Zentrum für Energietechnik

LEHRSTUHL FÜR TECHNISCHE THERMODYNAMIK UND TRANSPORTPROZESSE
PROF. DR.-ING. D. BRÜGGEMANN

International Seminar on ORC Power Systems, TU Delft, 2011

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Exergoeconomic analysis of a geothermal Organic Rankine Cycle with zeotropic fluid mixtures

UNIVERSITÄT BAYREUTH

Motivation
Geothermal power generation

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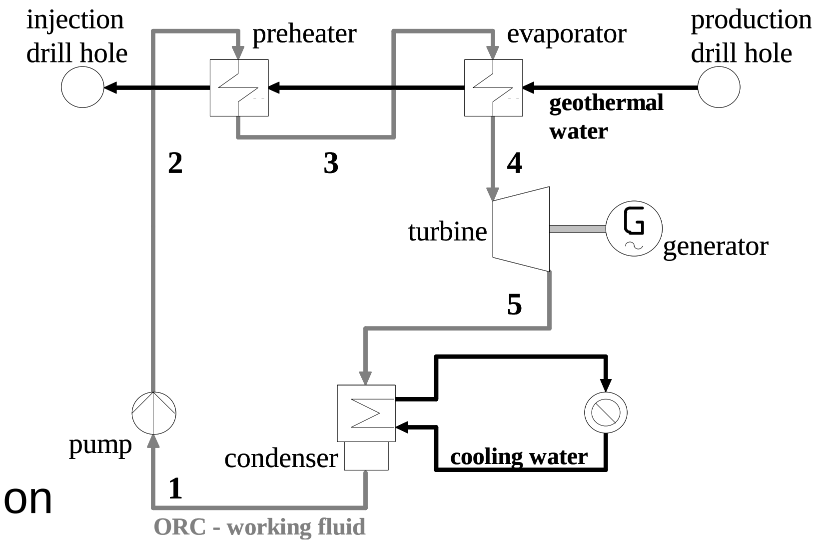
Application

Geothermal power generation in Germany



Objectives

- Zeotropic mixtures as working fluids
- Variation of ΔT at pinch point
- Identification of optimal process parameters
- Minimal specific costs for electricity generation

