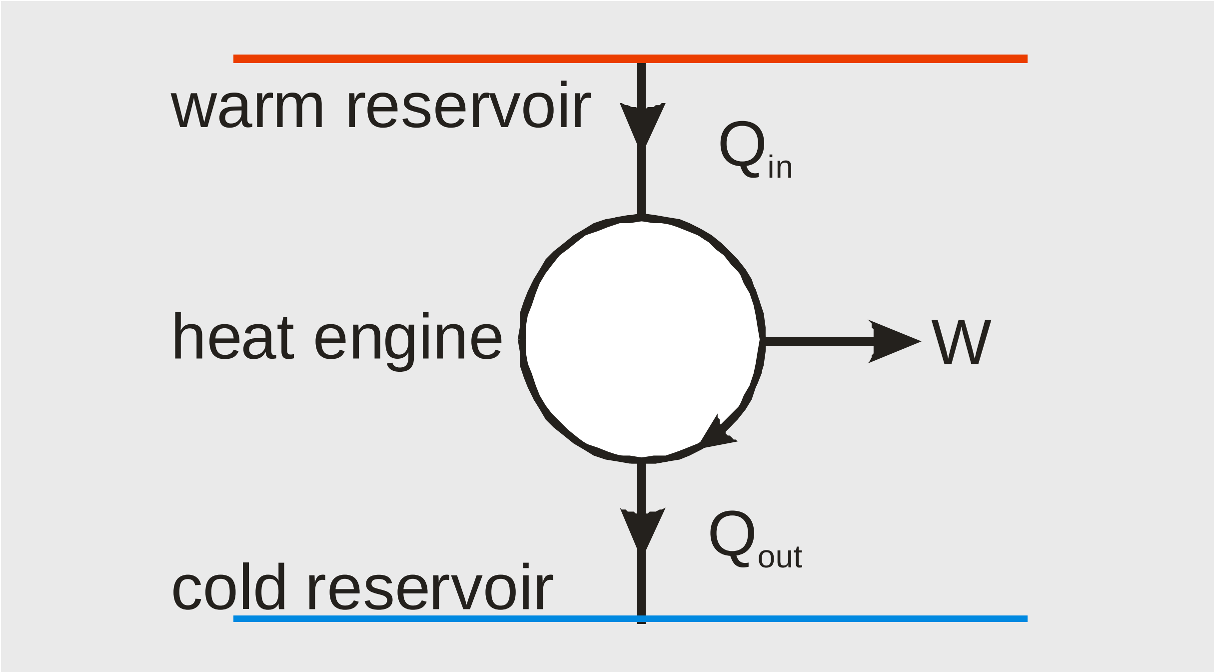
Low Enthalpy Cycles - Power Plant Concepts



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Situation

Heat source

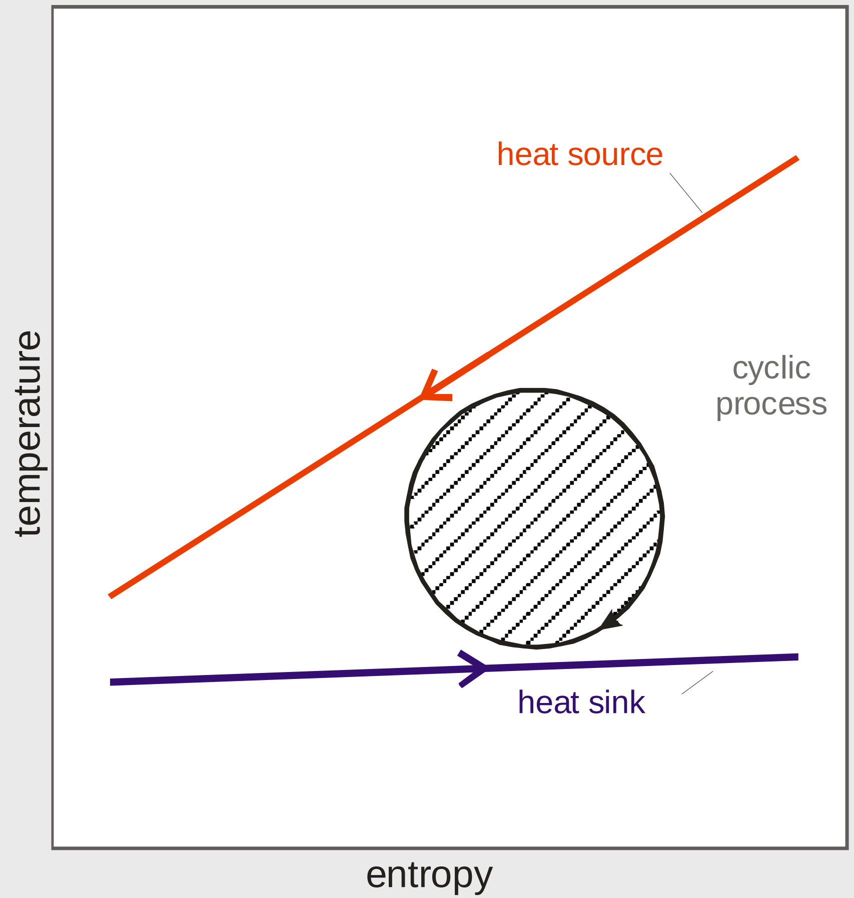
- Temperature
  100°C – 200°C
- Mass flow rate
  50 – 200 m³/h
  (~14 – 55 kg/s)
- Limited heat capacity
  ~ 5 to 50 MW_{th} per well
- Sensible heat

Goal: Electricity generation

Tools

- Cycles and systems
- Design and optimisation

→ Suitability of different cycles for particular applications



Optimisation of Ideal (Reversible) Cycles

Internally and externally reversible

- Carnot Cycle
- Lorentz Cycle
- Triangular Cycle

Internally reversible

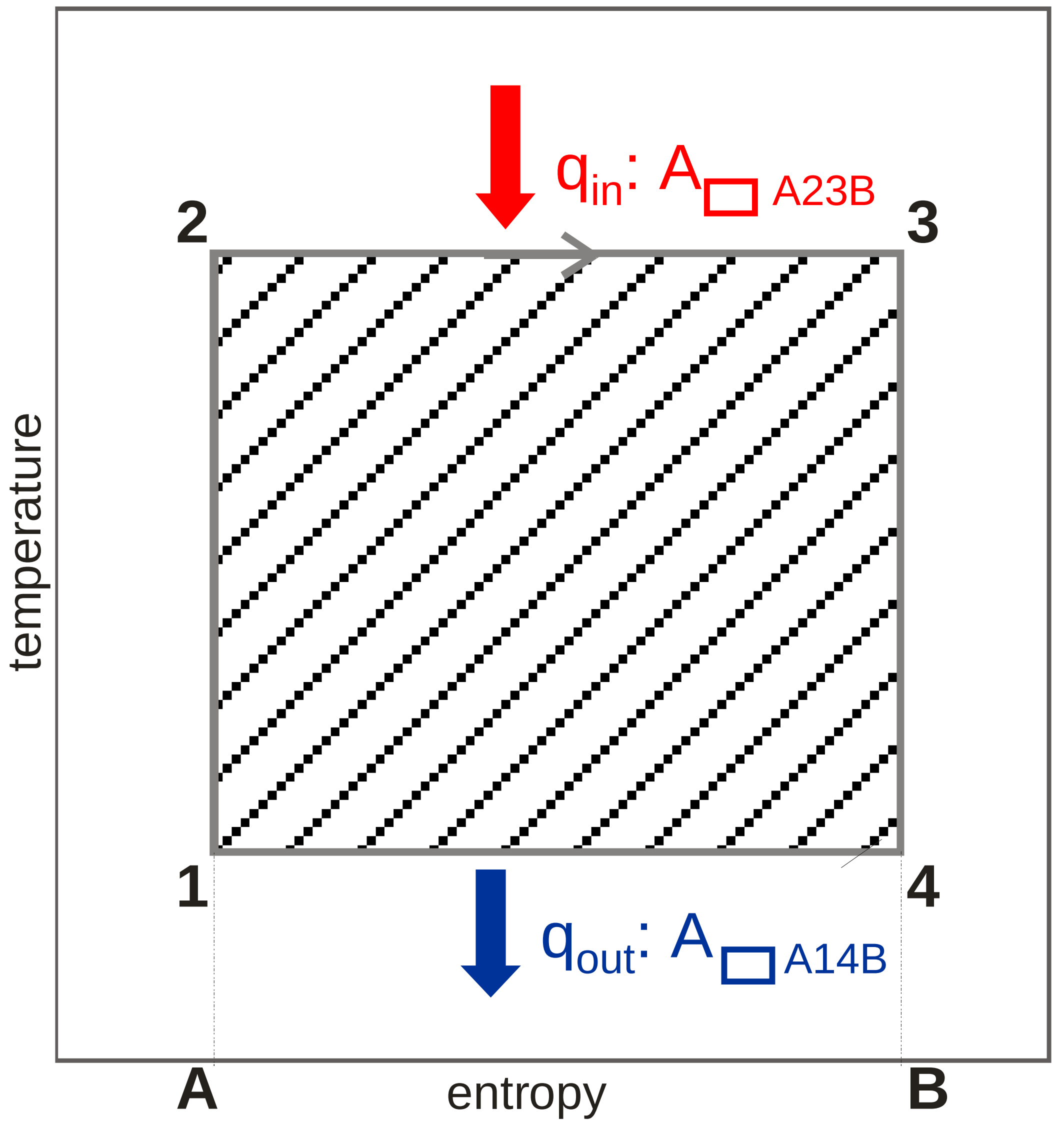
- Rankine Cycle - ideal cycle for steam power processes

Optimisation of the cycle locates the operating conditions for the optimal ideal cycle performance (Tamm et.al.)!

