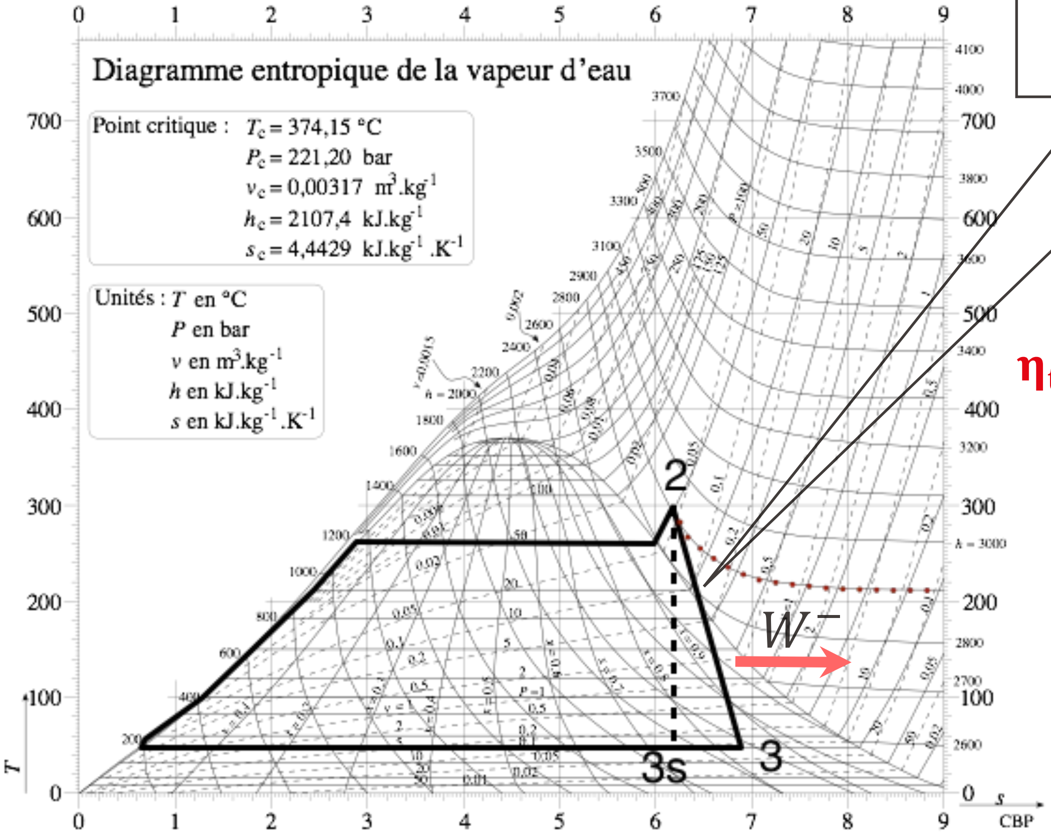
$\eta_t > 85\%$



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle

– Improvement (1) – Turbine (η_t)



(1) Higher **turbine** efficiency

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

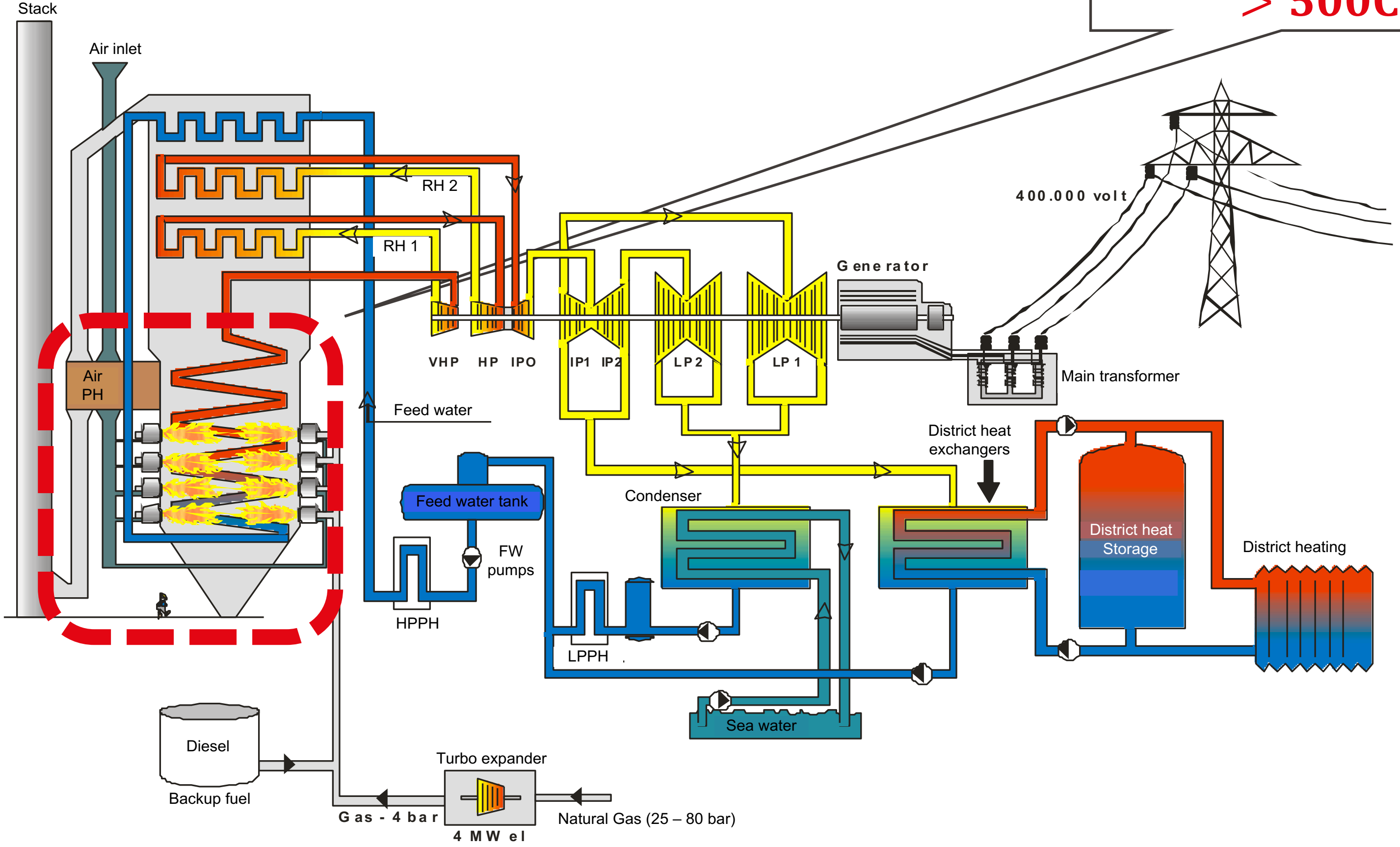
$$\frac{h_2(T_2, P_2) - h_3(T_3, P_3, x_3)}{h_2(T_2, P_2) - h_{is}(s_2(T_2, P_2), P_3)}$$

