Session 4: Thermoeconomics I

Techno-Economic Analysis of Sub-critical ORC with optimized Heat Transfer Process

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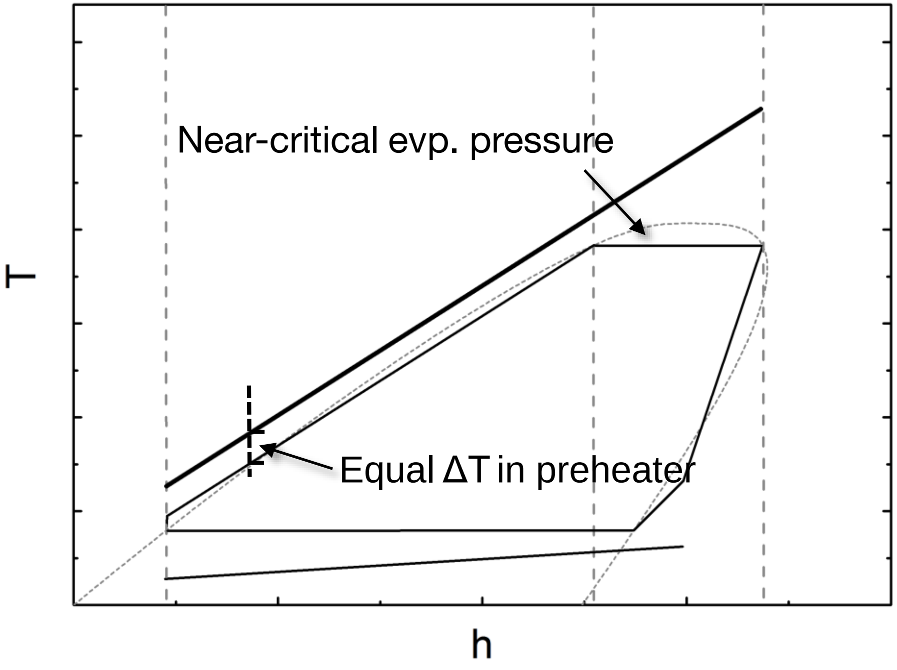
Agenda

1. **Motivation**
2. **Approach**
   - Input Parameters
   - Thermodynamic Model
   - Economic Model
   - Target Function
3. **Results**
4. **Conclusions & Future works**

1. Motivation

A thermodynamically optimal heat transfer process for sub-critical ORC.

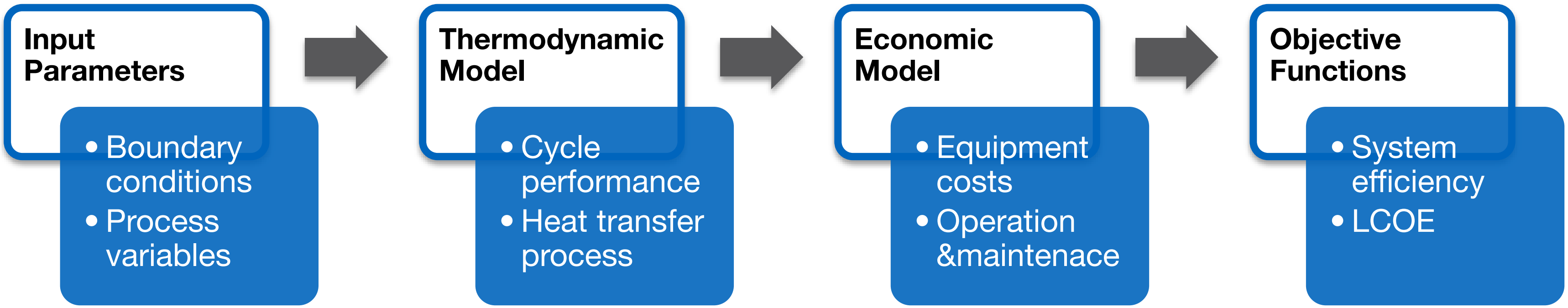


+ High exergetic efficiency
+ High system efficiency

– High evaporation pressure
– Large heat transfer area

❖ Technically feasible?
❖ Economically viable?

2. **Approach** - Overview

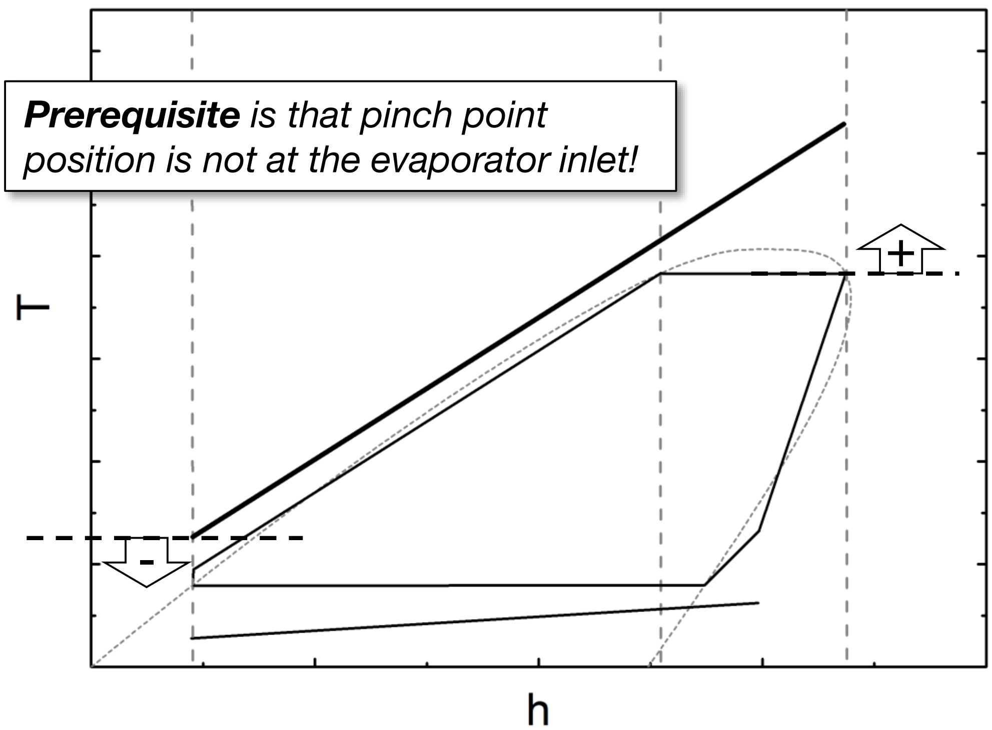


- Thermodynamic- and economic-related input parameters.
- Thermodynamic model based on a simple sub-critical ORC and OHST theory.
- Economic model based on <u>geothermal power plant</u> in Germany.
- LCOE as the main Obj. Function as it links thermodynamics with economics.