Optimisation approach:

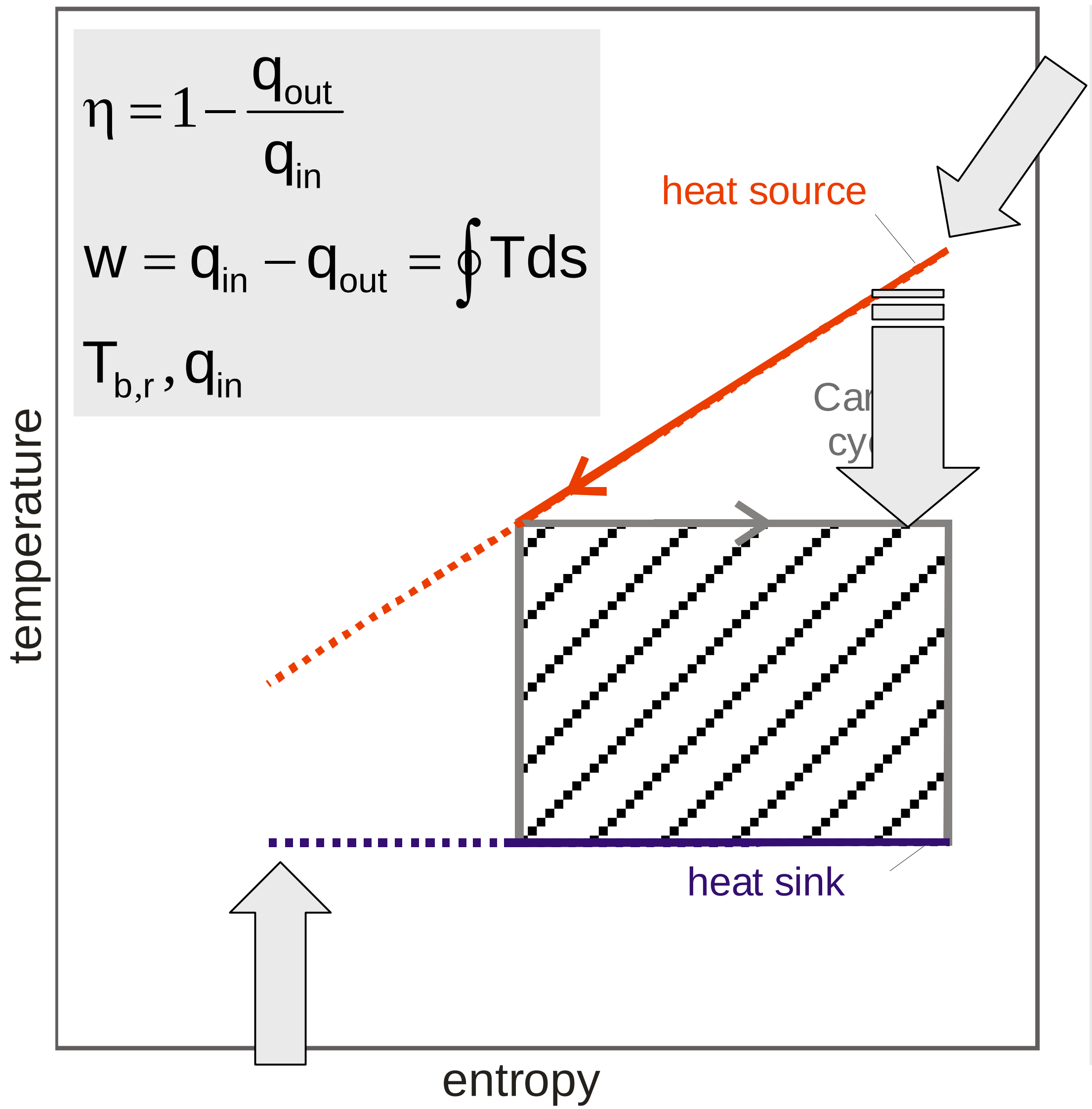
- Locate constraints → T, p
- Locate free variables
- Define optimisation criterium → objective function
- Find Max / Min by analytical or numerical solving of the function

Carnot Cycle



- $q = \int T ds$
- added heat q_{in}: $A_{\square A23B}$
- rejected heat q_{out}: $A_{\square A14B}$
- $w = q_{in} - q_{out} = \oint T ds$
- Net Work **w:** area A_{1234}
- Thermal efficiency η: area ratio $\dfrac{A_{1234}}{A_{\square A23B}}$

Optimisation of Carnot Cycle



Constraints

- Brine temperature, mass flow rate
- Heat sink temperature

Free variable

- Upper process temperature $\mathbf{T_e}$

Possible objective functions

- Thermal efficiency η
- Net Work **w**
- Added heat $\mathbf{q_{in}}$ / Cooling of the brine $\mathbf{T_{b,r}}$

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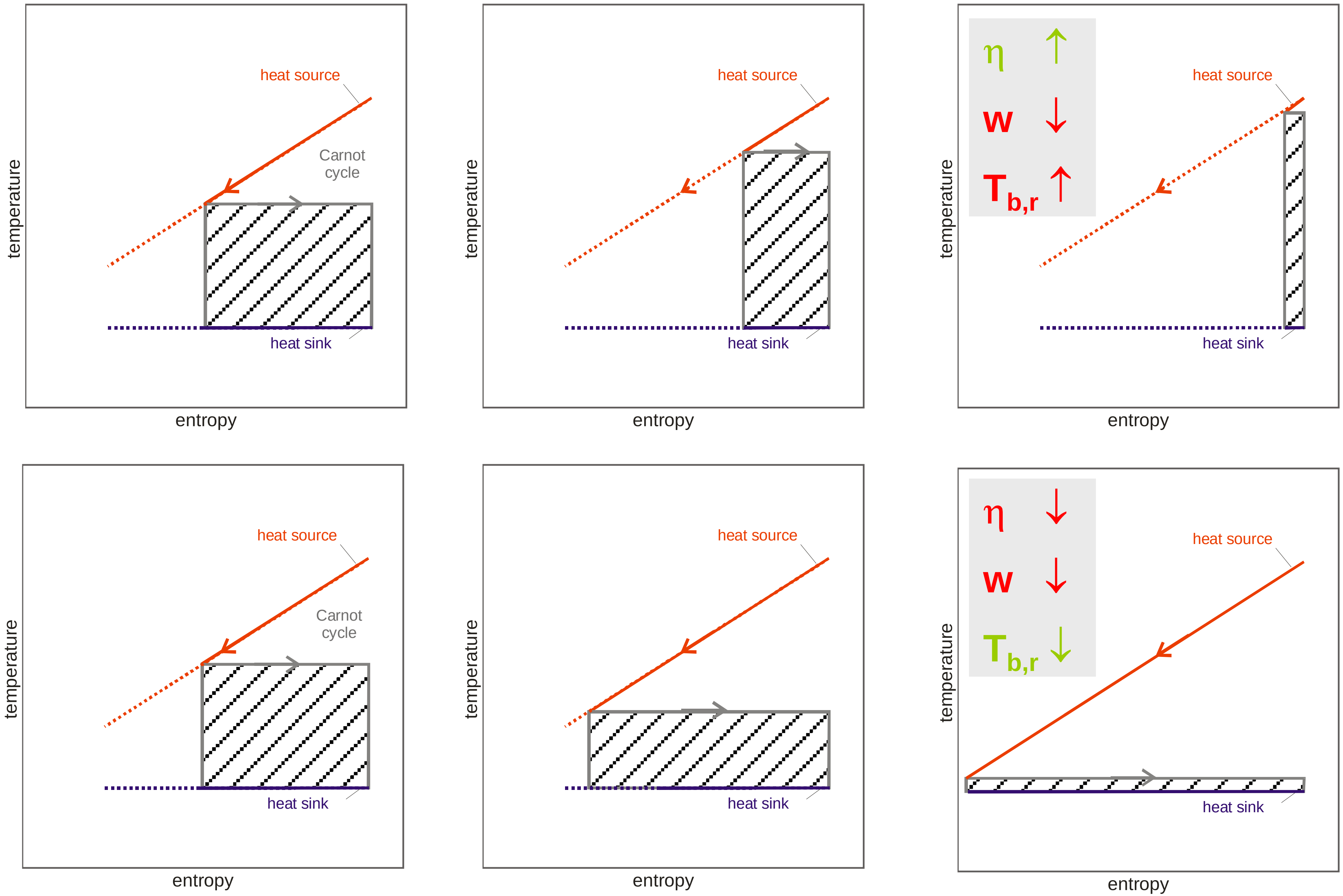
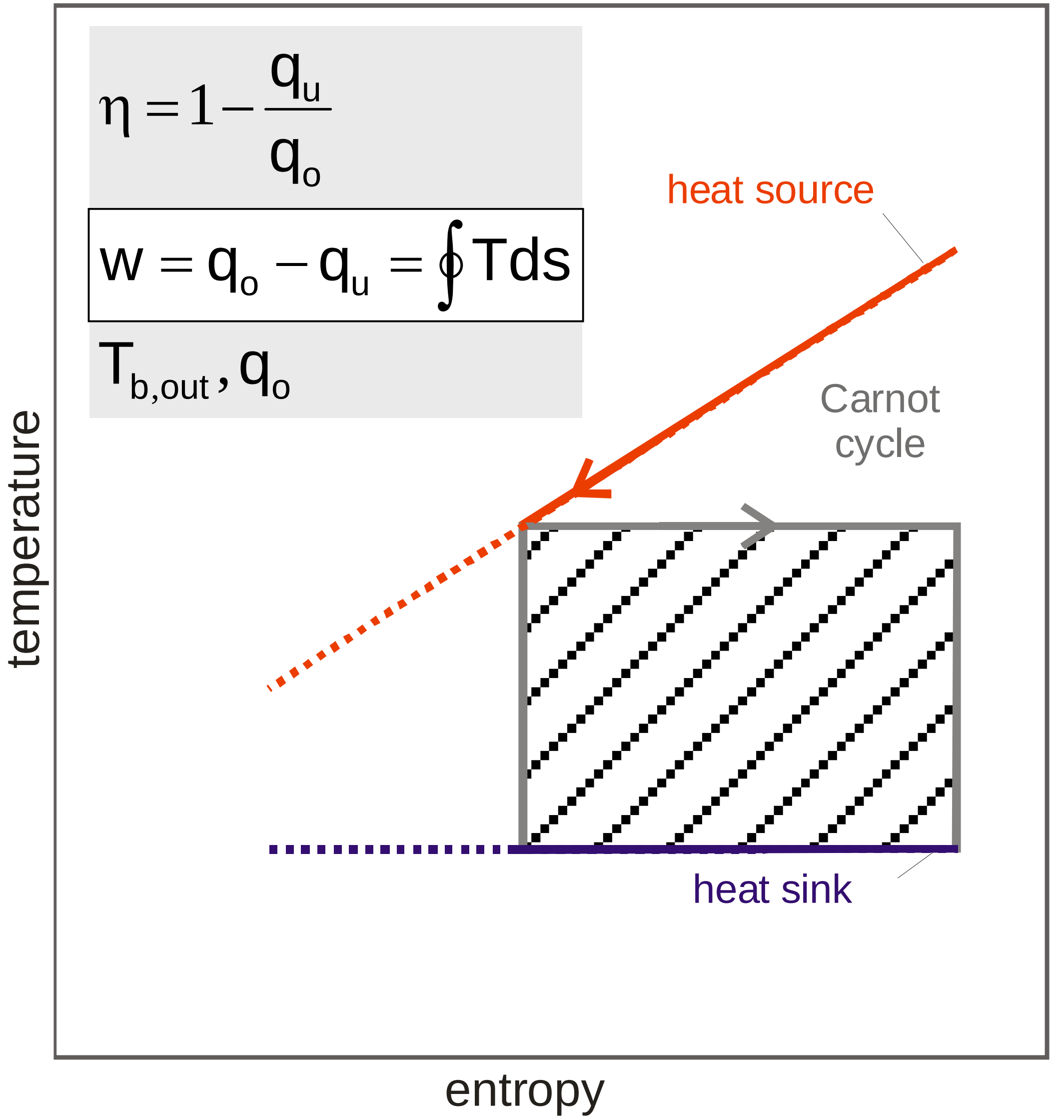
Optimisation of Carnot Cycle