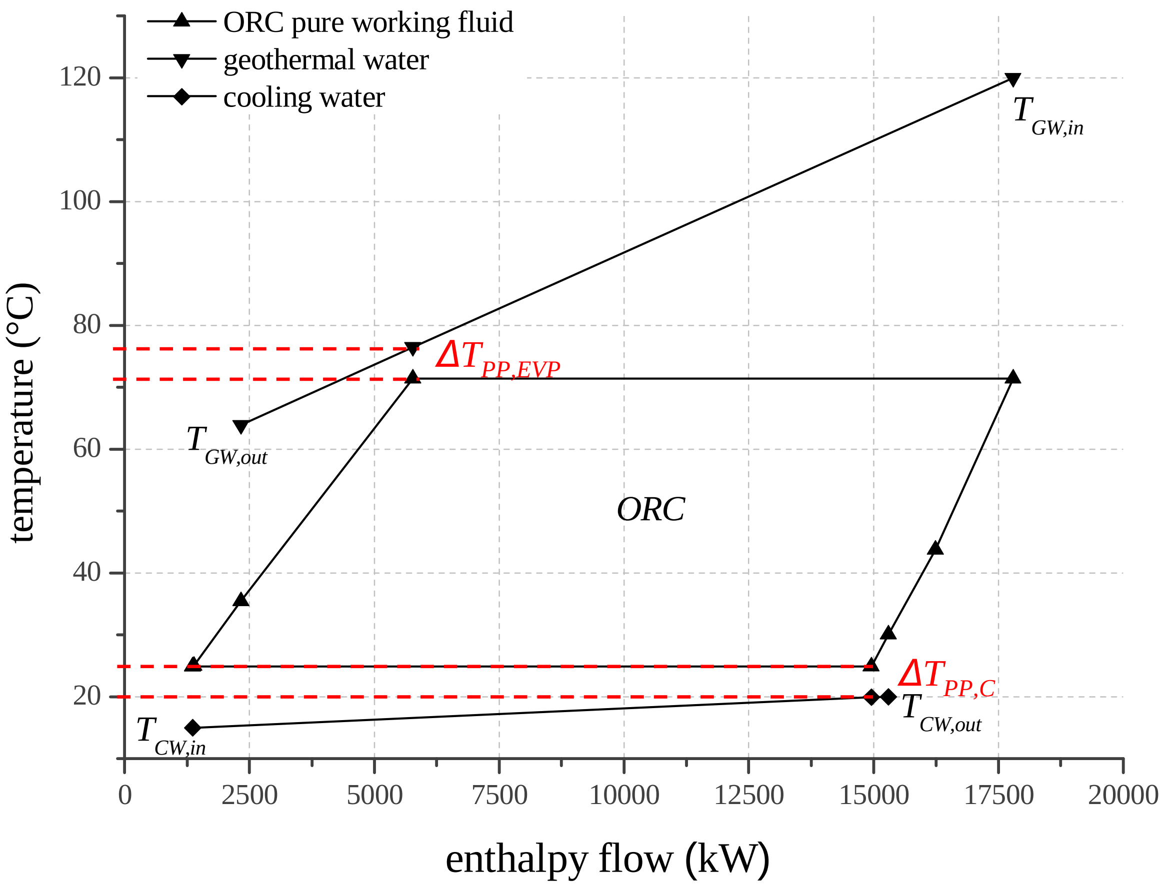
Methods

→ Exergy Analysis

→ Economic Analysis

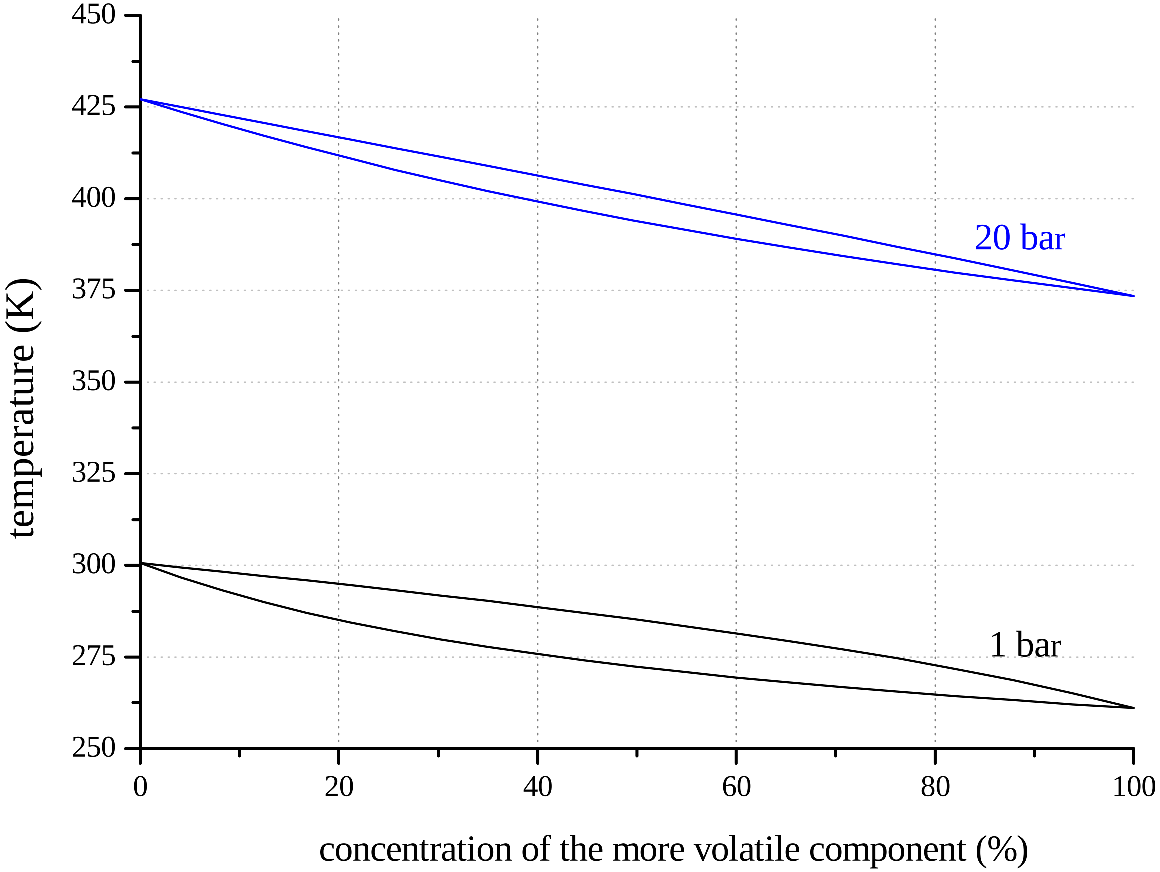
→ Exergoeconomic Analysis

Thermodynamics
ORC with pure fluids as working fluid



→ Adaption of working pressure to minimum temperature difference in the heat transfer units ($\Delta T_{PP,k}$)