2. Approach – Input Parameters

Thermodynamic-related	Economic-related
• Heat Source – Thermal water, 140 °C, 10 bar, 50 MW. • ORC Process – Working conditions – machinery efficiencies – Plate Heat Exchange • Cooling Unit – Cooling water, 8 °C, 1 bar • Reference state – 8 °C, 1 bar	• Initial investment cost – Drilling – Equipment Costs – Others (Construction, labor, etc.) • Operation & Maintenance • Generals – Annual discount rate: 8% – Lifetime: 25 years – Operation hrs: 8000 hrs – …

2. Approach – Thermodynamic Model (1)



Thermodynamic description

- System efficiency

  $\eta_{sys} = \eta_{th} \cdot \eta_{HT}$

  where

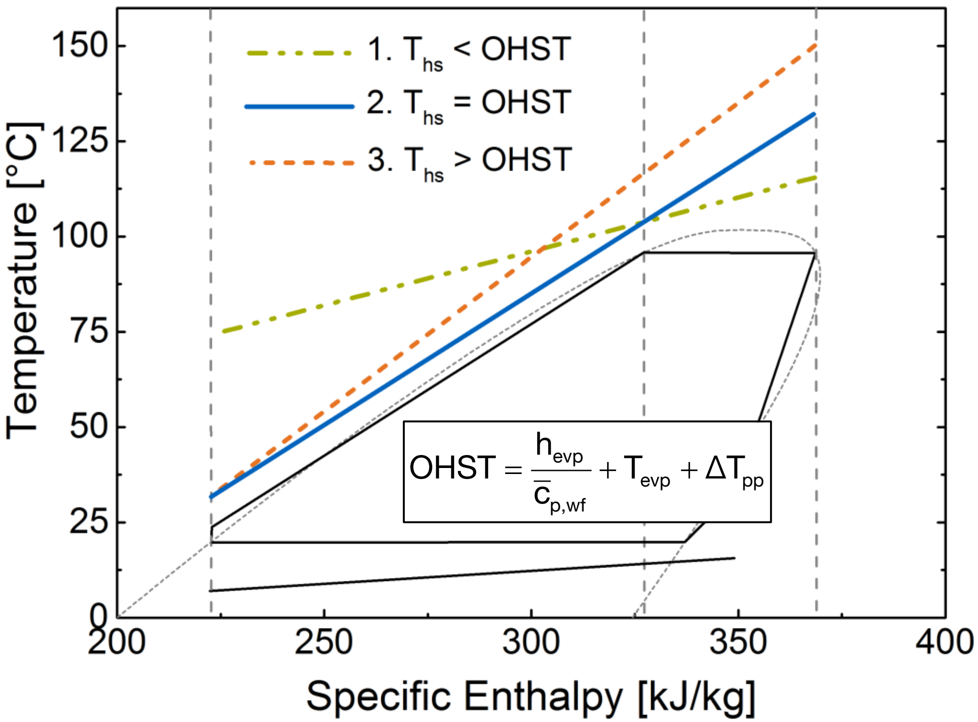
  $\eta_{th} = P_{el,net} / Q_{HT}$

  $\eta_{HT} = Q_{HT} / Q_{hs}$

- Practical means to improve η_{sys}
  - Increase evp. temperature T_4 → $\eta_{th} \uparrow$
  - Decrease thermal water outlet temperature T_8 → $\eta_{HT} \uparrow$

2. Approach – Thermodynamic Model (2)

| Optimal Heat Source Temperature (OHST)



Thermodynamic optimization
based on OHST theory*

Case	Pinch point Position	$p_{evp} \rightarrow \eta_{sys}$
1. T_{hs} < OHST	Evaporator inlet	max η_{sys} at an intermedium p_{evp}
2. T_{hs} = OHST	Evenly in preheater	η_{sys} increases with a higher p_{evp}
3. T_{hs} > OHST	Preheater inlet	η_{sys} increases with a higher p_{evp}

* Liu,et al. Optimal heat source temperature for thermodynamic optimization of sub-critical ORCs. Energy 2015.

2. Approach – Thermodynamic Model (3)

Working fluid screening*

Thermophysical properties

$90°C \leq T_c \leq 160°C$

(Heuristics for low-temperature ORC applications)

Pinch Point Position

Must not be at evaporator inlet under conditions:

1. High p_{evp} ($0.9 \cdot p_c$)
2. $\Delta T_{pp} = [4,15]$

Evaporation pressure

$0.9 \cdot p_c \leq 30$ bar

→ Taking into account pressure factor in manufacturing costs

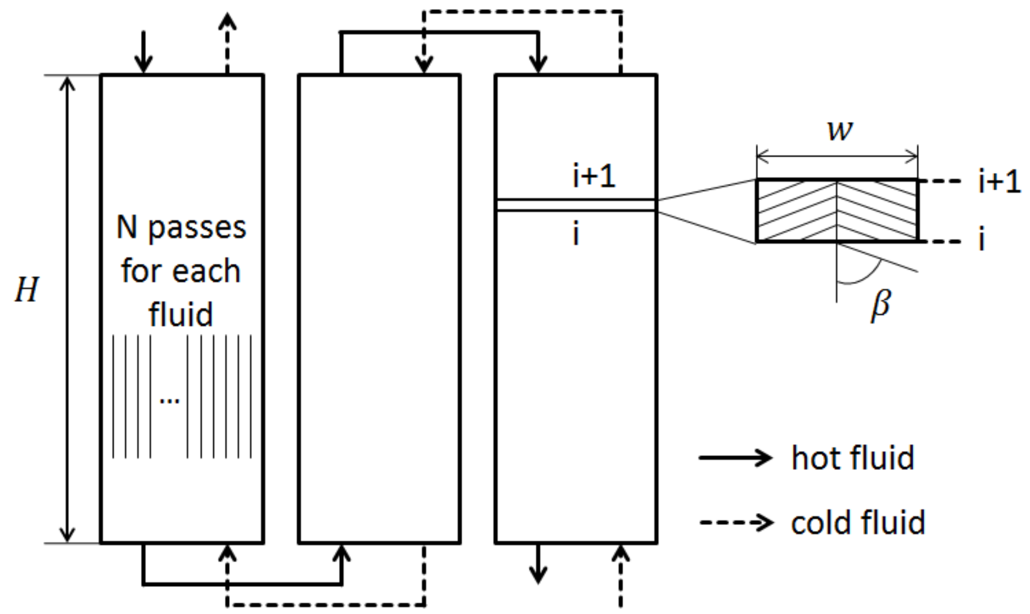
Environment, Safety

Toxicity, Flammability
ODP = 0

→ Destructive effect of non-ODP fluids on Ozone layer

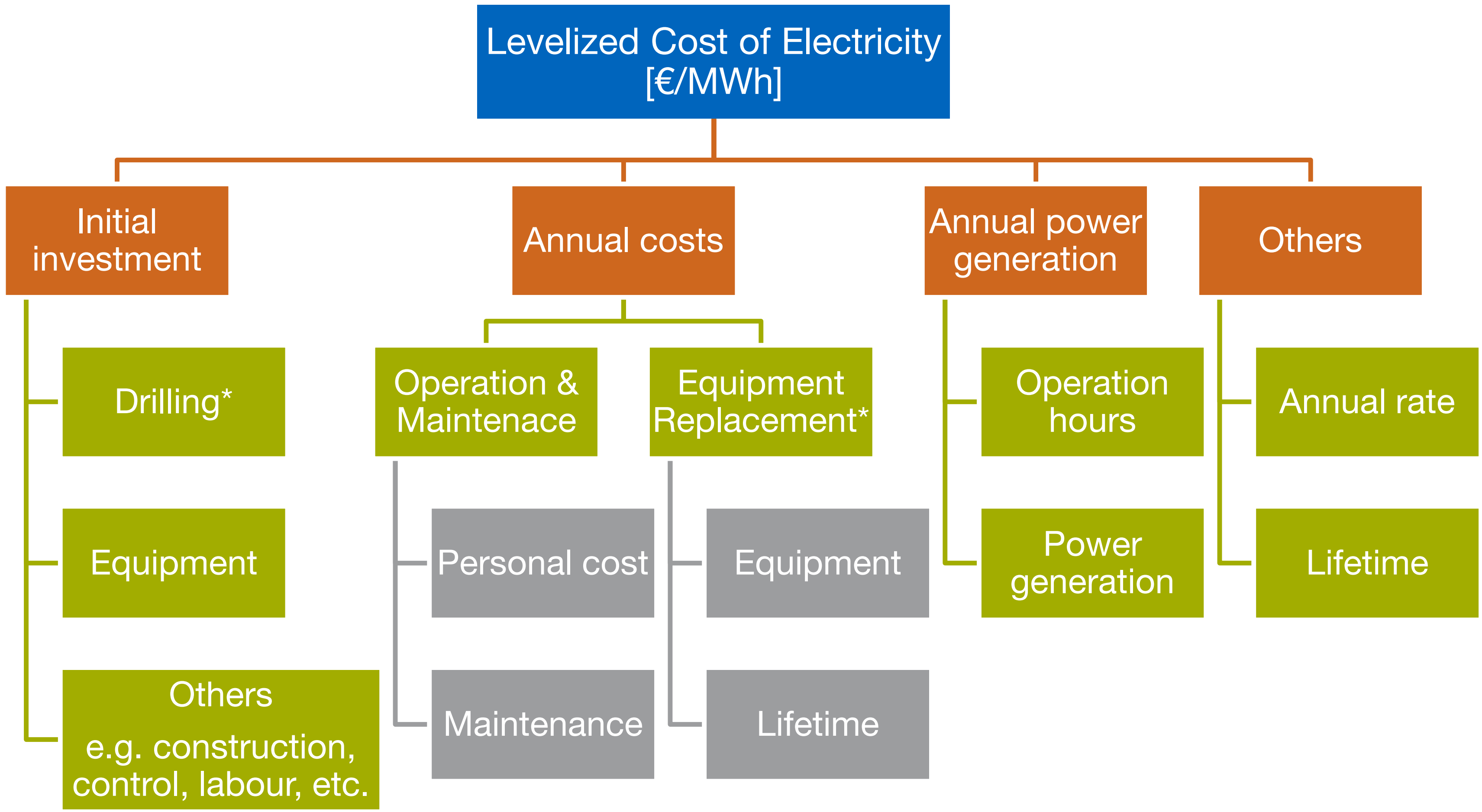
* Screening process based on 121 pure fluids from REFPROP 9.0.

2. Approach – Thermodynamic Model (4)



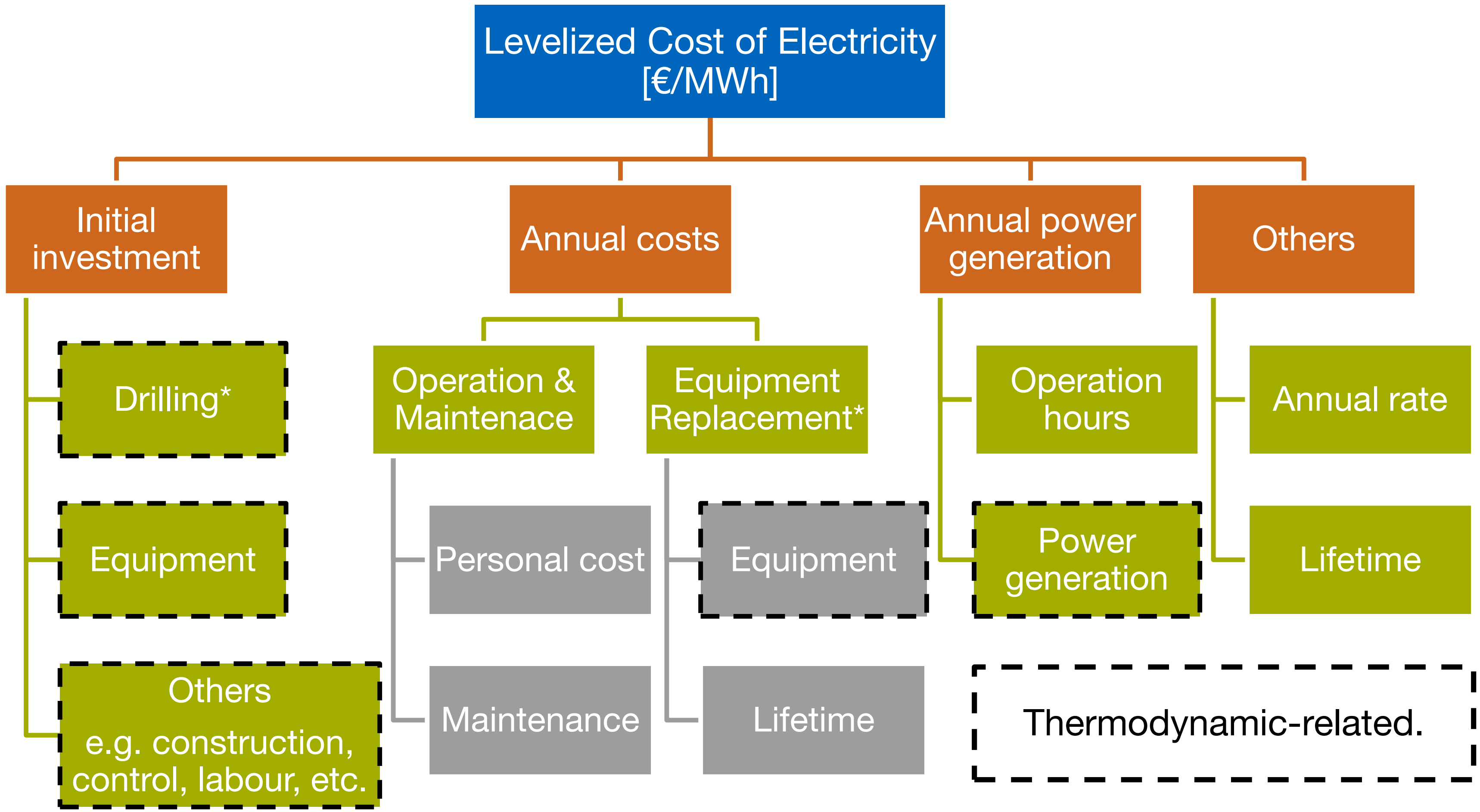
- Heat Transfer Process
  - exact pinch point position
  - required surface area