HELMHOLTZ GEMEINSCHAFT



Optimisation of Carnot Cycle



$$\eta = 1 - \frac{q_u}{q_o}$$

$$w = q_o - q_u = \oint T ds$$

$$T_{b,out}, q_o$$

Constraints

- Brine temperature, mass flow rate
- Heat sink temperature

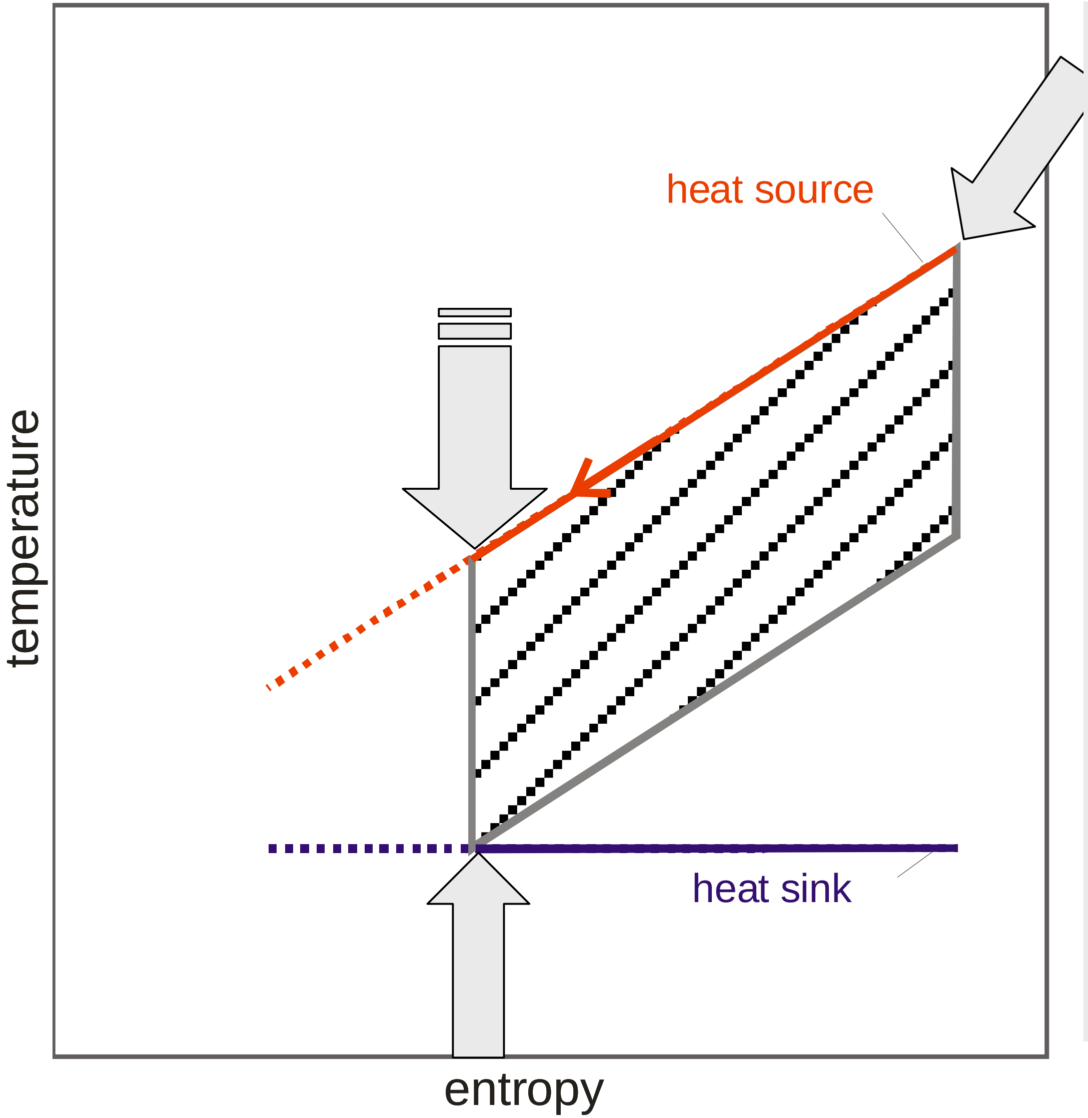
Free variable

- Upper process temperature

Possible objective functions

- ~~Thermal efficiency~~ η
- **Net Work w**
- ~~Cooling of the brine~~ $\mathbf{T_{b,r}}$

Lorentz Cycle



Constraints

- Brine temperature, mass flow rate
- Heat sink temperature

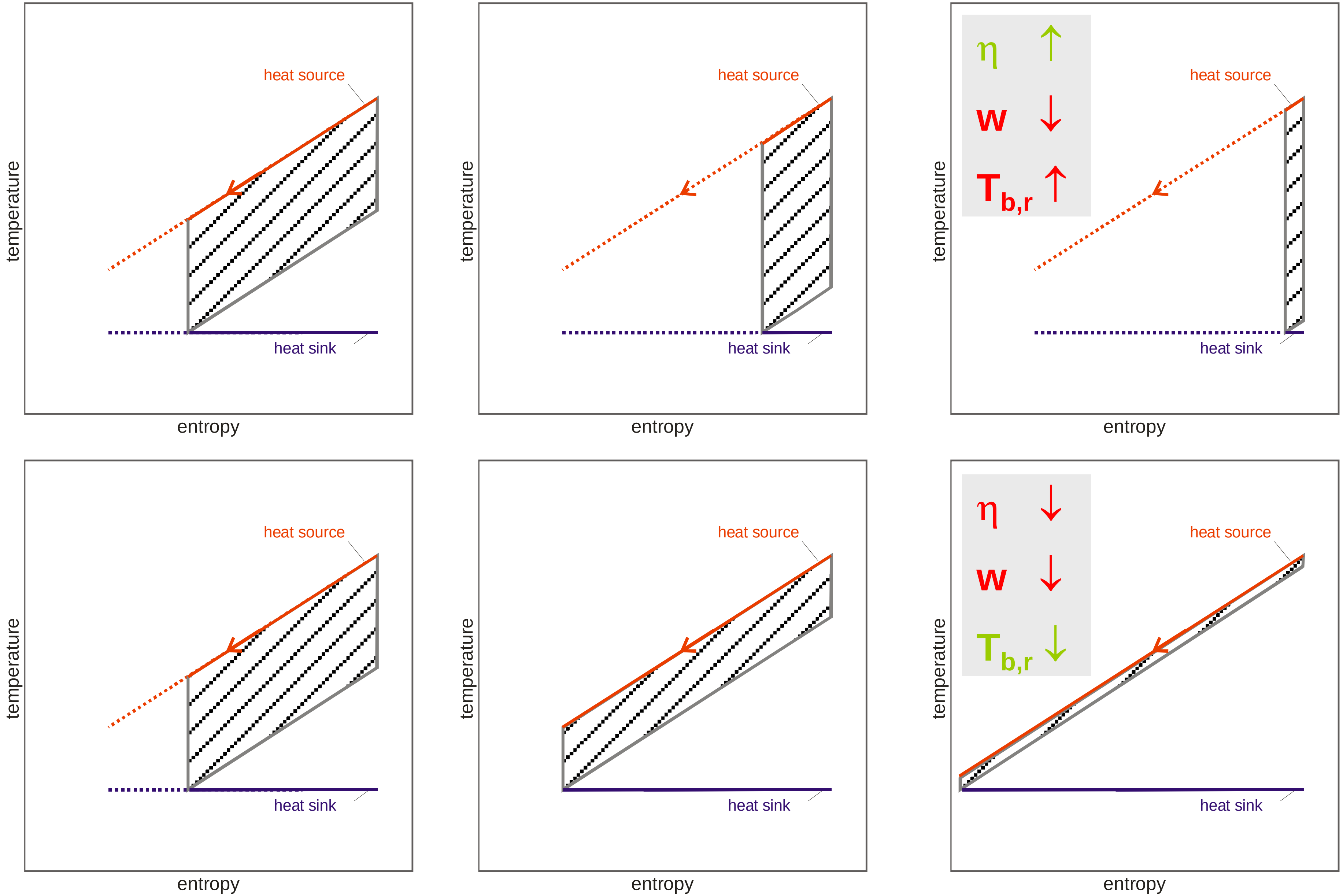
Free variable

- Upper process temperature $\mathbf{T_e}$

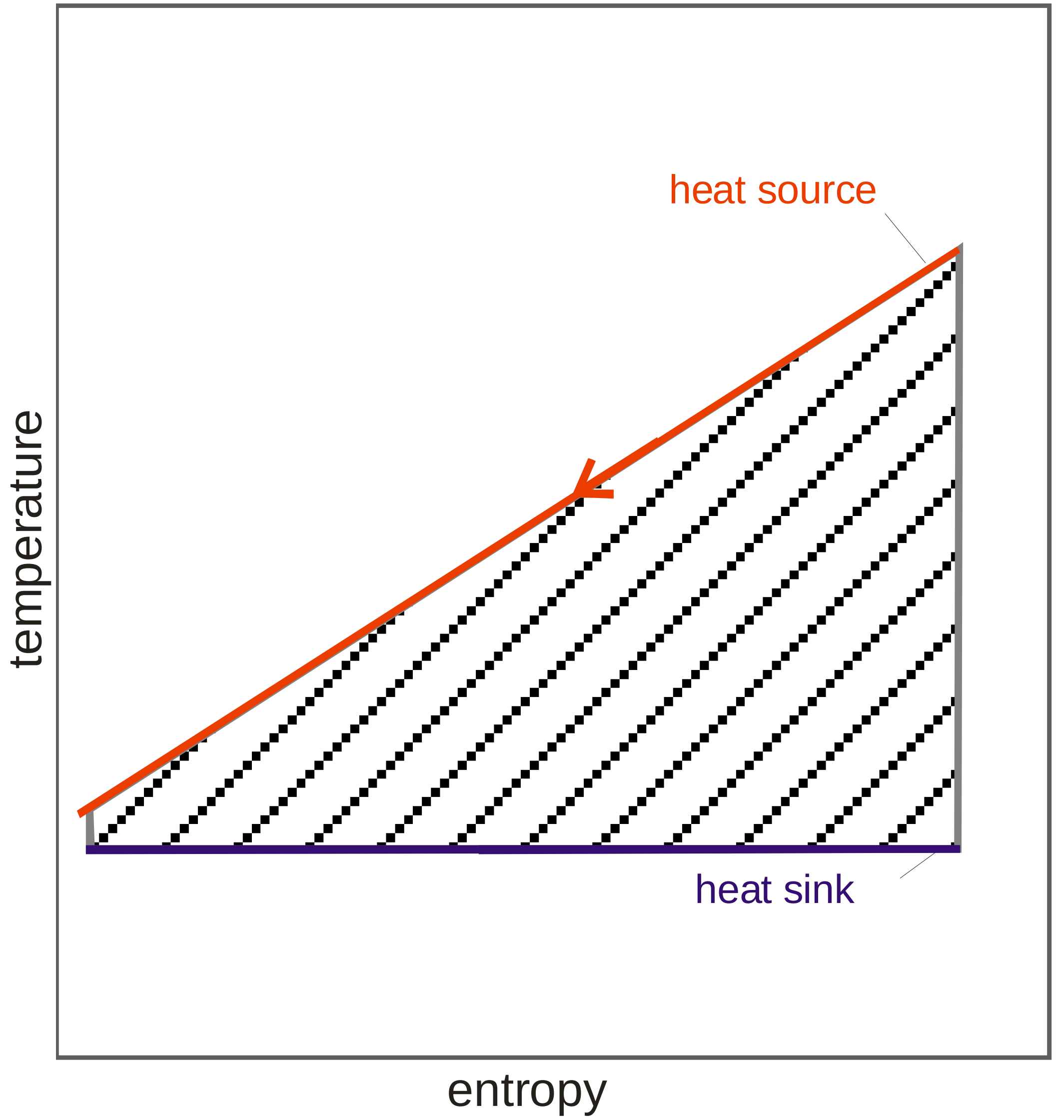
Possible objective functions

- Thermal efficiency η
- Net Work **w**
- Added heat $\mathbf{q_{in}}$ / Cooling of the brine $\mathbf{T_{b,r}}$