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle

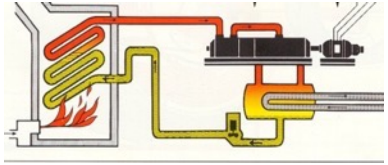
– Improvement (2) – Superheating

(2) Higher **boiler** temperatures
> 500C

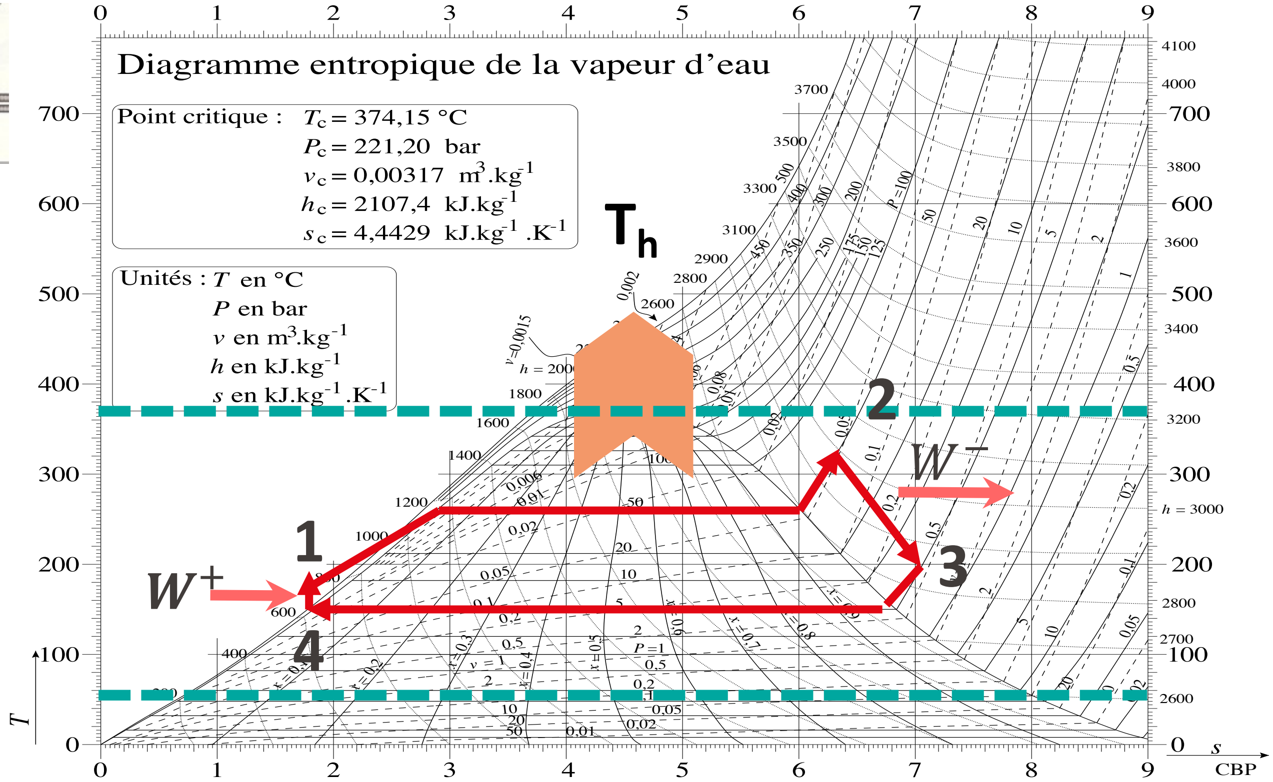


Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle
– Improvement (2) – Superheating