2. Approach – Economic Model



* Schlagermann, P., Exergoökonomische Analyse geothermischer Strombereitstellung am Beispiel des Oberrheingrabens. 2015

2. Approach – Economic Model



* Schlagermann, P., Exergoökonomische Analyse geothermischer Strombereitstellung am Beispiel des Oberrheingrabens. 2015

2. Approach – Target Function

- Thermodynamic optimization: *max* System Efficiency

$$\eta_{sys} = \frac{P_{el,net}}{\dot{Q}_{hs}}$$

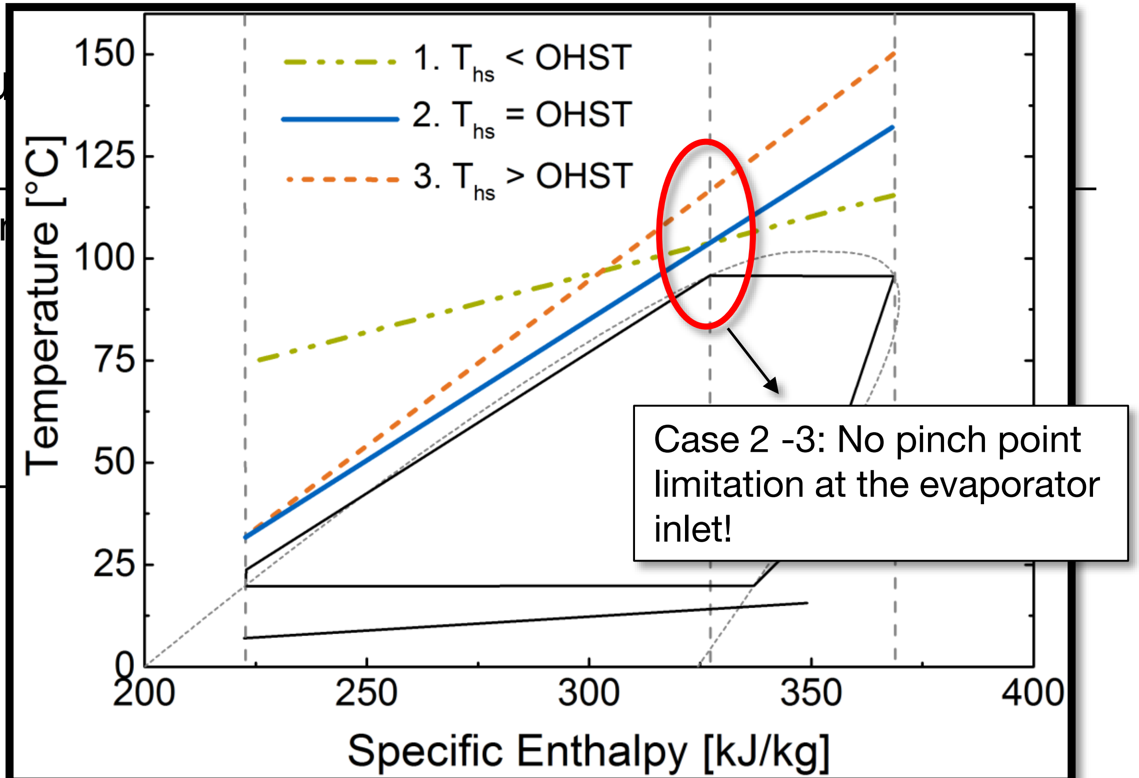
- Economic optimization: *min* LCOE

$$LCOE = \frac{I_0 + \sum_1^n \frac{A_t + I_t}{(1+r)^t}}{\sum_1^n \frac{W_{el}}{(1+r)^t}}$$

- Optimization Variable (p_{evp} or ΔT_{pp}):

Case 1. T_{hs} < OHST	p_{evp} with $\min(\Delta T_{pp})$
Case 2. T_{hs} = OHST	ΔT_{pp} with $p_{evp}=0.9 \cdot p_c$
Case 3. T_{hs} > OHST	ΔT_{pp} with $p_{evp}=0.9 \cdot p_c$