Optimisation of Lorentz Cycle



Reversible Triangular Cycle



Fits in heat source / heat sink characteristics

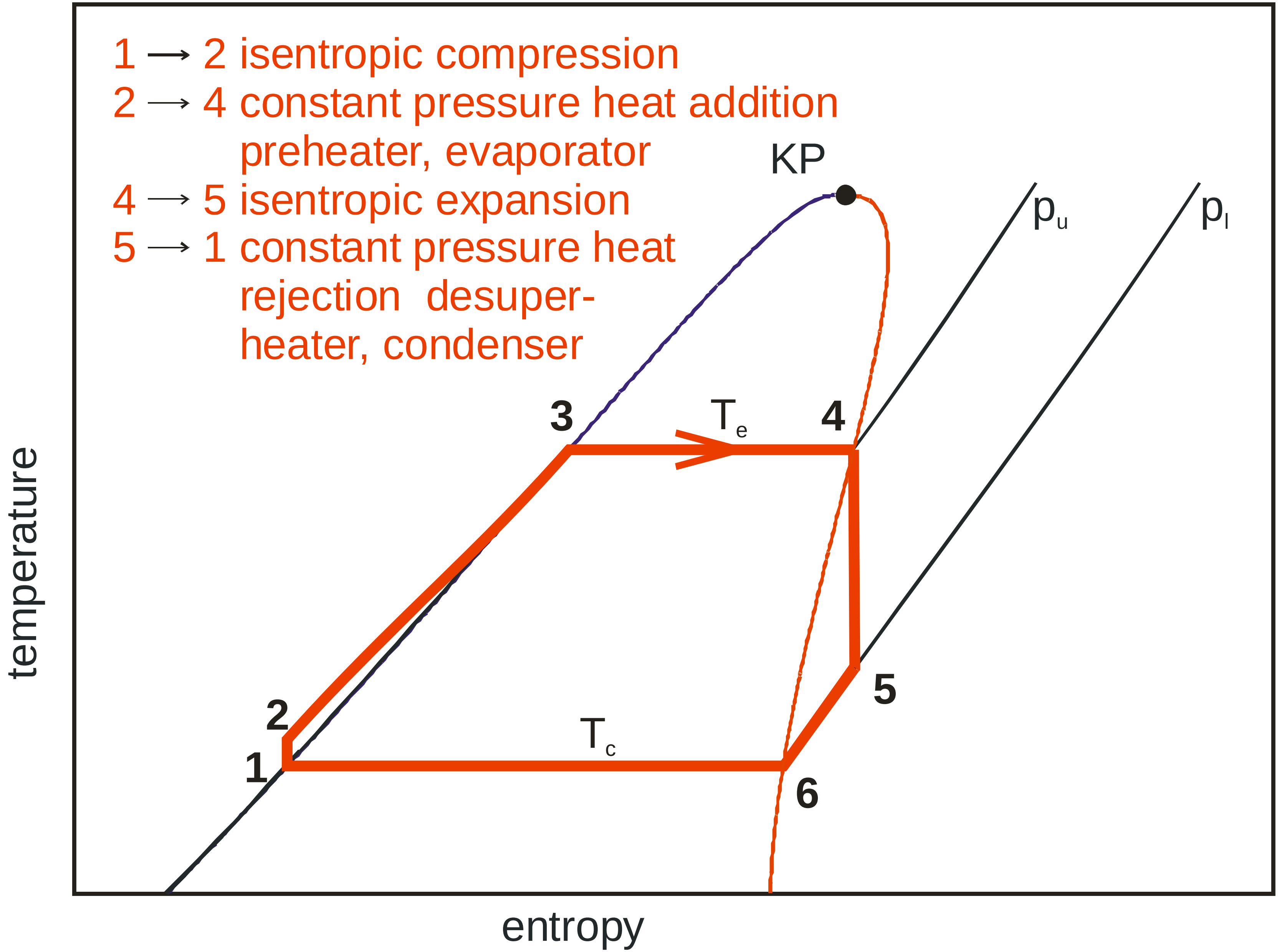
No optimisation

Availability? – not all state changes can be realized with available hard ware

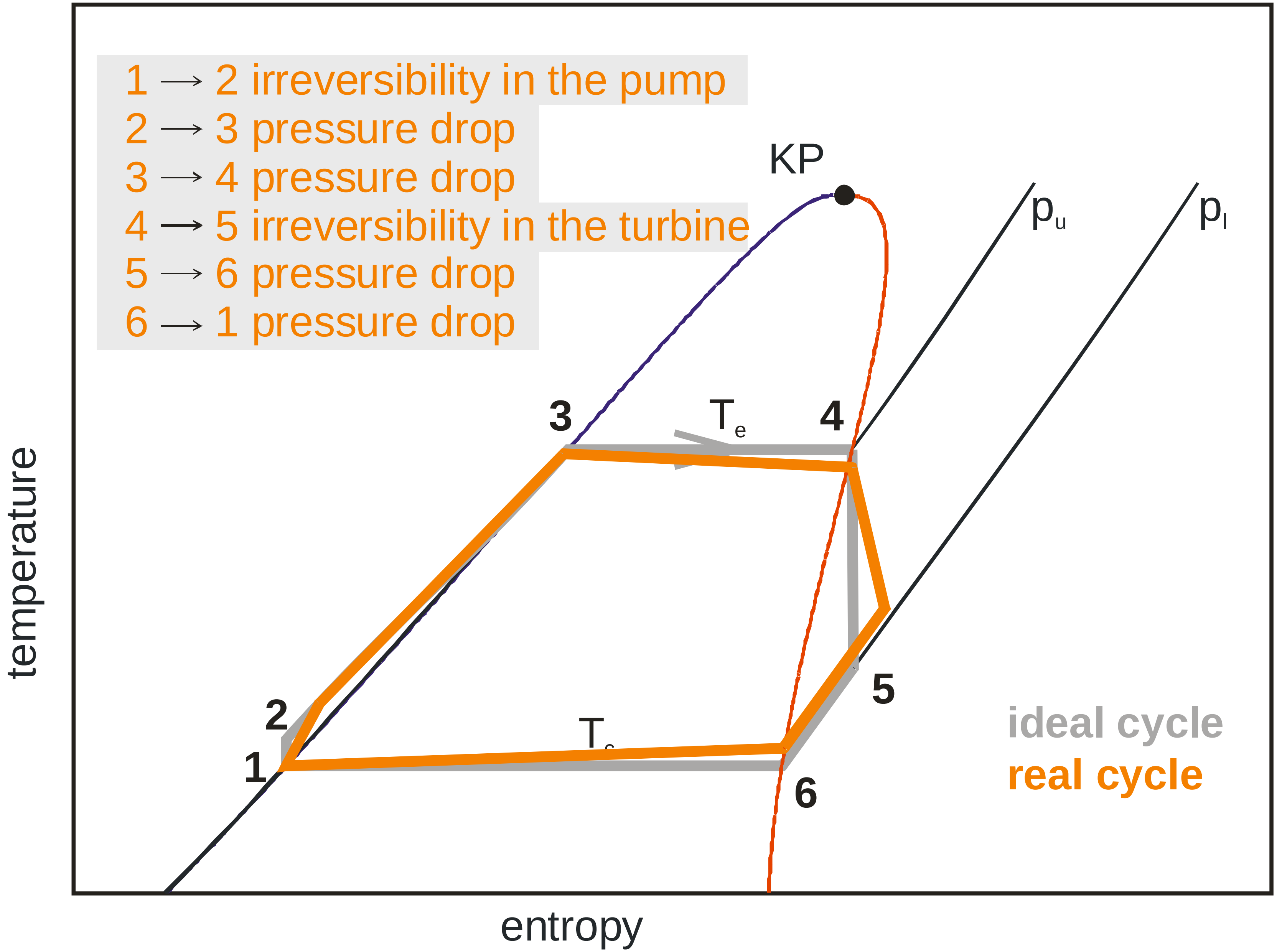
Ideal cycles help to analyse complex problems