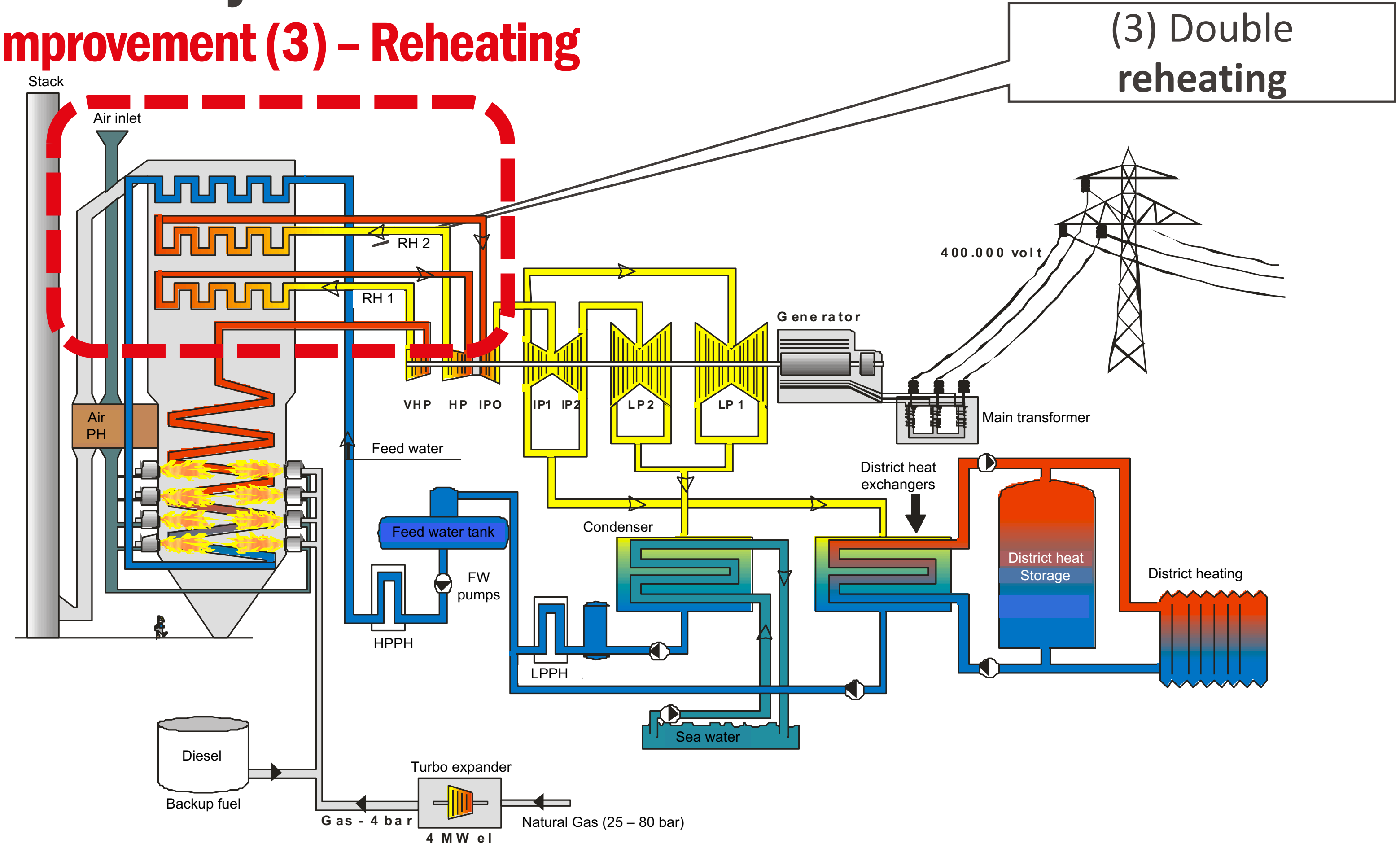
$$\theta = 1 - \frac{T_c}{T_h}$$



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle

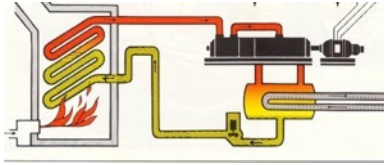
– Improvement (3) – Reheating



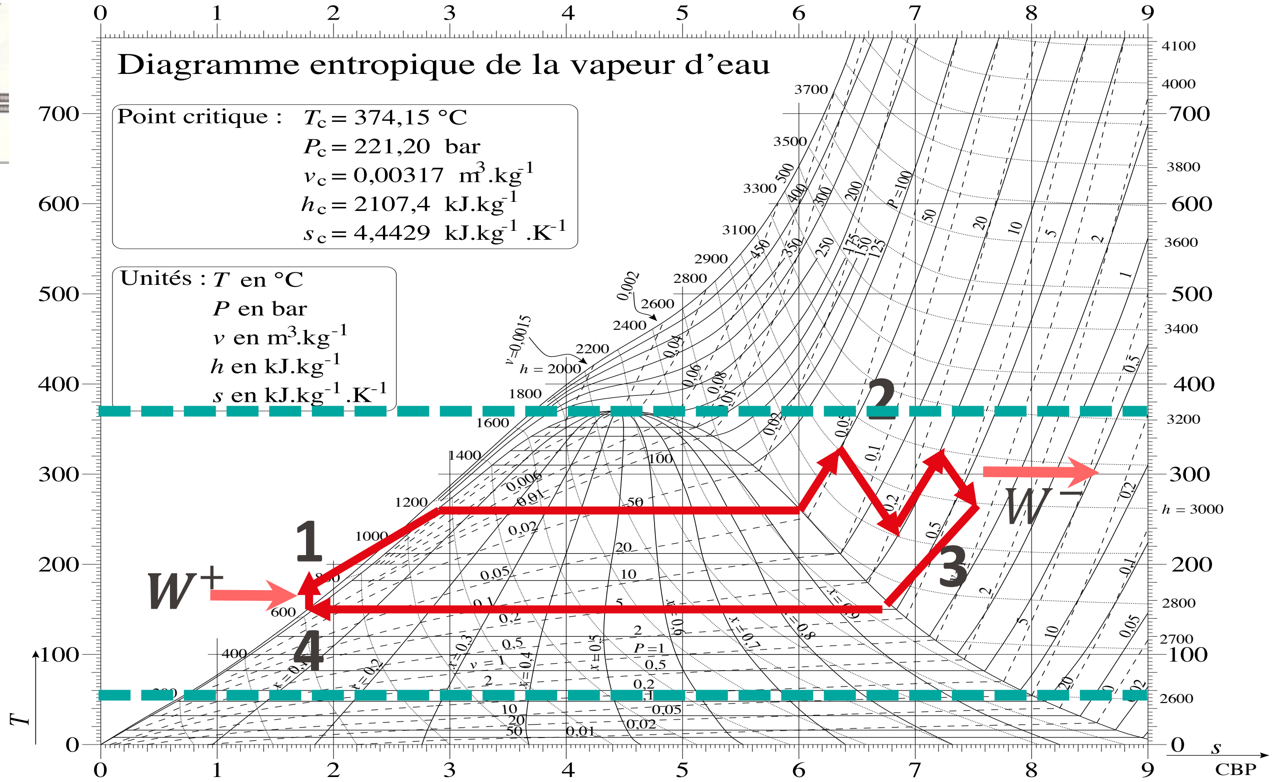
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle

– Improvement (3) – Reheating



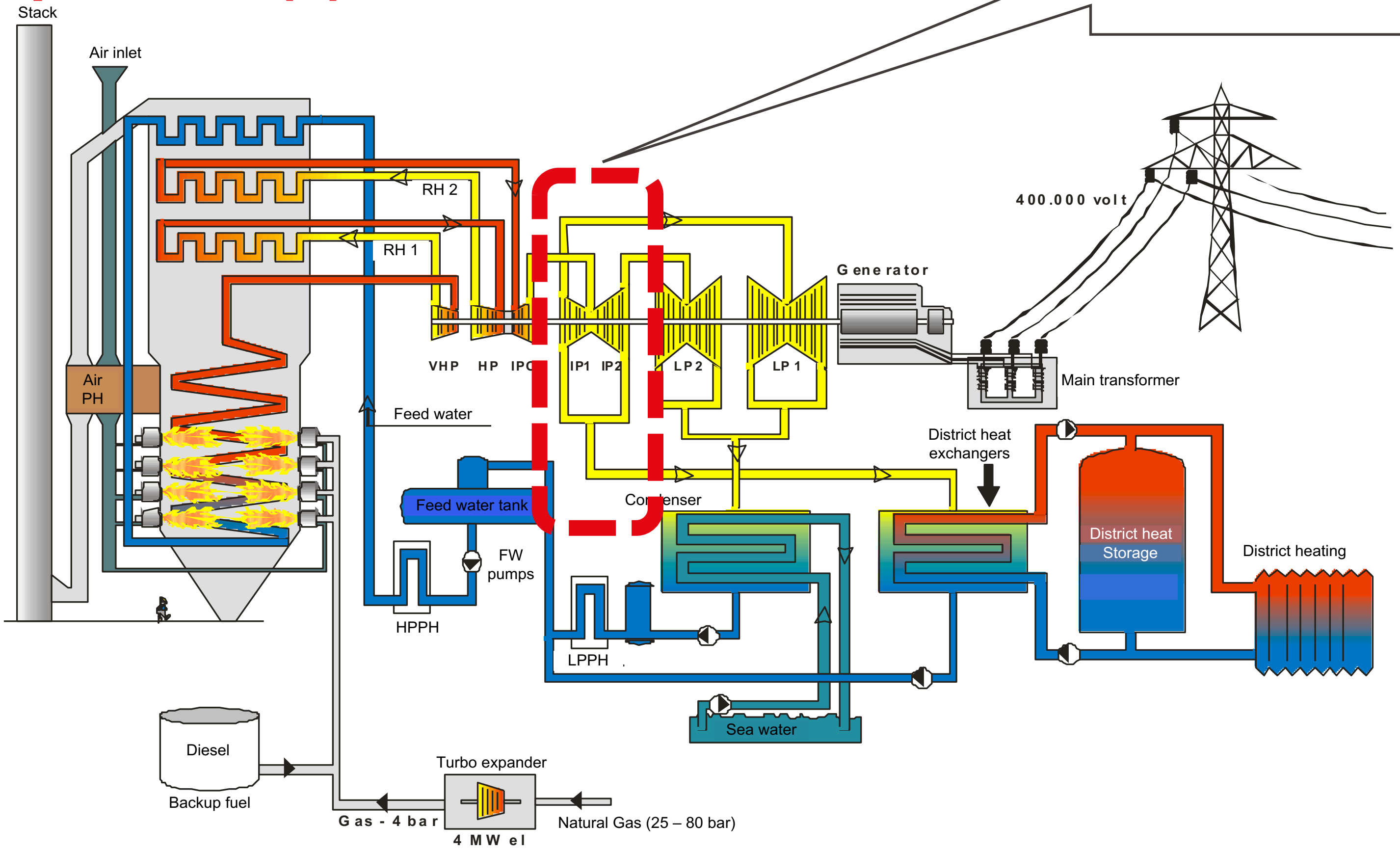
$$\theta = 1 - \frac{T_c}{T_h}$$



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle
– Improvement (4) – Draw-off