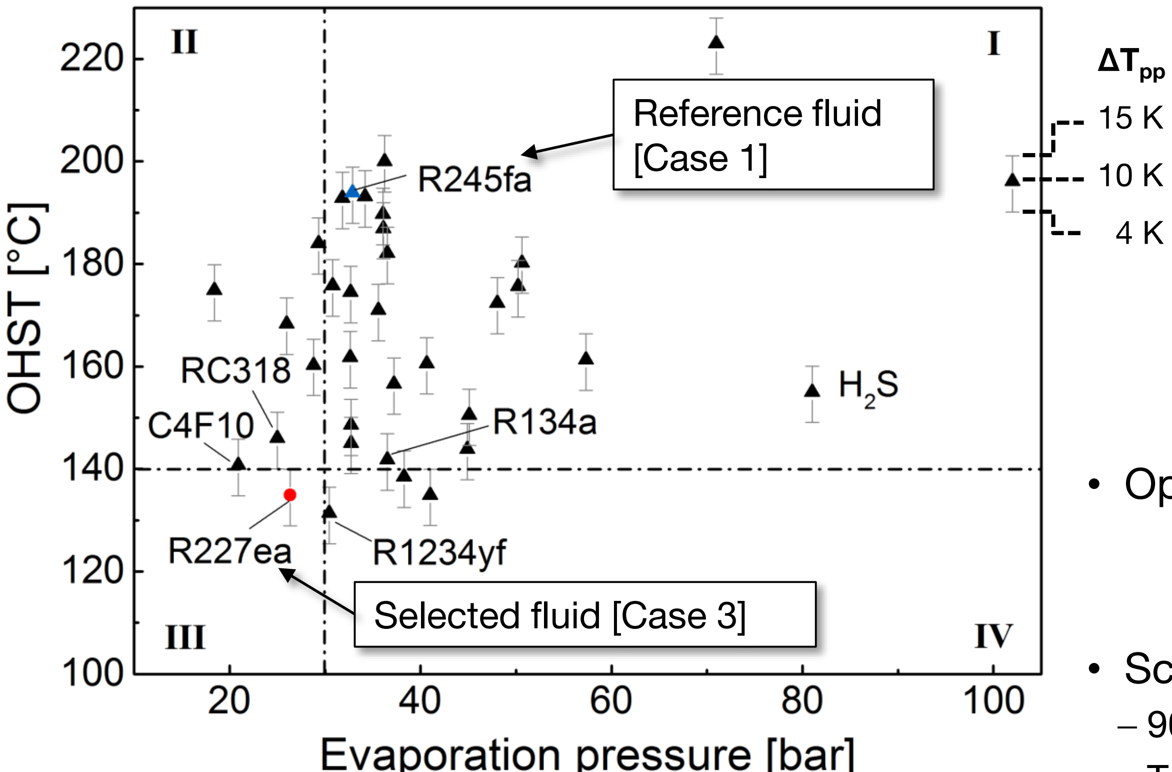
2. Approach – Target Fu



- Thermodynamic optimizatio
- Economic optimization:
- Optimization Variable (p_{evp} or ΔT_{pp}):

Case 1. T_{hs} < OHST	p_{evp} with min(ΔT_{pp})
→ Case 2. T_{hs} = OHST	ΔT_{pp} with $p_{evp}=0.9 \cdot p_c$
→ Case 3. T_{hs} > OHST	ΔT_{pp} with $p_{evp}=0.9 \cdot p_c$