Real cycles suffer losses

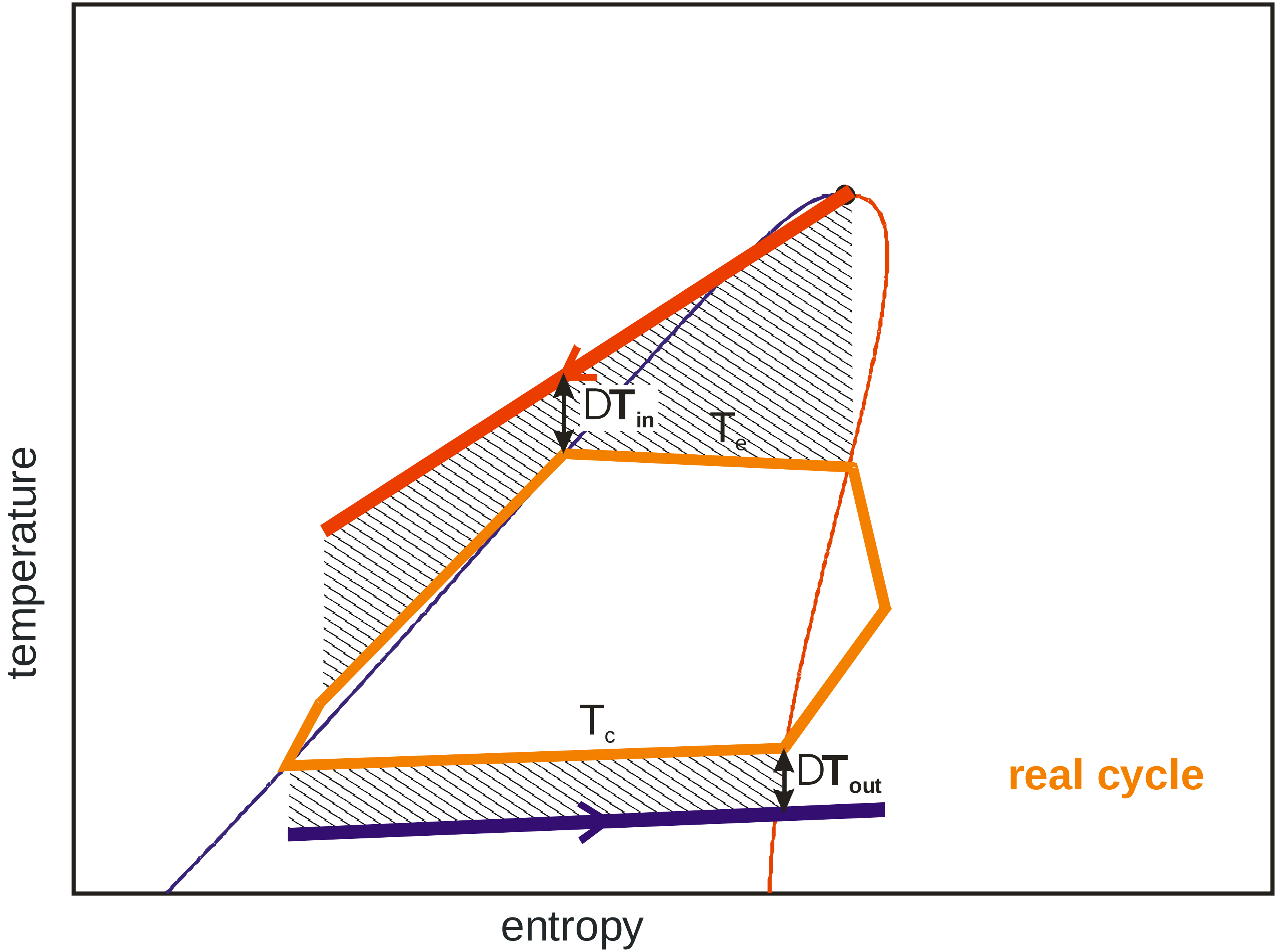
Rankine Cycle (Organic Working Fluid)



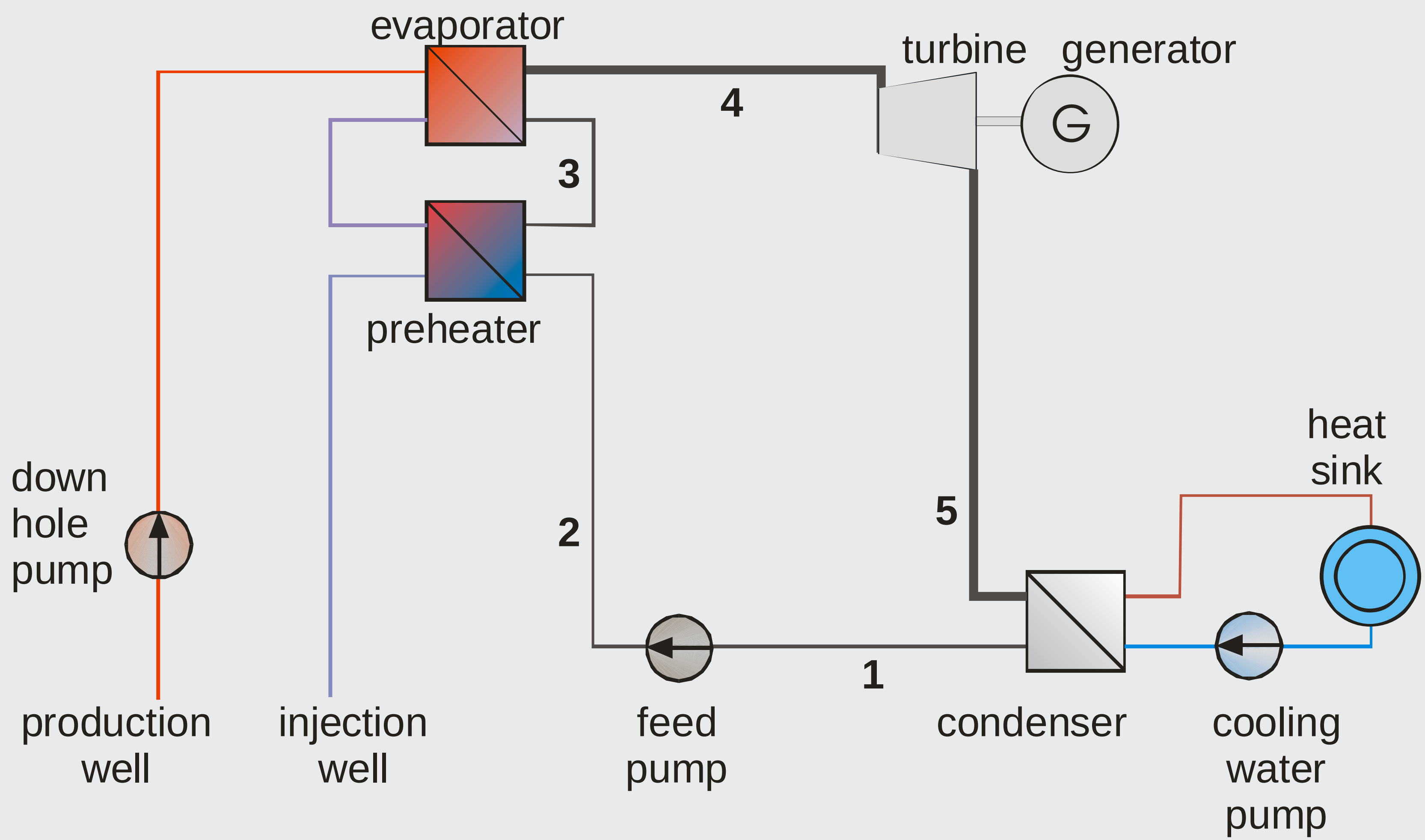
Actual Vapor Power Cycle (Organic Working Fluid)



Irreversible Heat Transfer

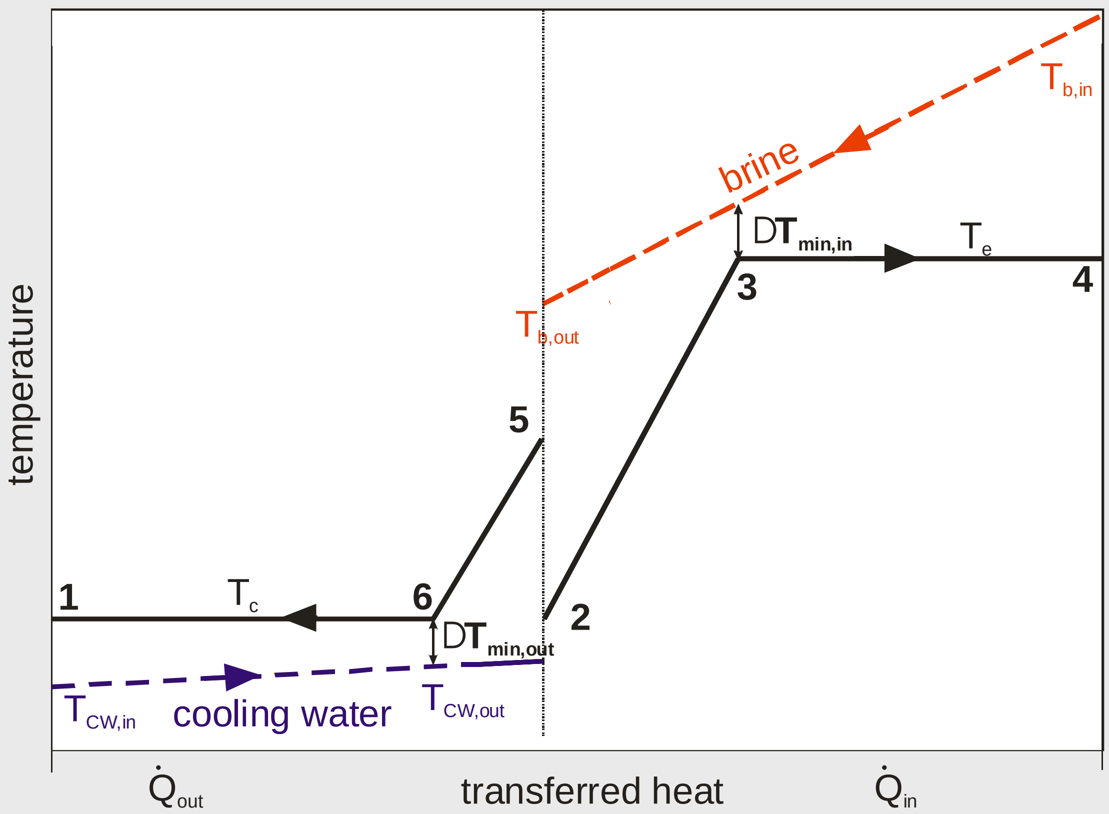


ORC Layout



evaporator
turbine
generator
G
4
3
preheater
heat
sink
down
hole
pump
2
5
1
production
well
injection
well
feed
pump
condenser
cooling
water
pump

Heat Transfer Diagram ORC



Constraints

- Brine: $T_{b,in}$, mass flow rate, specific heat capacity
- Cooling medium: $T_{CW,in}$, $T_{CW,out}$, specific heat capacity