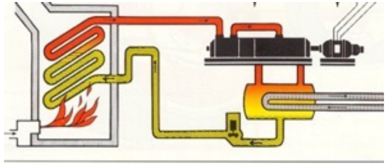
(4) Steam **draw-off**



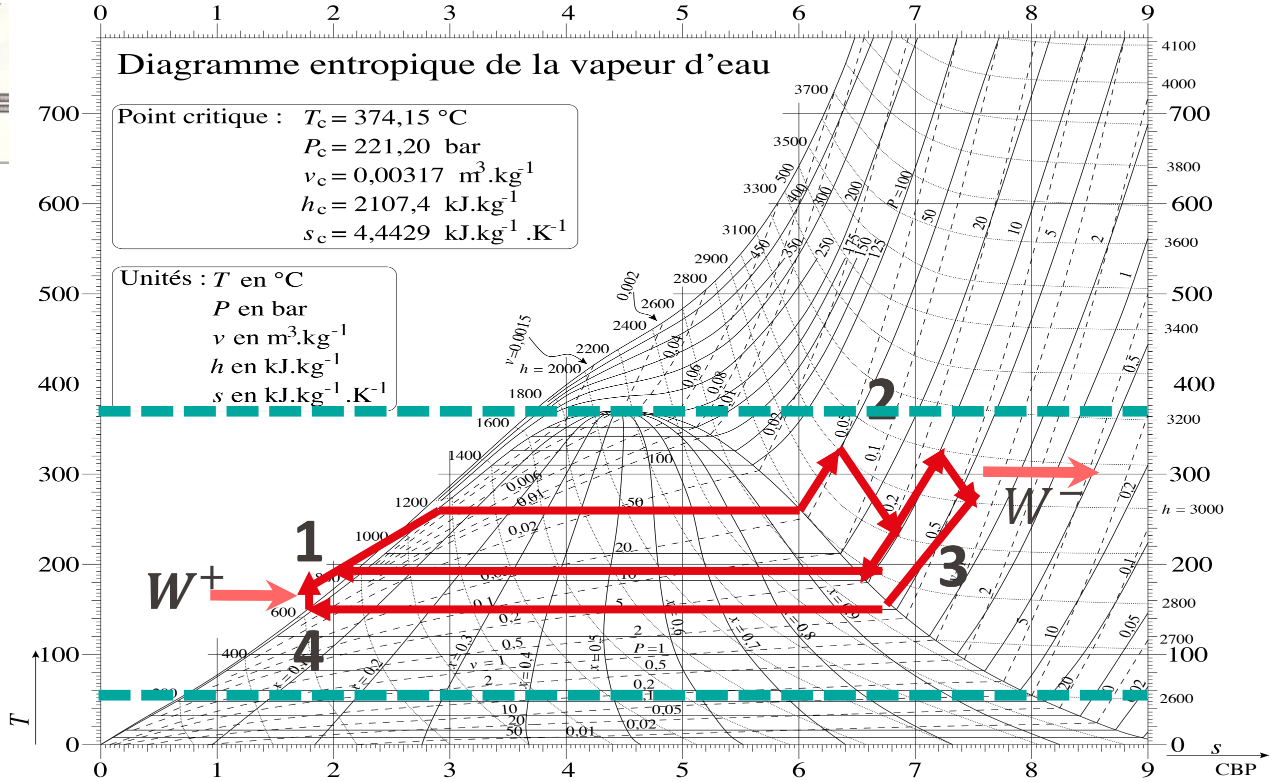
Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Rankine cycle