Thermodynamics
Non-isothermal phase change of zeotropic mixtures



→ Non-isothermal phase change of zeotropic mixtures

→ Better glide matching at evaporation and condensation

Thermodynamics
ORC with a zeotropic mixture as working fluid

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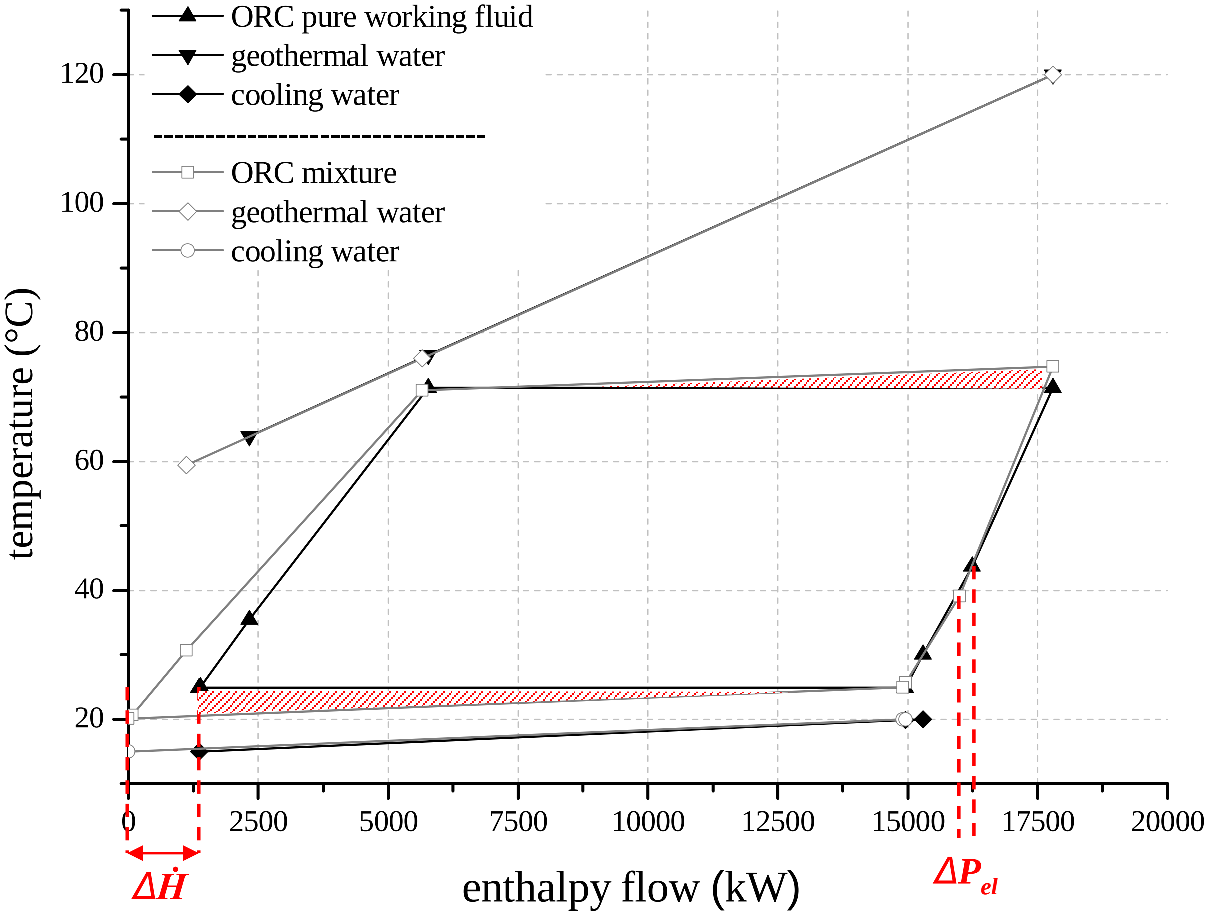