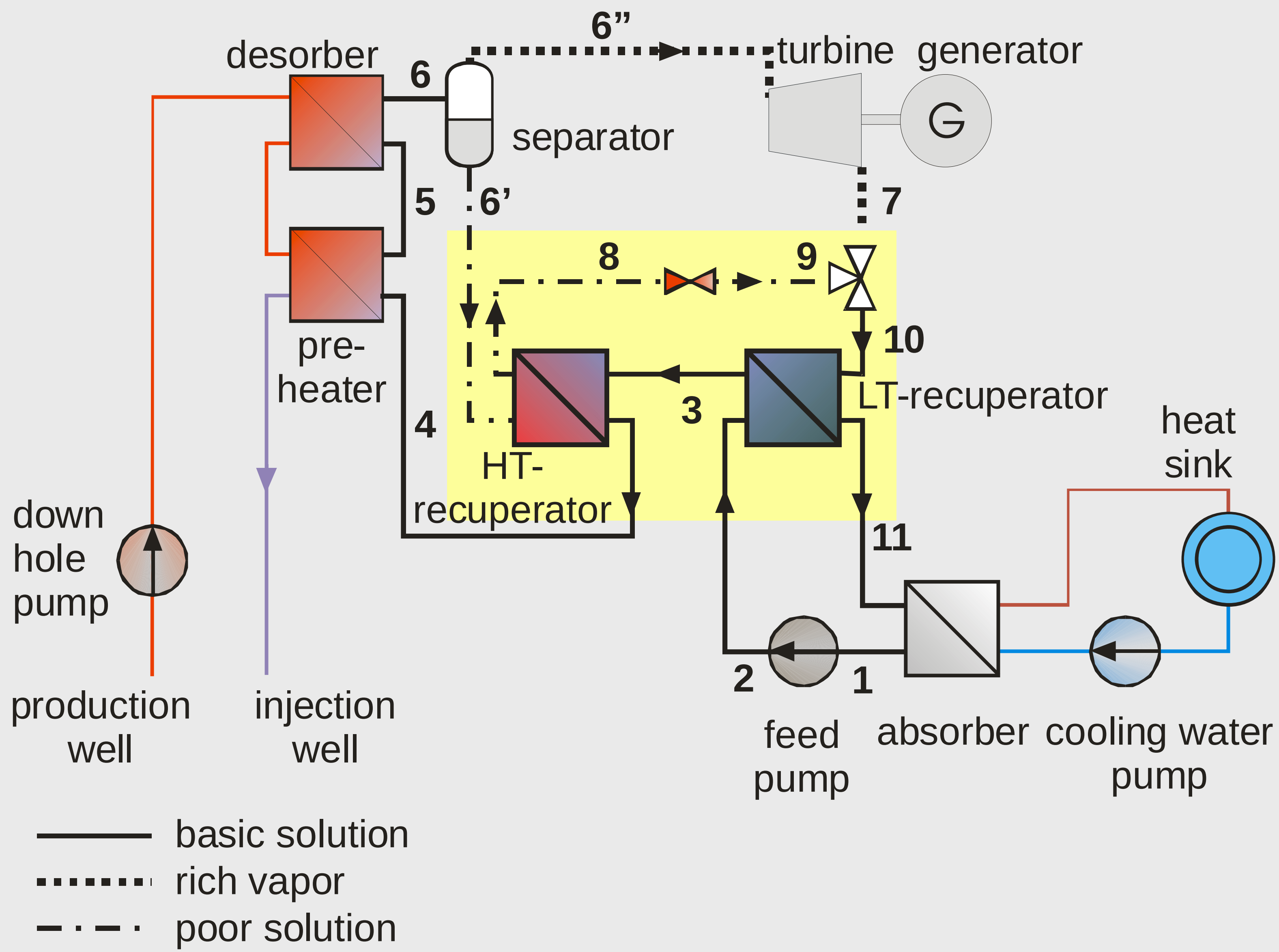
Free variables

- Working fluid
- T_e
- $\Delta T_{min,in}$, $\Delta T_{min,out}$

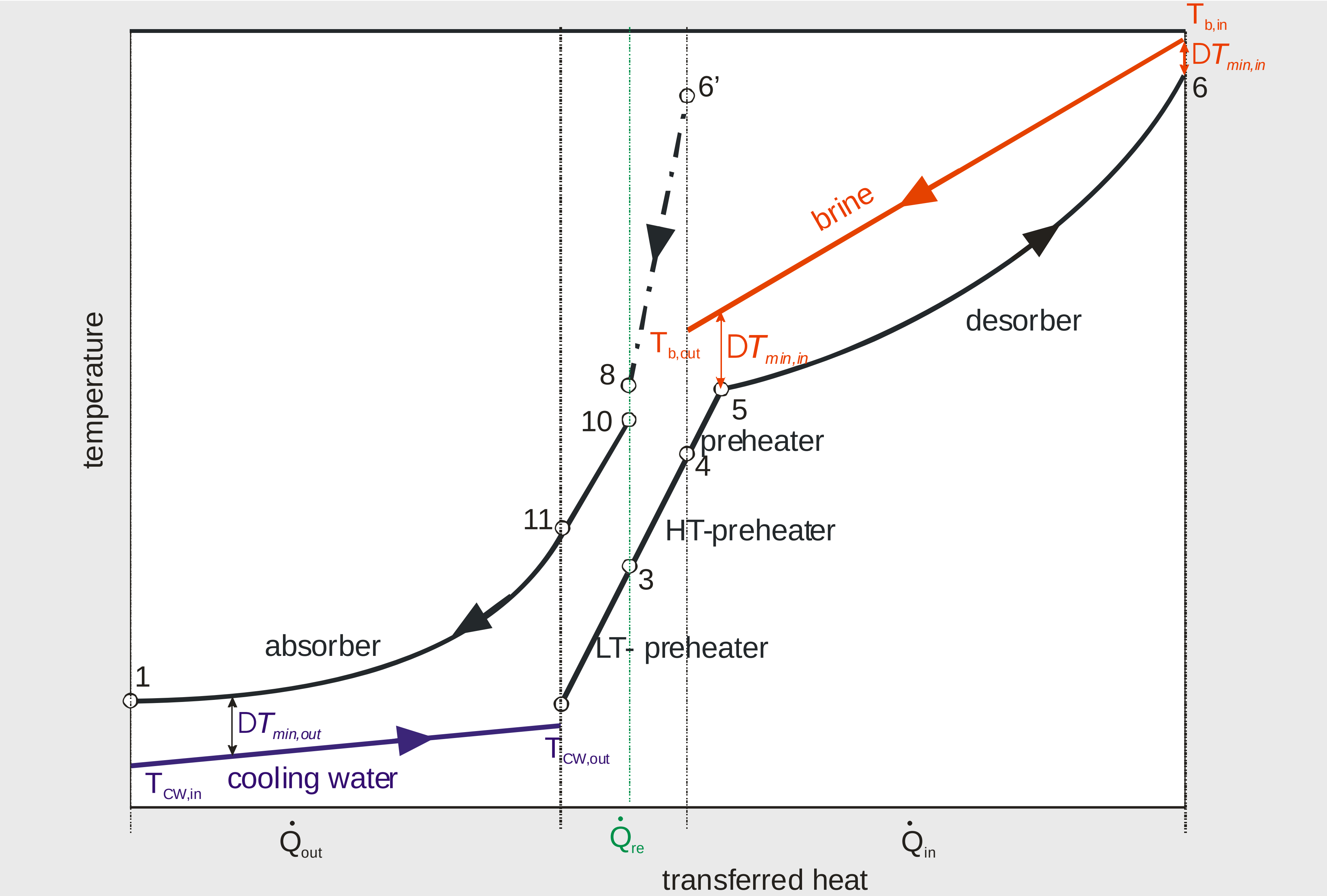
Objective function

- Generator capacity
- Heat transfer area
- (Ratio heat transfer area / generator capacity, ~ €/kW)

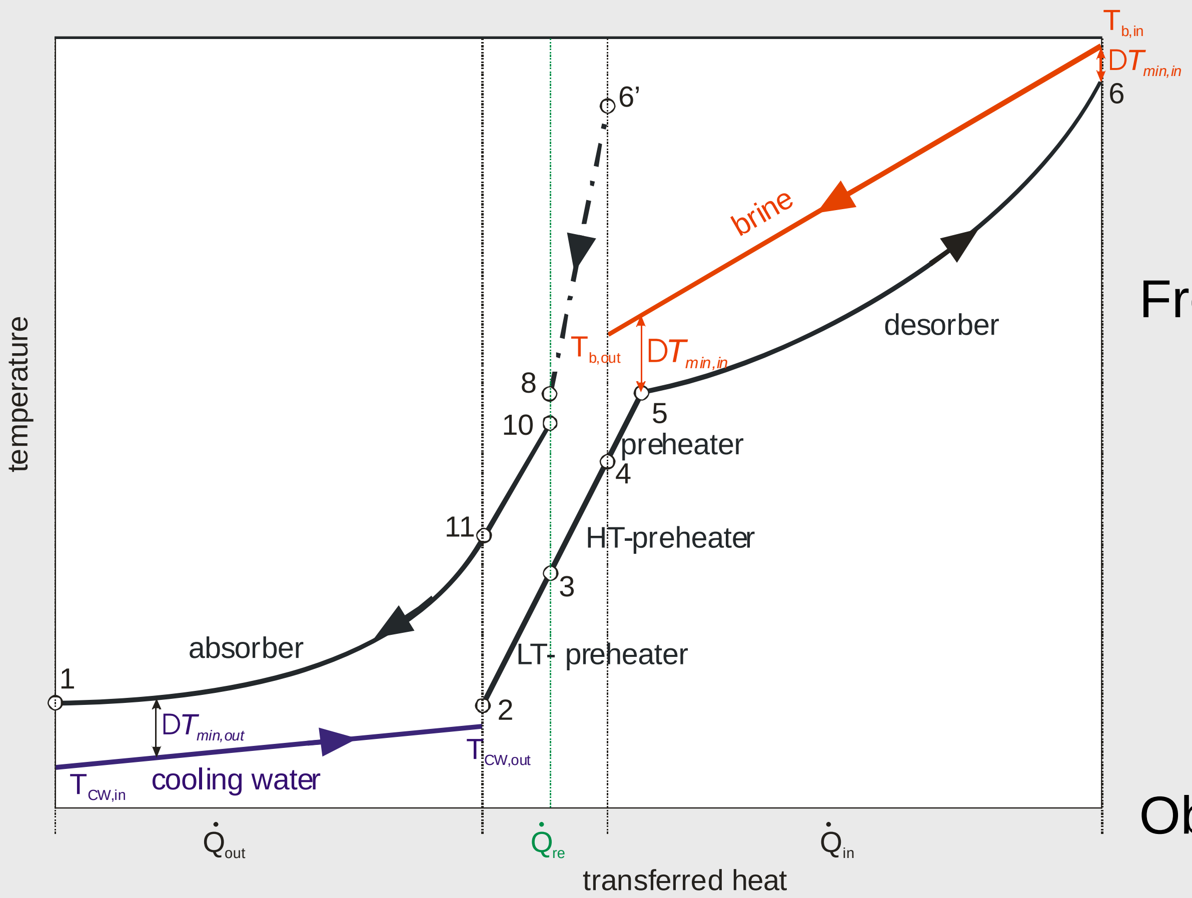
Kalina KCS 34 Layout



Heat Transfer Diagram Kalina



Heat Transfer Diagram Kalina



Constraints

- Brine: $T_{b,in}$, mass flow rate, specific heat capacity
- Cooling medium: $T_{CW,in}$, $T_{CW,out}$, specific heat capacity