3. Results – Fluid Screening

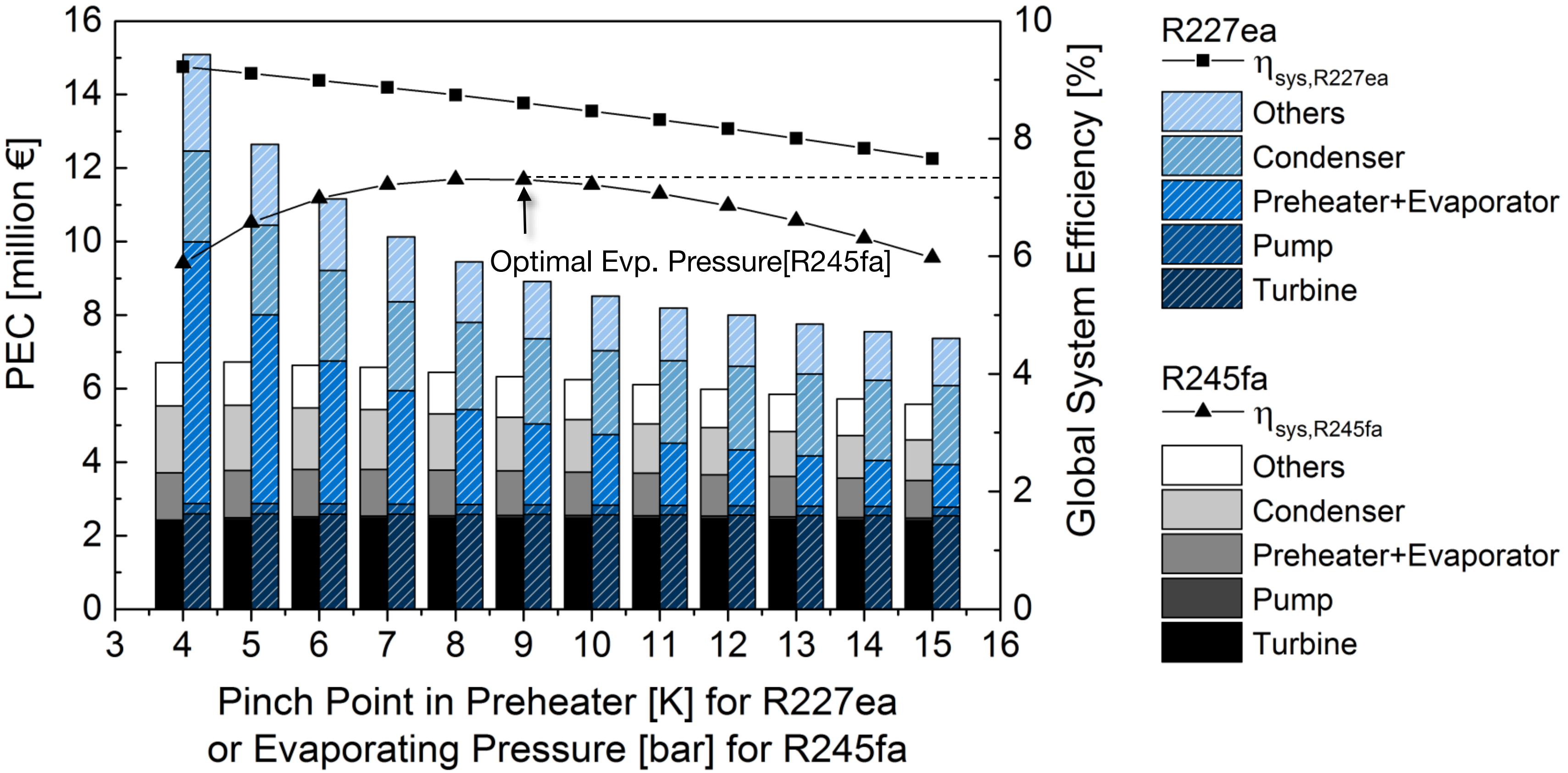


- Opt. Heat Source Temperature

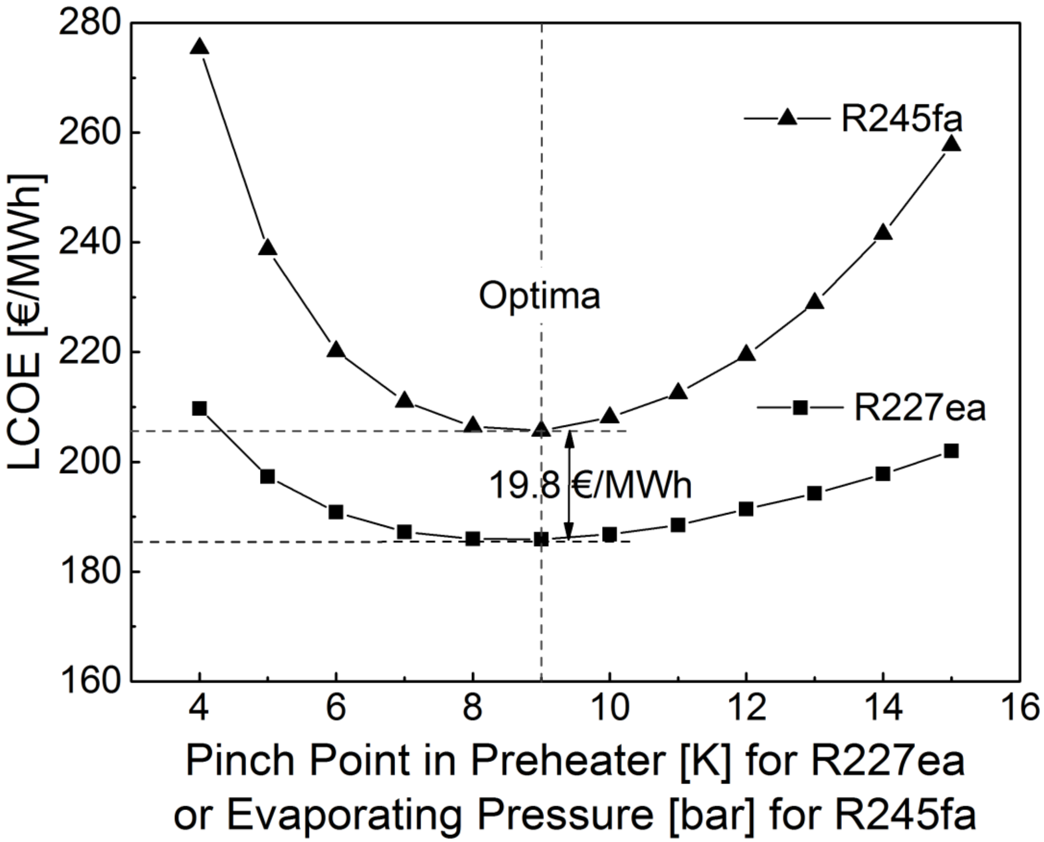
$$OHST = \frac{h_{evp}}{\overline{c}_{p,wf}} + T_{evp} + \Delta T_{pp}$$

- Screening Criteria:
  - $90°C \leq T_c \leq 160°C$;
  - $T_{hs} \geq OHST(0.9 \cdot p_c, 4 \leq \Delta T_{pp} \leq 15K)$;
  - $0.9 \cdot p_c \leq 30$ bar; - Env., Safety, ODP

3. Results – Parameter Variation



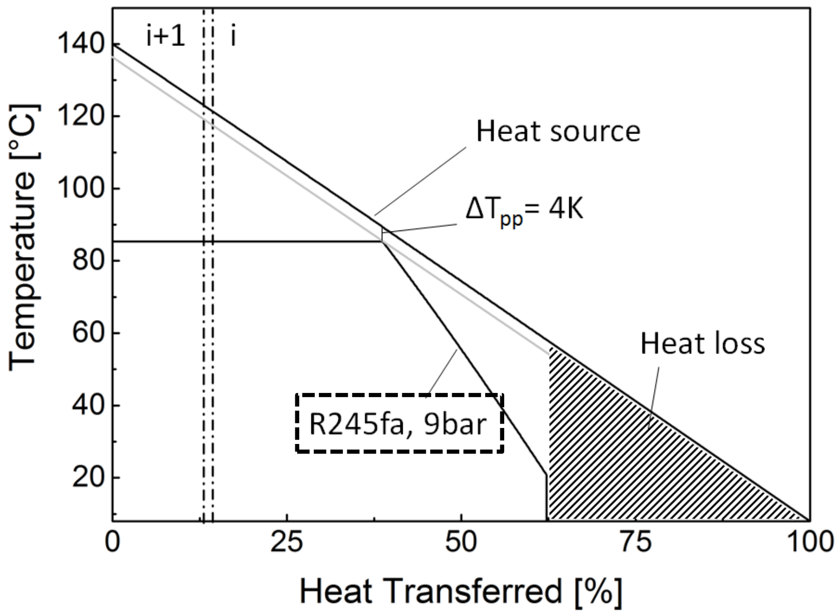
3. Results – Levelized Cost Of Electricity

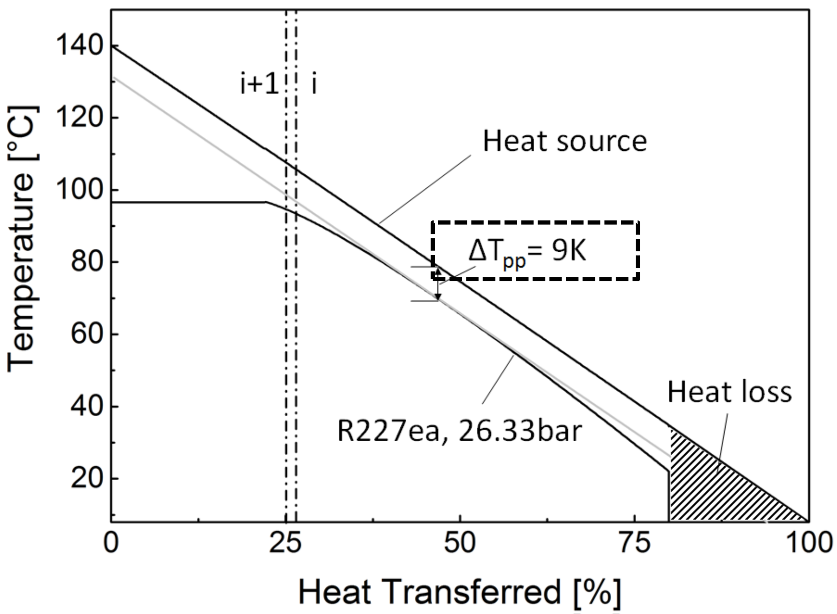


$$LCOE = \frac{I_0 + \sum_{1}^{n} \frac{A_t + I_t}{(1+r)^t}}{\sum_{1}^{n} \frac{W_{el}}{(1+r)^t}}$$

- Optima based on minimum LCOEs
- 9.63% lower LCOE by R227ea compared to R245fa

3. Results – Optimal cases





Fluid	Thermodynamic						Economic	
	T_{evp} [°C]	p_{evp} [bar]	$T_{pp,evp}$ [K]	η_{sys} [%]	η_{HT} [%]	W_{el} [MWh]	PEC [m. €]	LCOE [€/MWh]
R227ea	96.60	26.33	9.000	8.607	79.47	29006	8.739	185.9
R245fa	85.33	9.000	4.000	7.306	63.51	23762	7.306	205.7

4. Conclusions & Future works

✓ Technically feasible

– Suitable working fluid selection → pinch point location not at evaporator inlet;

– System efficiency strongly influenced by ΔT_{pp}.

✓ Economically viable

– An optimum found for ΔT_{pp} where LCOE is minimized;

– Despite higher PECs, a lower LCOE is resulted.

To-do

- Pressure drops to be considered through the ORC loops;
- Heat transfer mechanism for near-critical states

Thanks for your attention!