→ Higher amount of heat is coupled to the process

→ Higher power output

→ Lower irreversibilities at phase change

Methods
Software and parameters

Process simulation

- Software: Matlab
- Fluid properties: RefProp Version 8.0 (NIST)

Optimization

- Outlet temperature of heat source is adapted to the maximum power output

Geothermal parameters		
temperature of geothermal water	120	°C
mass flow rate of geothermal water	65	l/s

ORC boundary conditions		
inlet temperature of cooling water	15	°C
temperature difference of cooling water	5	K

Methods
Exergy analysis

Second law analysis

- Second law efficiency:

$$\eta_{II} = \frac{|P_T + P_P|}{\dot{m}_{GW} e}$$

- Irreversibilities

$$\dot{I} = T_0 \frac{ds_g}{dt} = \dot{m} T_0 \left[\sum_{out} s - \sum_{in} s - \sum_i \frac{q_i}{T_i} \right]$$

- Dead state

$$T_0 = T_{\min,System} = T_{CW,in} \qquad p_0 = 1.013 \text{ bar}$$

Case Studies

- Fluids: isobutane/isopentane
- Parameter variation: $\Delta T_{PP,k}$ = 1...12 K

Results
Variation of temperature difference at the pinch point

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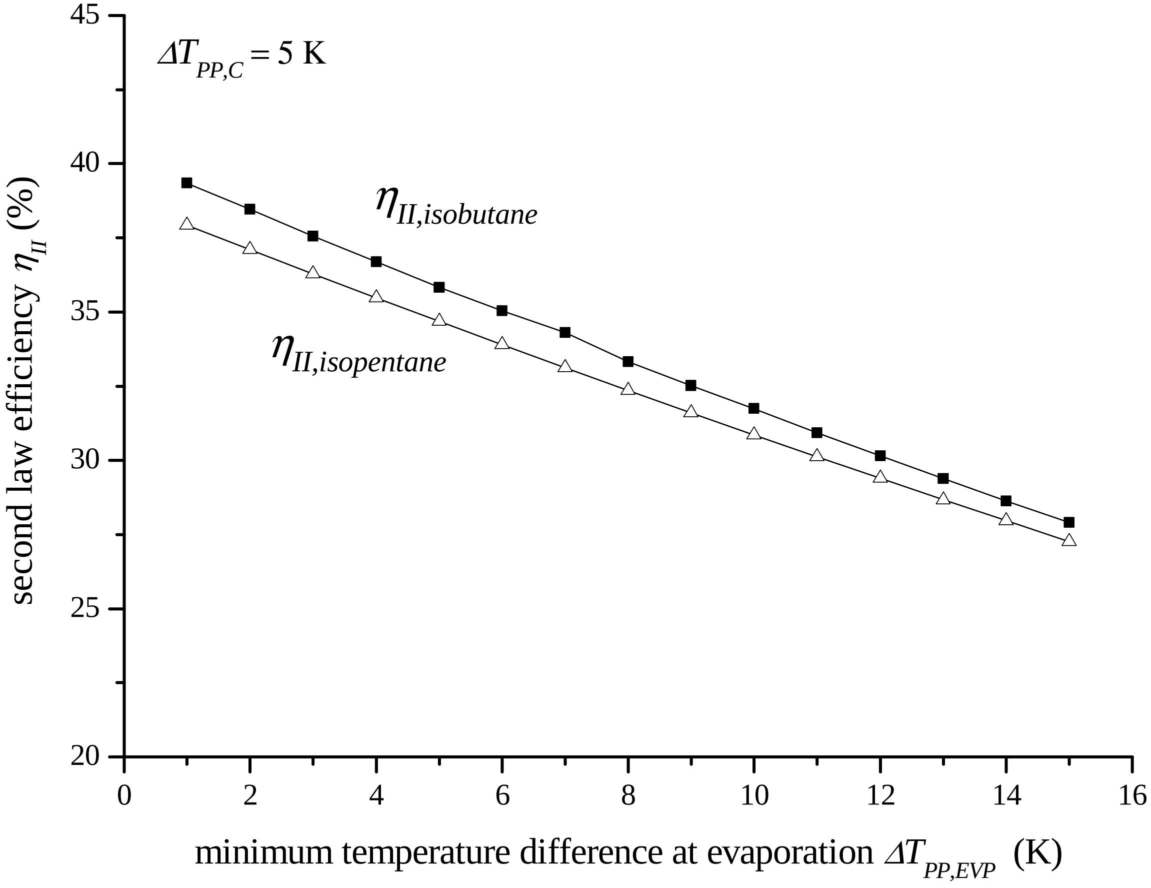
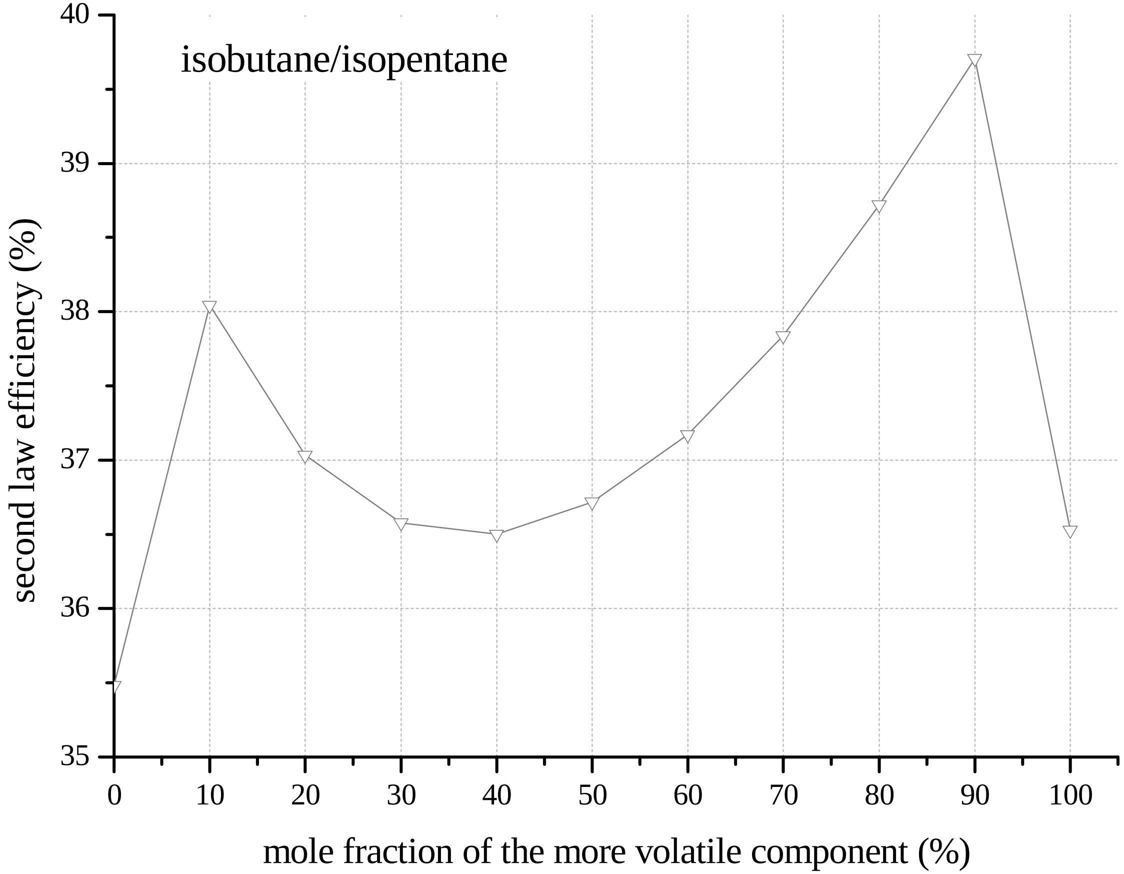