Free variables

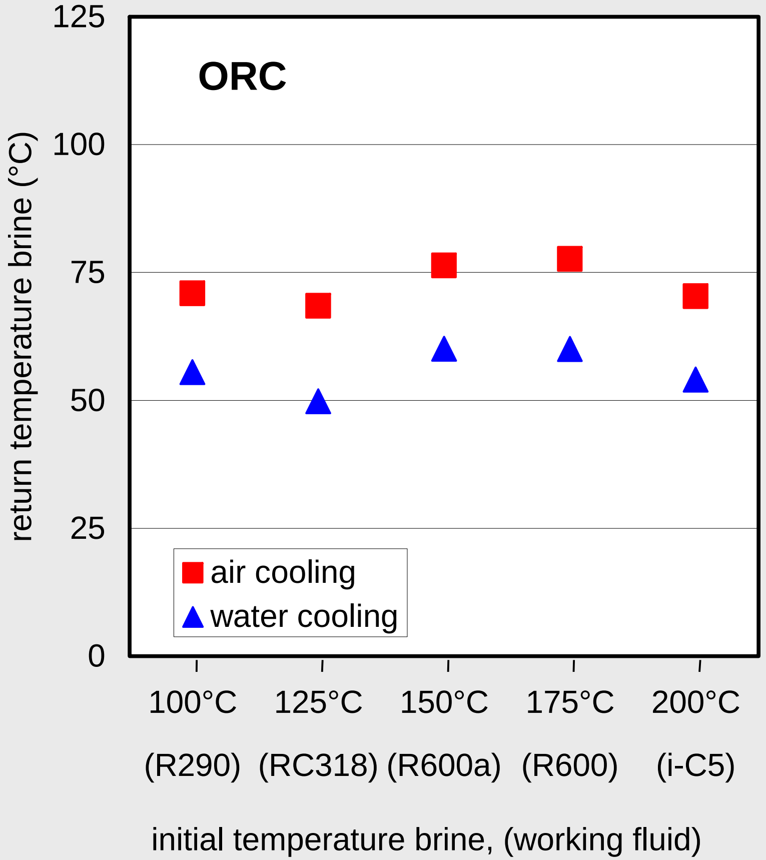
- Composition basic solution
- Pressure desorption
- Pressure absorption
- $\dot{Q}_{des}$
- Mass flow rate basic solution
- $\dot{Q}_{re}$

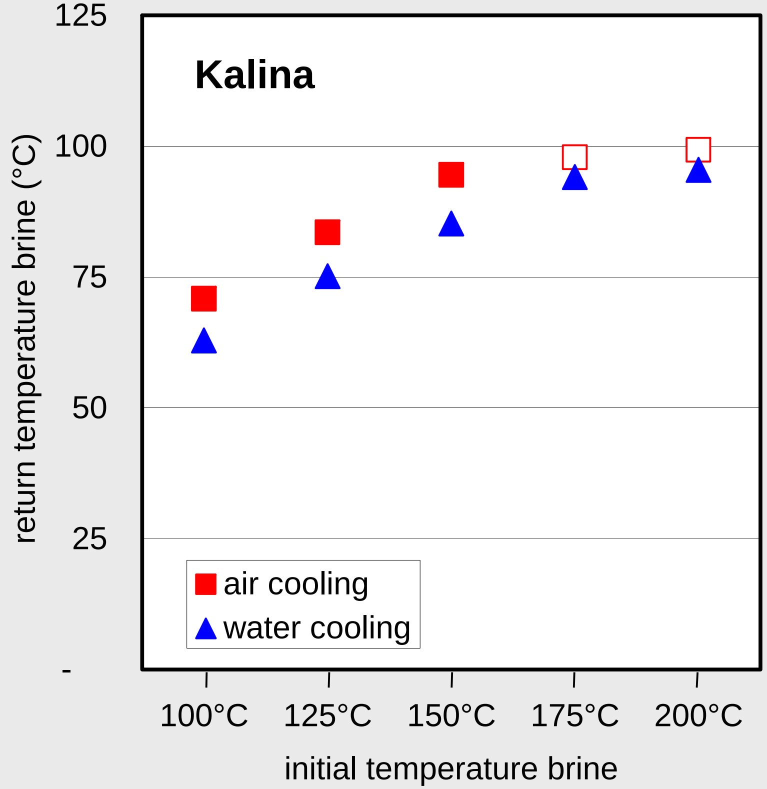
Objective function

- Generator capacity
- Heat transfer area
- (Ratio heat transfer area / generator capacity, ~ €/kW)

Return Temperature Brine, ORC & Kalina

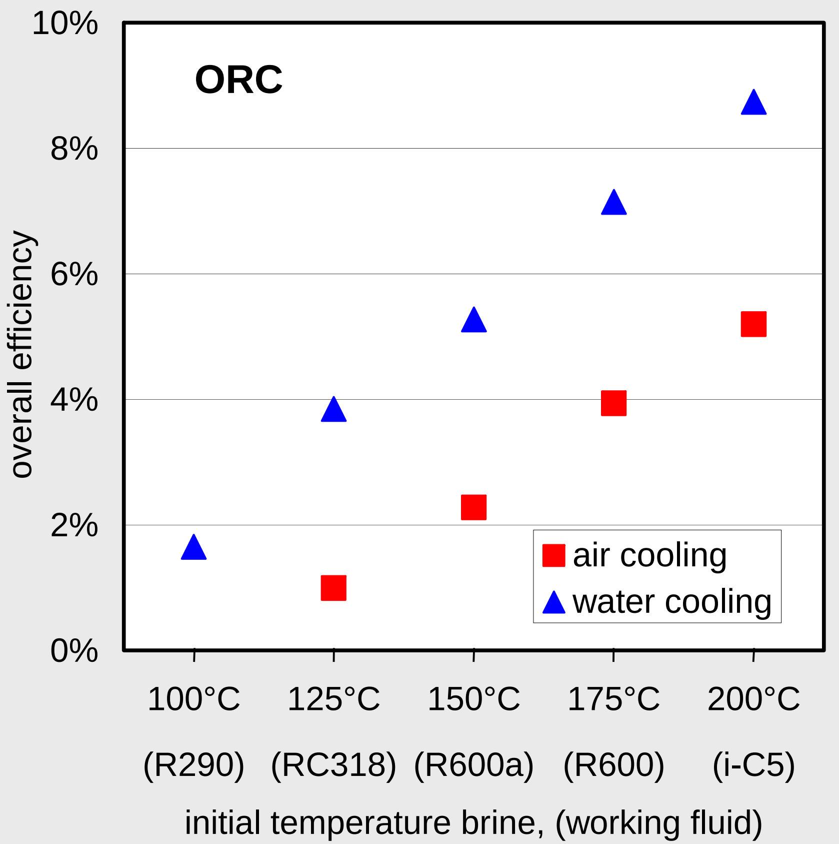
Optimised for work output

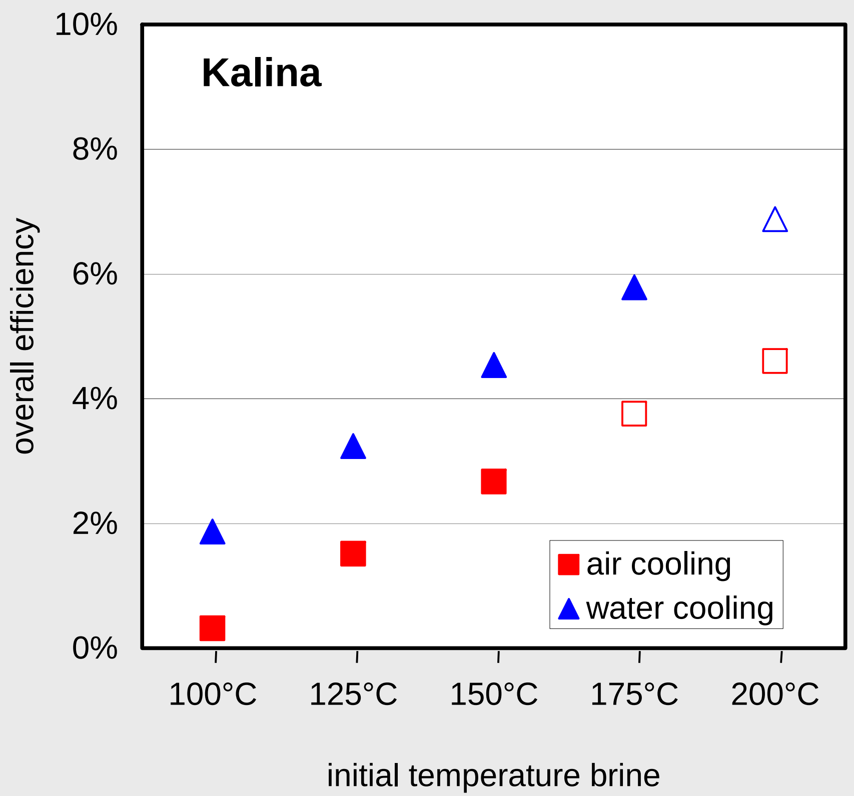




Overall Efficiency ORC & Kalina

Optimised for work output





$$\eta_{sys} = \frac{P_{net}}{\dot{Q}_{brine}} = \frac{P_{gen} - P_{DHpump} - P_{FeedPump} - P_{CWpump}}{\dot{m}_{brine} c_b \left(T_{b,in} - T_0\right)}$$

Conclusions of Comparison

Both systems are suitable for power production from low enthalpy reservoirs

With given constraints from heat source and heat sink

- ORC cool the brine more
- Kalina reach higher thermal efficiency
- High parasitic loads at ORC, especially for air cooling
- ORC are more sensible to changes ORC of heat sink

Suitability of the systems

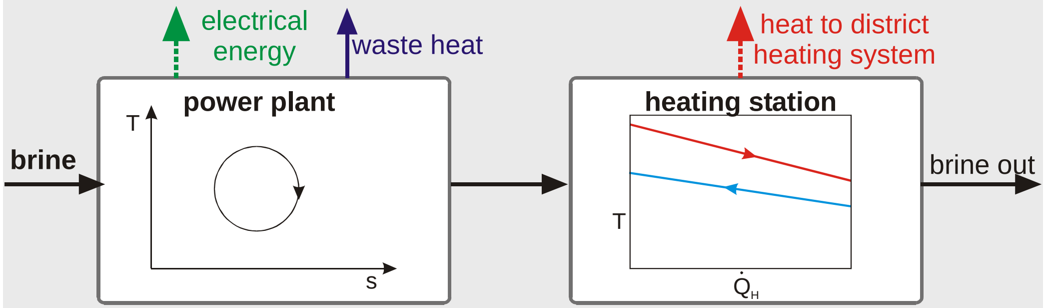
- Kalina KCS34 up to 150 °C brine *or* CHP
- ORC from 150 °C brine temperature

Improvements

- Supercritical ORC may improve thermal efficiency
- Other Kalina systems may improve cooling of brine

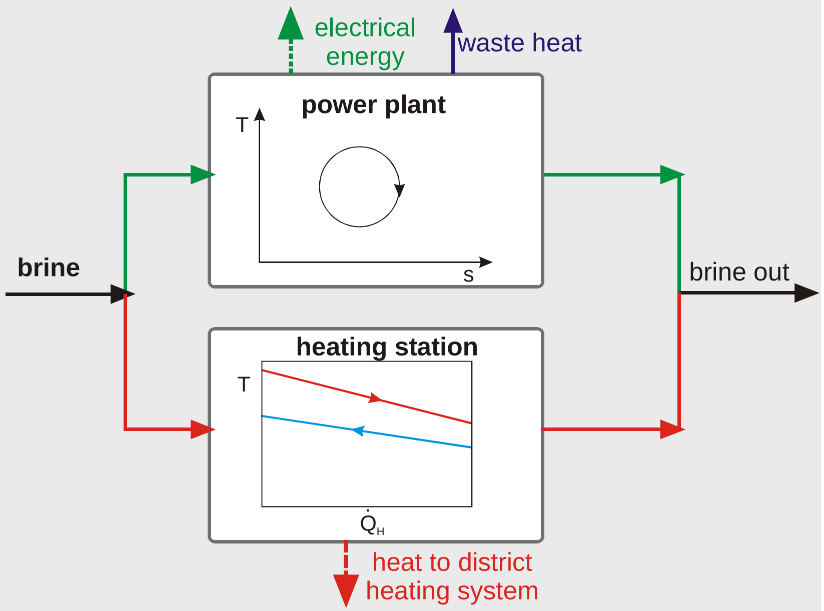
Geothermal Heat and Power

Serial



- brine temperature > temperature for heating purposes
- Not necessarily simultaneous production