– Improvement (4) – Draw-off

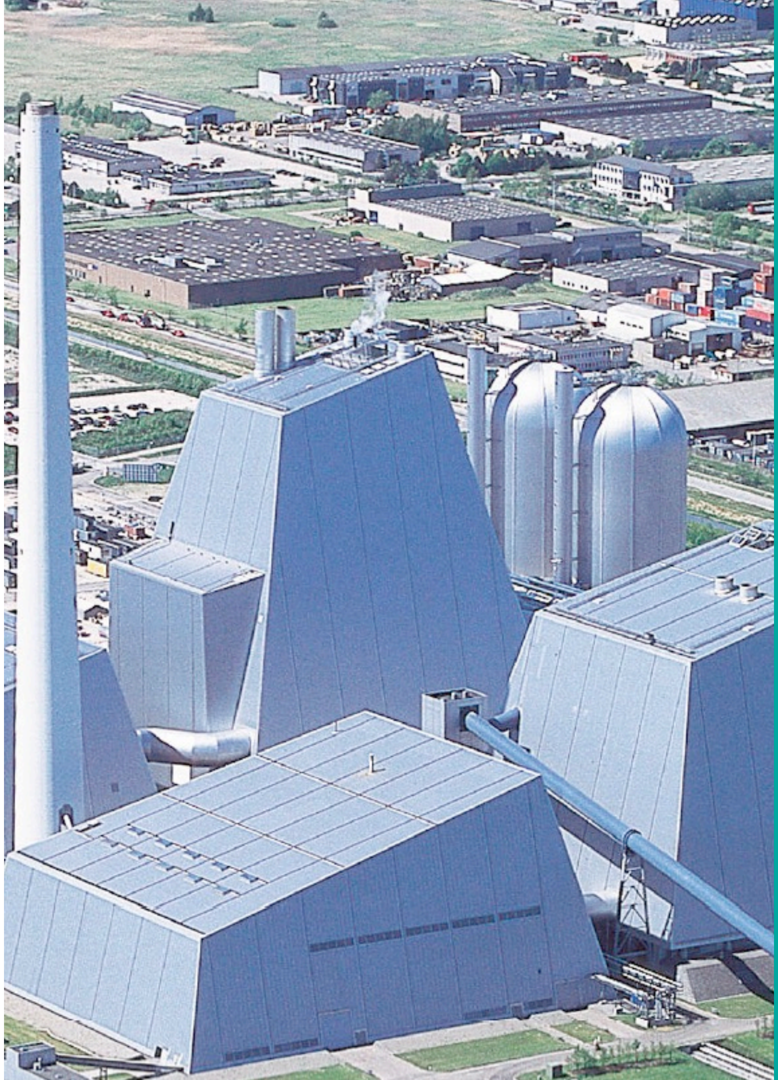


$$\theta = 1 - \frac{T_c}{T_h}$$



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

EPFL

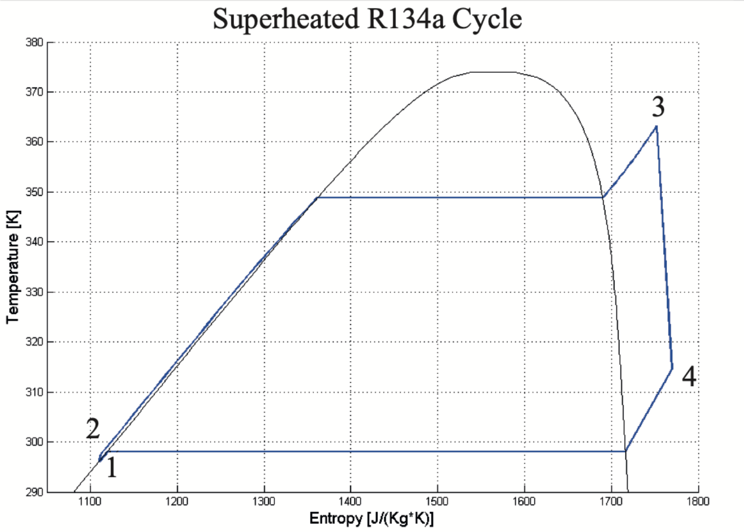


Rankine Cycles
Working fluids

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Changing the fluid : Organic Rankine cycles

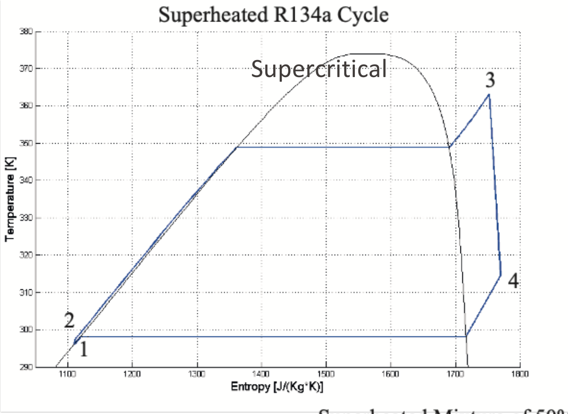
- When T source is low e.g. below 100°C
  - Difficulty working in sub-atmospheric conditions
  - Difficulty with phase change (water)
- Use of refrigerant => evaporation at higher pressure & lower temperature

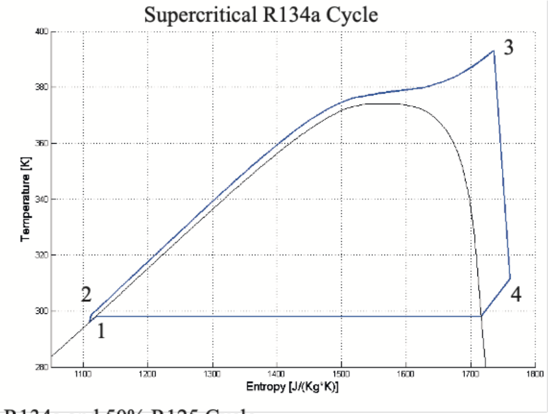


Different configurations

- The advantage of organic fluids:

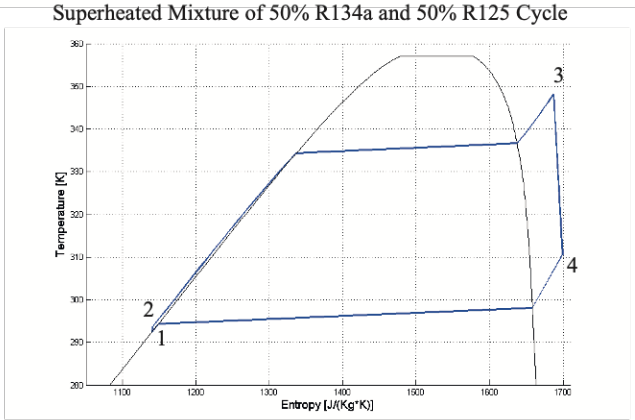
Many fluids = many possibilities in terms of operating pressure and temperature