Questions?

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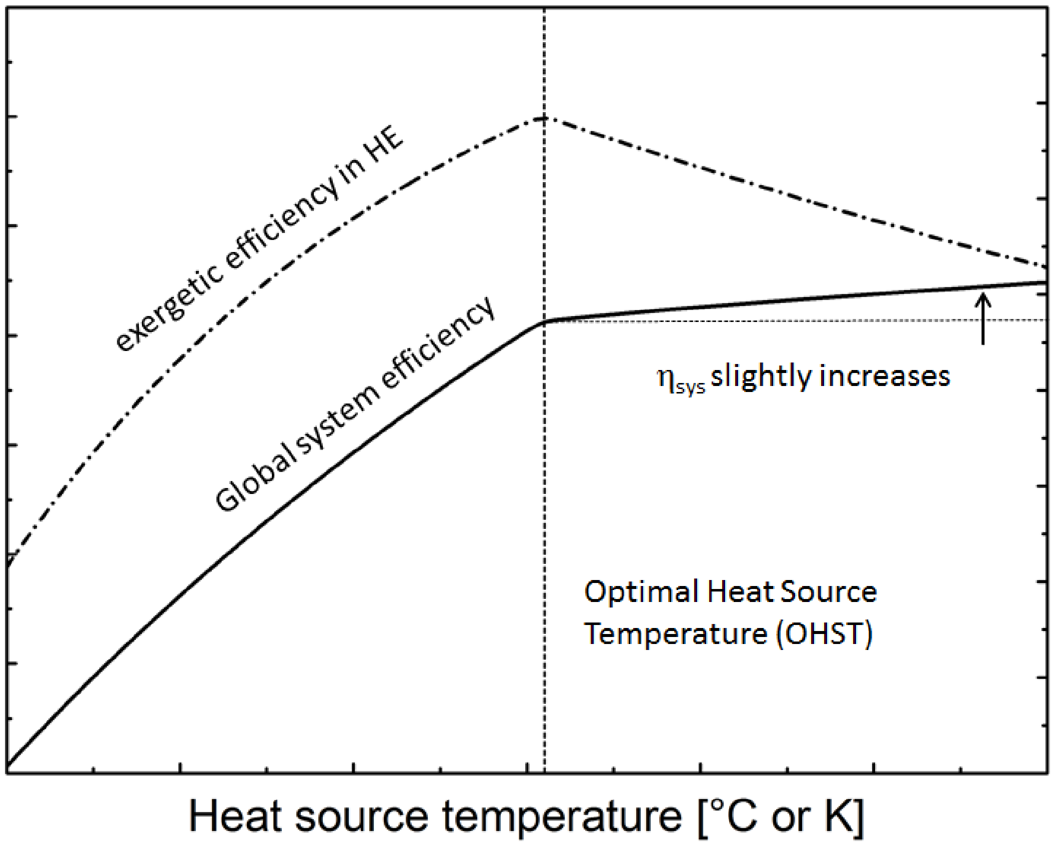
Appendix – The thermodynamic-related inputs

Heat source temperature	T_{hs}	140 °C	Cooling water temperature	T_{cw}	8 °C
Heat source pressure	p_{hs}	10 bar	Cooling water pressure	p_{cw}	1 bar
Heat source thermal amount	$\dot{Q}_{hs}$	50 MW	Isentropic efficiency Turbine	$\eta_{is,turbine}$	0.85
Evaporating pressure	p_{evp}	< 30 bar	Isentropic efficiency Pump	$\eta_{is,pump}$	0.75
Pinch point in heat exchanger	$\Delta T_{pp,HE}$	Variable	Mechanical efficiency	η_{mech}	0.98
Condensation temperature	T_{cond}	20 °C	Generator/Motor efficiency	η_G/η_M	0.95
Pinch point in the condenser	ΔT_{cond}	5 K	Reference state	p_0, T_0	1 bar, 8 '

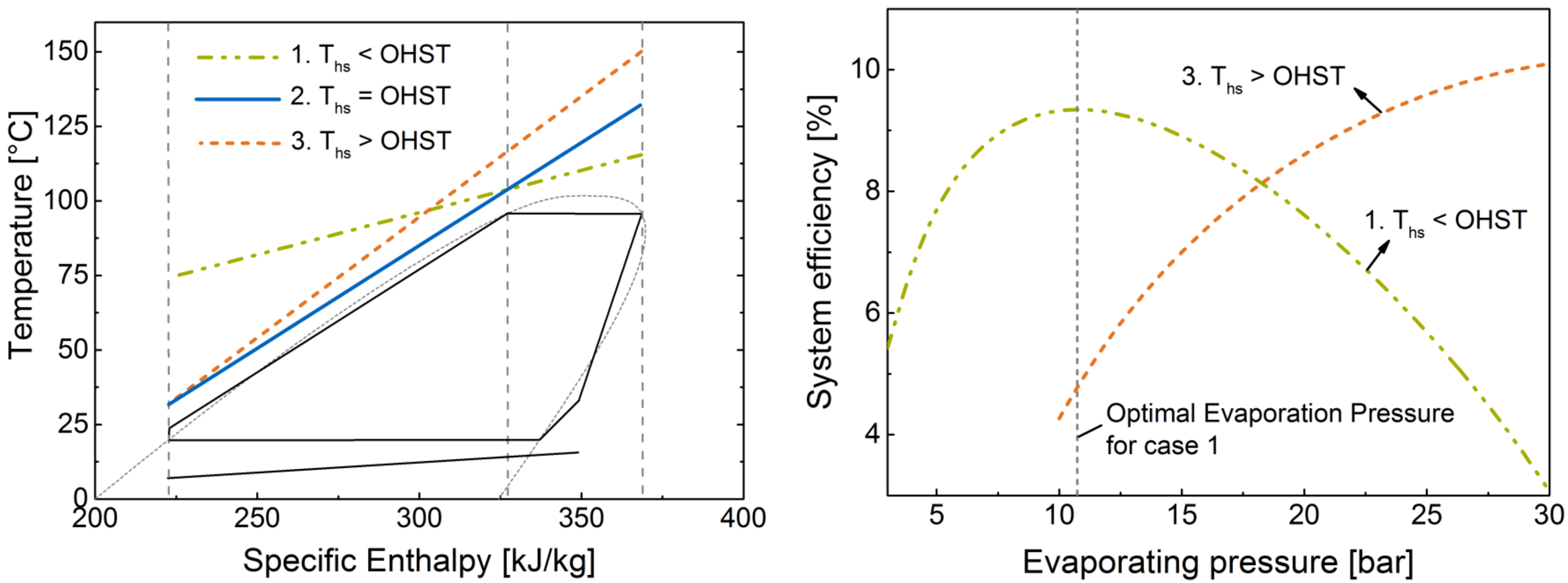
Appendix – Qualitative demonstration of OHST