Parallel

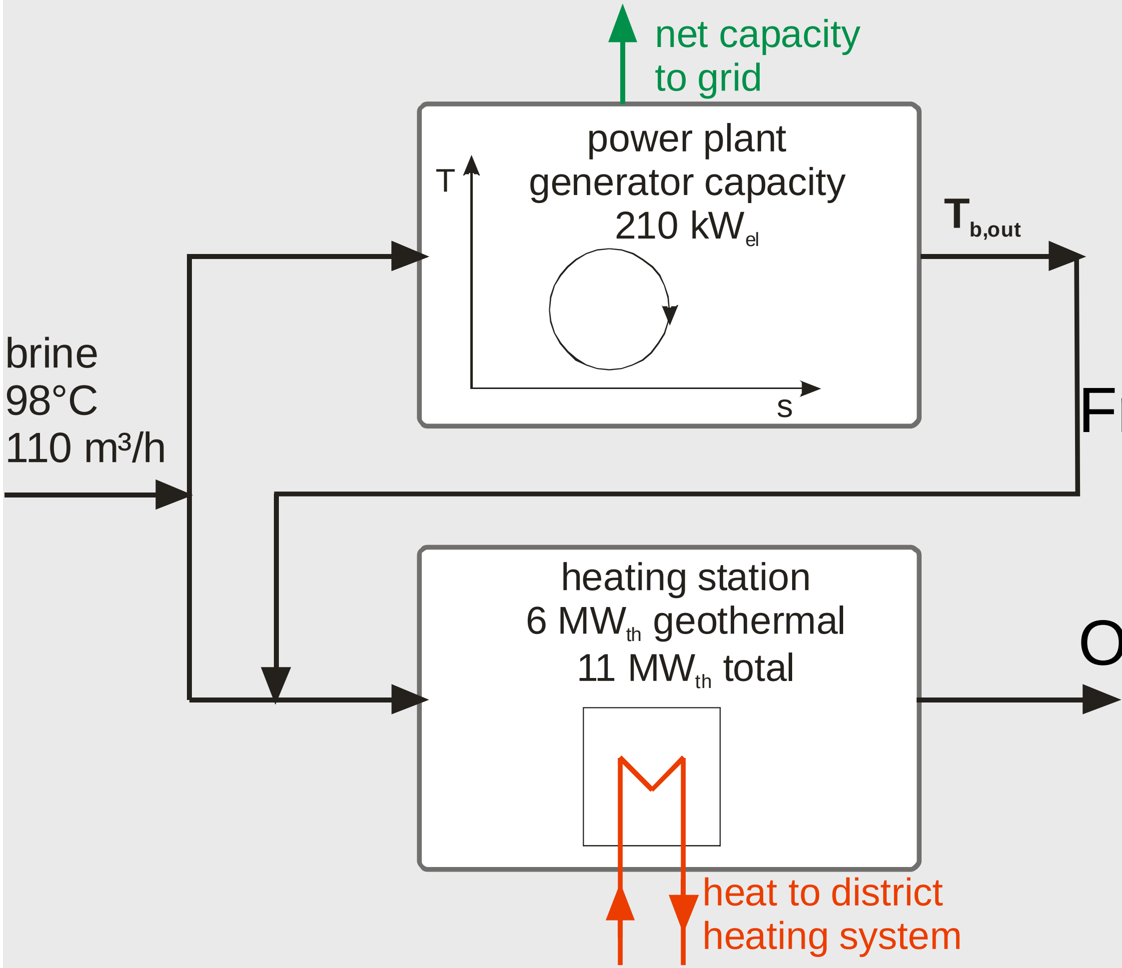


- brine temperature ≈ temperature for heating
- Subsystems compete

Additional constraints due to heating demand!

- Outlet temperature brine
- Mass flow rate brine

Neustadt-Glewe



Constraints

- Brine temperature, mass flow rate
- Heat sink temperature
- Heating capacity in district heating system

Free variable

- Portion of brine through plant / upper process temperature

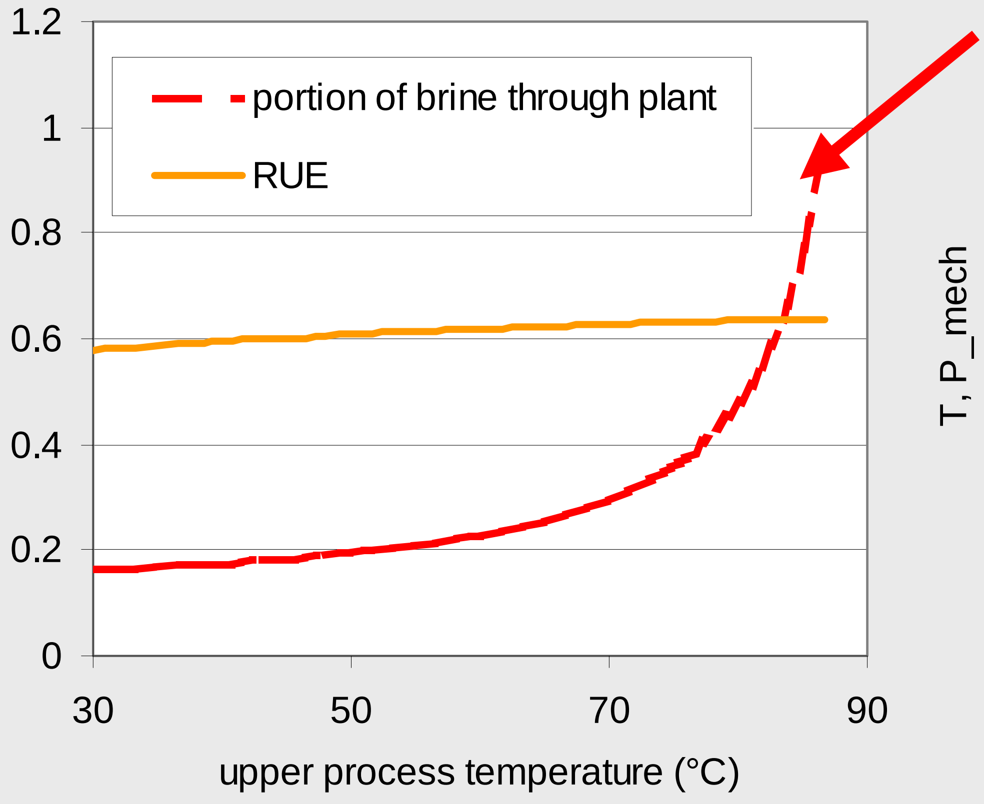
Objective functions

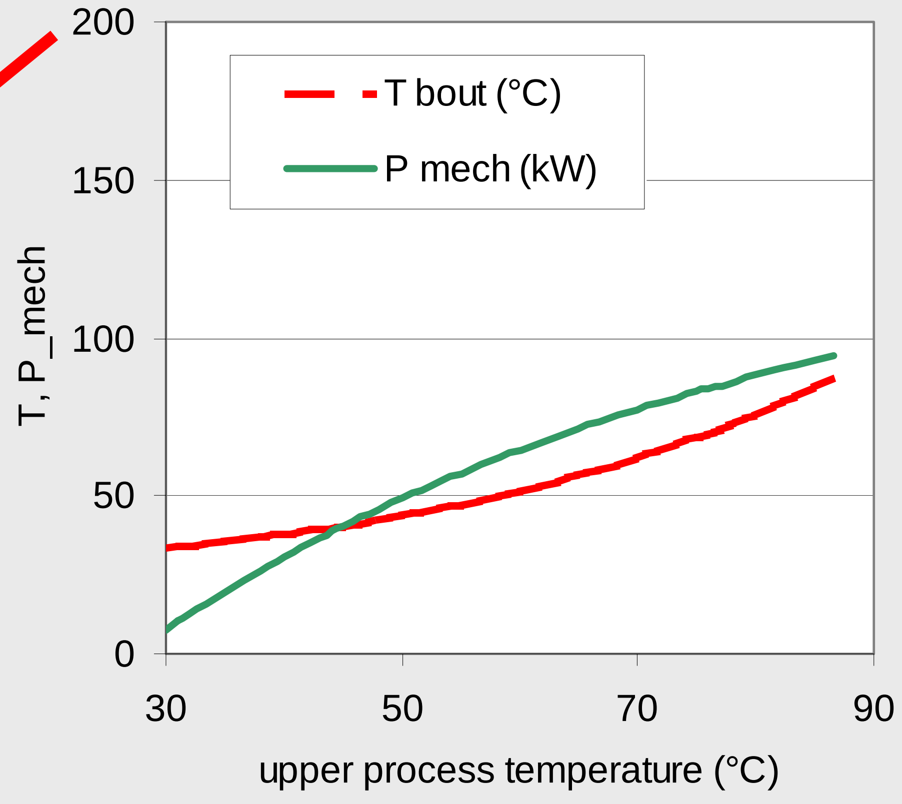
- Generator capacity ~ $\mathbf{P_{mech}}$
- Cooling of the brine $\mathbf{T_{b,out}}$
- Resource Utilization Factor **RUE** (overall exergetic efficiency)

$$RUE = \frac{P_t - P_p + \dot{m}_{heatingsystem} \cdot \left(h_{HS} - h_{HS,0} - T_0 \cdot \left(s_{HS} - s_{HS,0}\right)\right)}{\dot{m}_{brine} \cdot \left(h_{in} - h_0 - T_0 \cdot \left(s_{in} - s_0\right)\right)}$$

Results of Optimisation

- Brine 35 kg/s, 98 °C
- District heating system (assumed) 50 kg/s, 70/55, 3.1 MW_{th}
- Working medium power plant Perflourpentane, water cooling 15/20





$$\dot{Q}_{in} = const = \dot{m}_{brine} c \cdot \left(T_{b,in} - T_{b,out}\right)$$

Summary

ORC & Kalina follow the same rules, but deal differently with the losses.

Losses

- Irreversible heat transfer
- Internal irreversibilities (non-isentropic state changes turbine and pump, pressure losses)
- Parasitic loads (cycle pump, down hole pump, cooling devices)

Constraints

- Heat source and heat sink

Free Variables

- Layout
- Working fluid (medium, composition)
- Upper process temperature

Power plant: optimised for work output

CHP: optimised for RUE