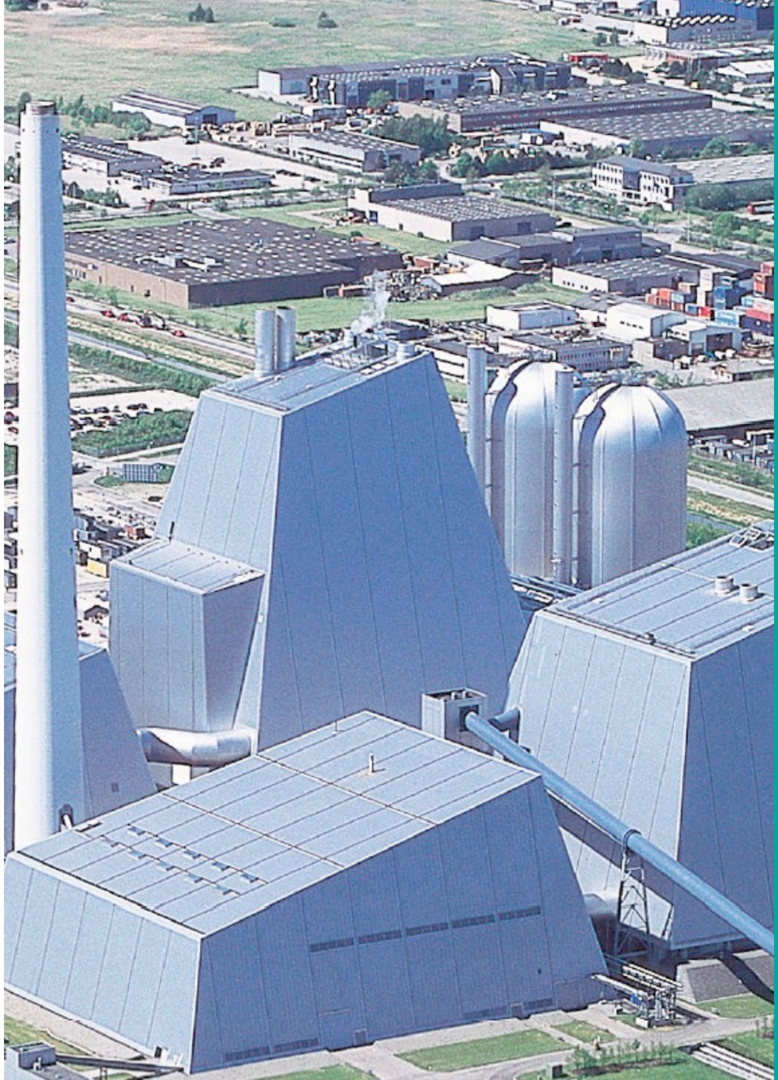


- Use of mixtures to adjust the properties and increase the efficiency

Mixtures



EPFL



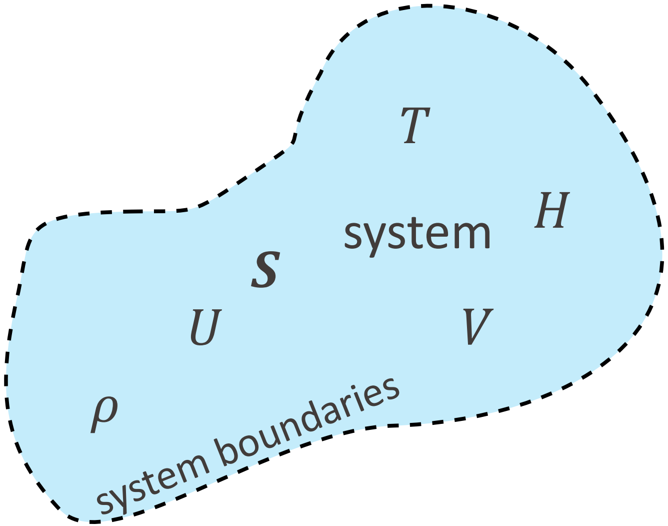
Take-home message

Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Take-home message

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

Gibbs' phase rule: F = C+2

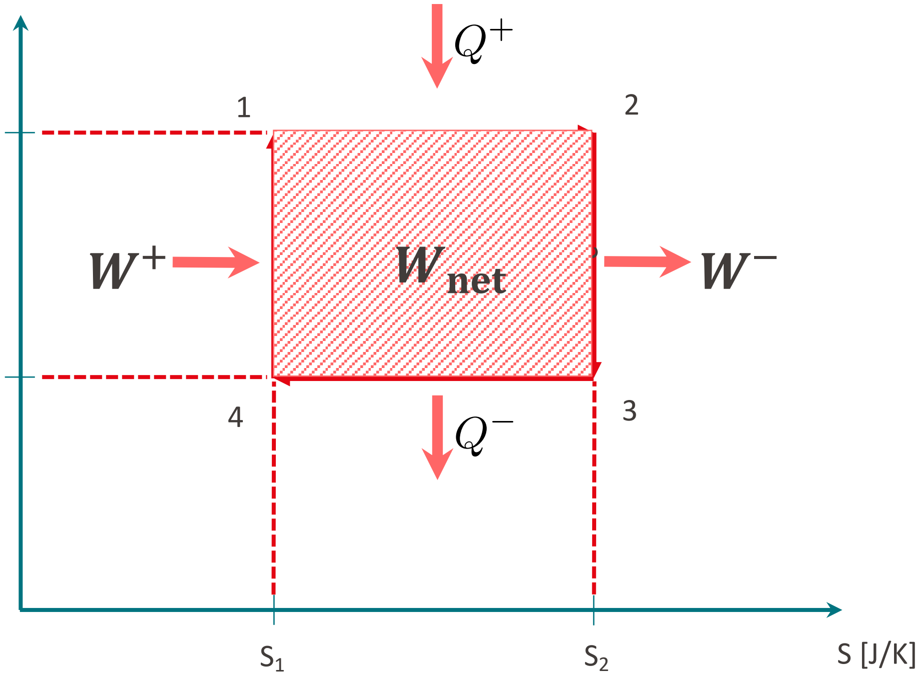


Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Take-home message