OHST corresponds to:

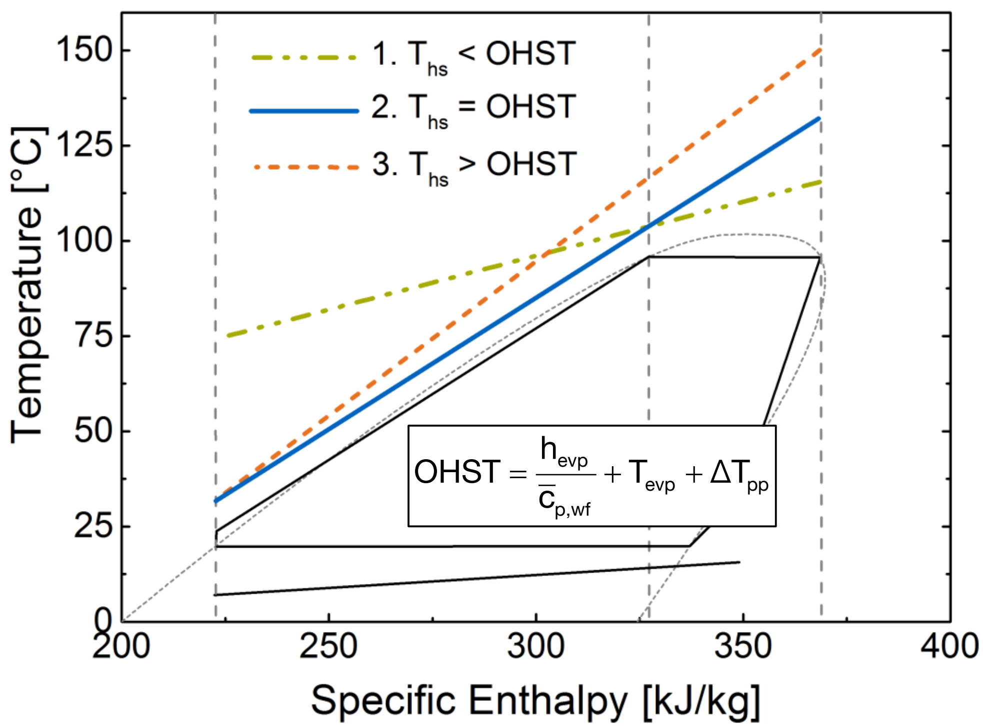
- an almost maximized η_{sys};
- Maximal exergetic efficiency in heat transfer process.

Appendix – Tendency prediction of η_{sys} for difference cases



Appendix – Optimal Heat Source Temperature

| Optimal Heat Source Temperature (OHST)



Max η_{sys}

Thermodynamic optimization
based on OHST theory*

Case	Pinch point Position	$p_{evp} \rightarrow \eta_{sys}$
1. T_{hs} < OHST	Evaporator inlet	max η_{sys} at an intermedium p_{evp}

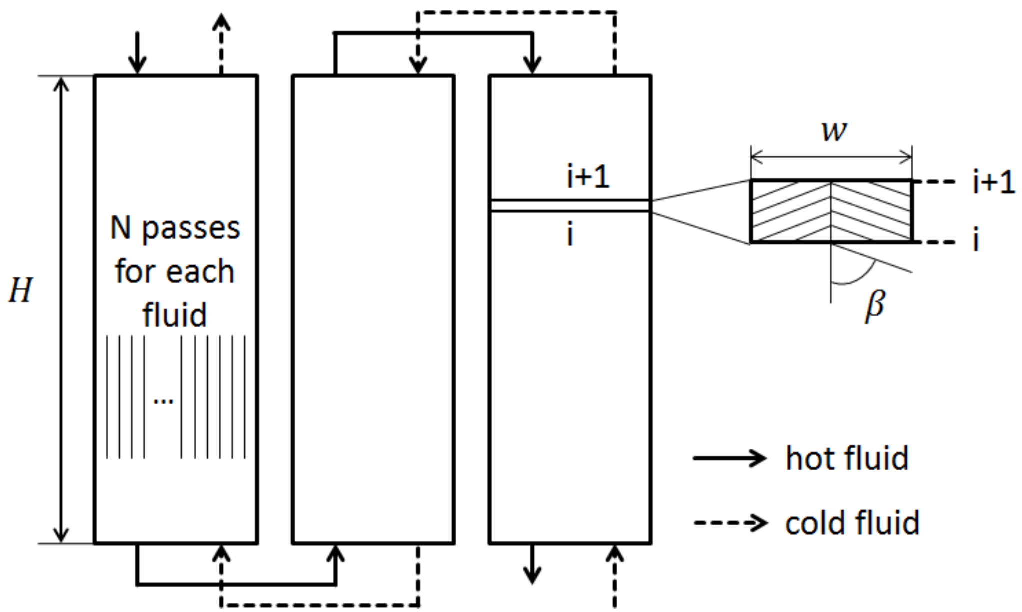
OHST is defined as a heat source temperature, for which system efficiency of ORC almost reaches maximum with a fluid at a constant sub-critical evp. pressure.

OHST depends on fluid's physical properties and pinch point temperature.

* Liu,et al. Optimal heat source temperature for thermodynamic optimization of sub-critical ORCs. Energy 2015.

Appendix – Heat transfer process

***Aim**:1) exact pinch point position; 2) required surface area.*



Heat Transfer Process

- Asummptions:
  - Stationary process,
  - Zero pressure drop.
- Plate Heat Exchanger
  - three-pass counter flow,
  - Predefined geometrics for plates.
    → adjustable # of plate.
- Mathematical Model
  - Discretized heat transfer process
  - Single phase fluid
    Chisholm and Wanniarachchi
  - Multiple phase fluid
    *Yan and Lin for evaporation**
    Yan for condensation

* Evaporation model is modified for a continuous heat transfer coefficient.

Appendix - LCOE

Net **P**resent **V**alue (NPV): the sum of the present values of incoming and outgoing cash flows over a period of time.

$$K_0 = -I_0 + \sum_{t=1}^{n} \frac{E_t - A_t}{(1+i)^t}$$

- K_0: NPV,
- I_0: Investment,
- E_t: Incoming cash of year t,
- A_t: outgoing cash of year t,
- t: year of operation,
- n: period of operation,
- i: annual interest.

Asumming $K_0 = 0$, one has:

$$\sum_{t=1}^{n} \frac{\overset{\text{LCOE} \times W_{el}}{\cancel{E_t}}}{(1+i)^t} = I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}$$

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{W_{el}}{(1+i)^t}}$$

$$= \frac{\boxed{\frac{I_0}{\sum_{t=1}^{n} \frac{1}{(1+i)^t}} + A_t}}{W_{el}}$$

← Annuity