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

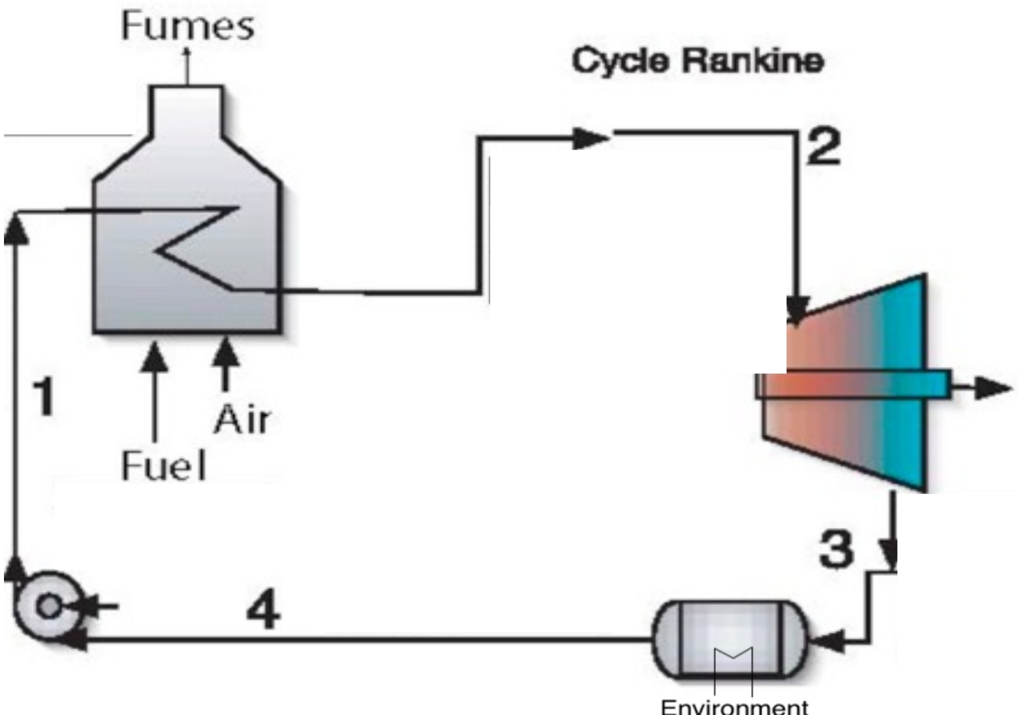
$$\boldsymbol{\theta} = 1 - \frac{T_c}{T_h}$$



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Take-home message

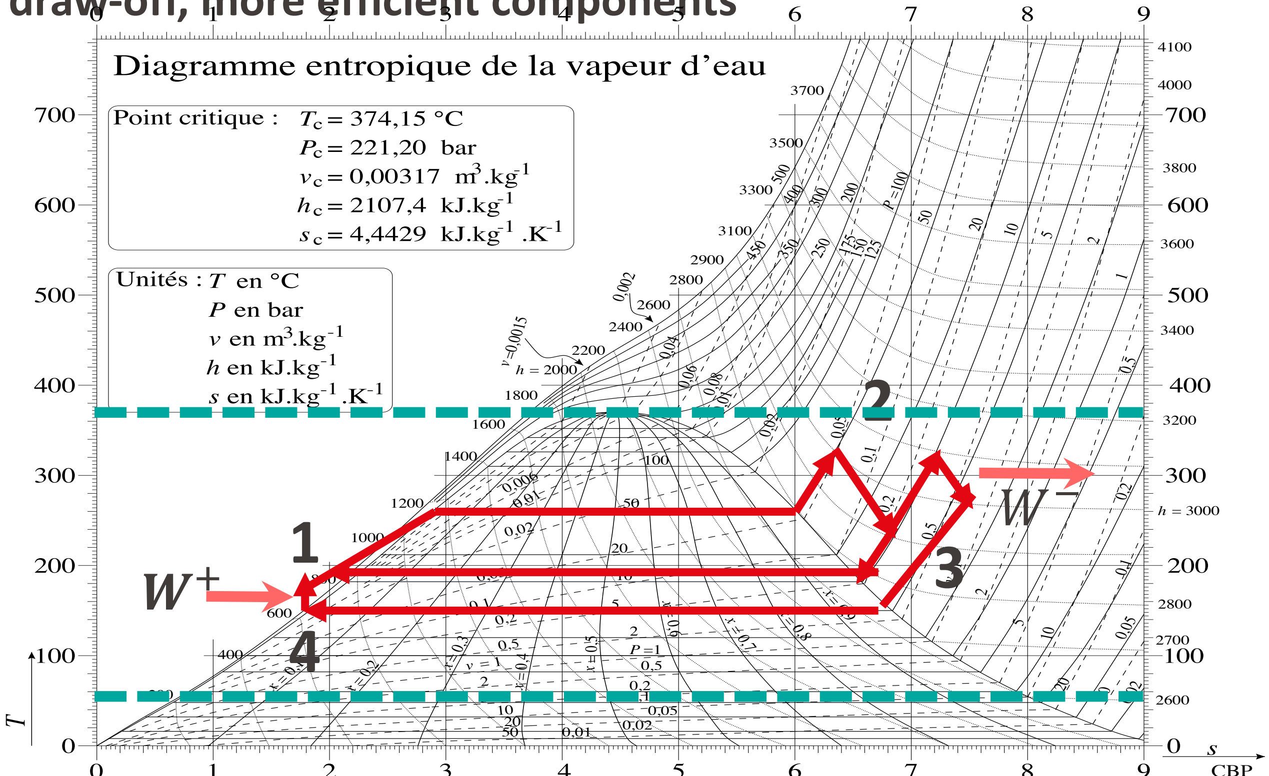
- Which process is **most used** in **power plants**? **Rankine cycle**



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Take-home message

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



Tuong-Van Nguyen – tuong-van.nguyen@epfl.ch

Questions?