→ Lower temperature differences lead to higher efficiency, due to higher process pressures and higher amount of transferred heat

Results
Second law efficiency



→ Local maxima for efficiency according to glide match of the temperature profiles in the condenser

$$\frac{\eta_{II,90/10}}{\eta_{II,Isobutan}} = 7.7\%$$

$$\frac{\eta_{II,90/10}}{\eta_{II,Isopentan}} = 15.4\%$$

Results
Irreversibilities

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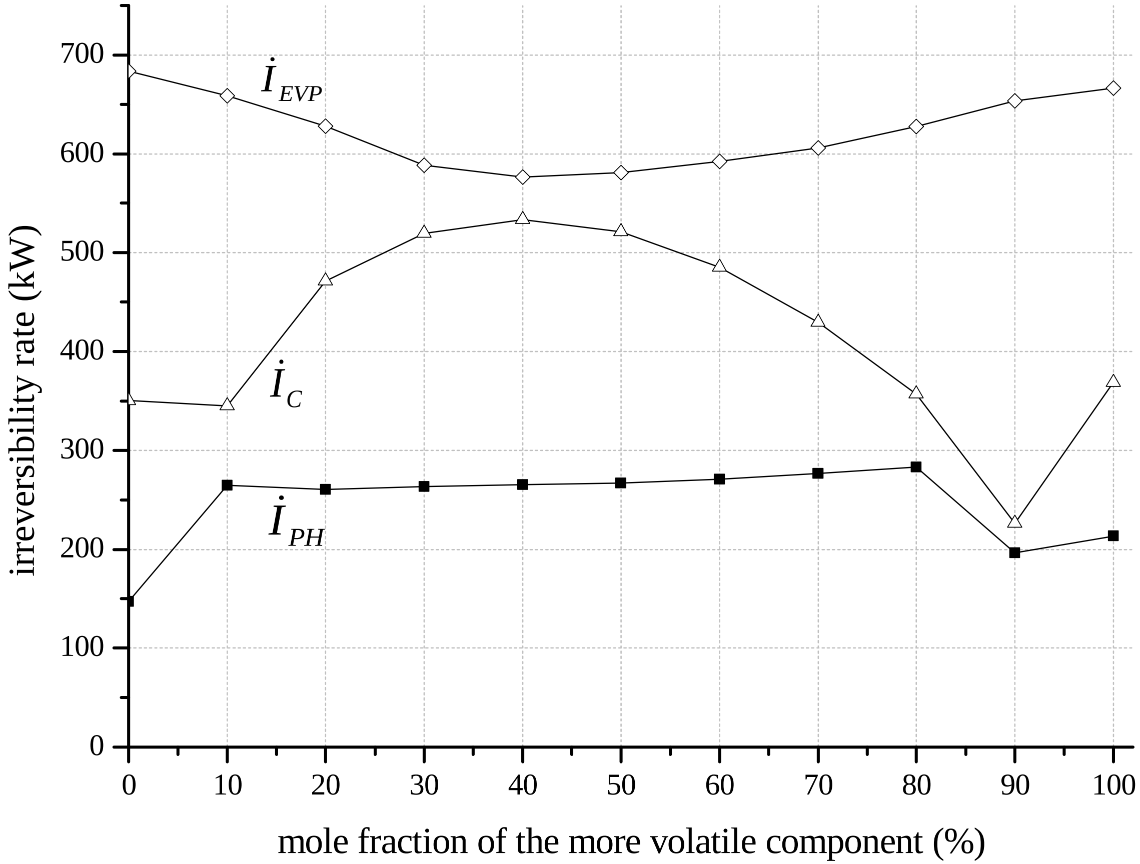
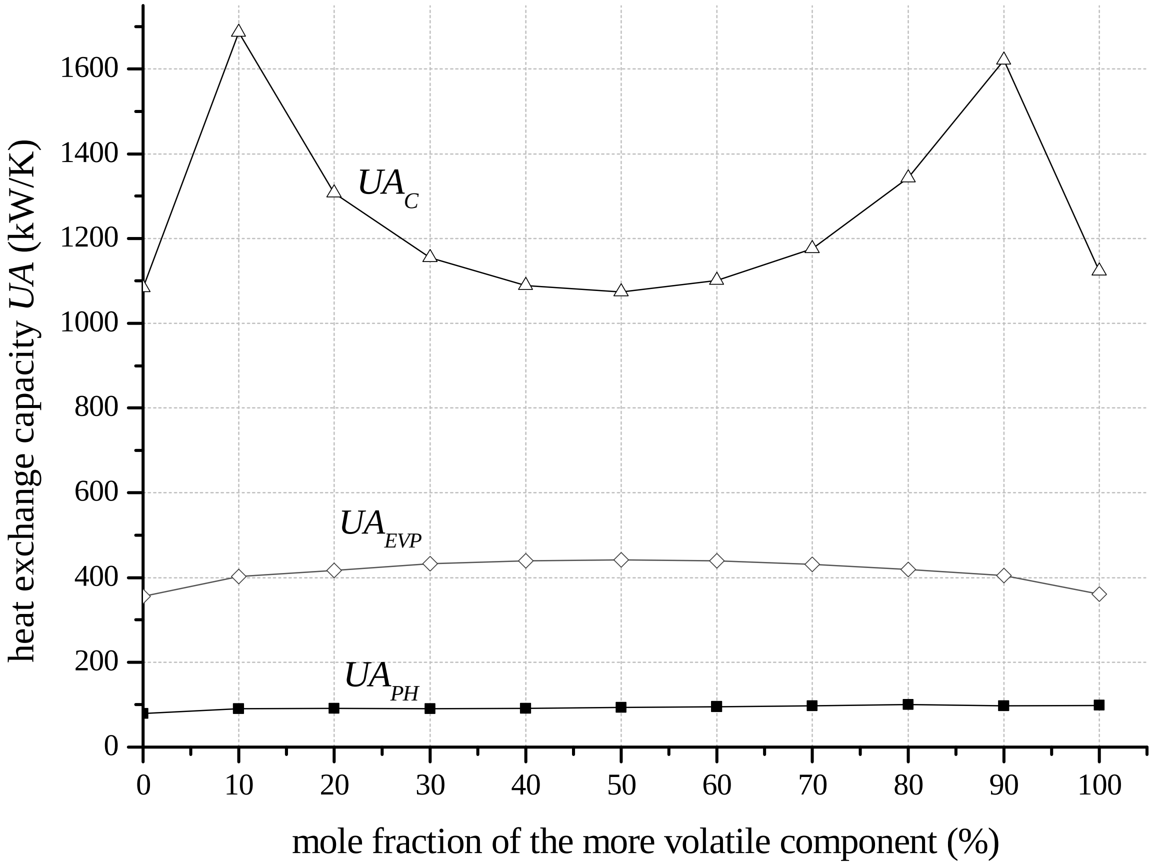


→ Lowest irreversibilities for mixtures

→ Temperature glide equal to temperature difference of cooling water

Results
Heat exchange capacity



→ High UA-values for the condenser because of a higher amount of heat and the lower thermodynamic mean temperatures

→ Heat transfer coefficient of mixtures is reduced compared to pure fluids

→ Economic analysis

Purchased equipment costs (PEC)

- Empiric correlation for pumps, turbines and heat exchanger equipment based on manufacturing data [Turton et al.]:

$$log_{10}\ PEC = K_1 + K_2\ log_{10}\ X + K_3(log_{10}\ X\ )^2$$

Calculation of heat transfer surface

- Heat exchanger design: ideal counter flow double pipe
- Correction factors according VDI-Wärmeatlas

  plate heat exchanger → NTU-Method

  heat transfer coefficient for mixtures [Schlünder], [Shah]

Results

Heat exchange surface as function of temperature difference at the pinch point

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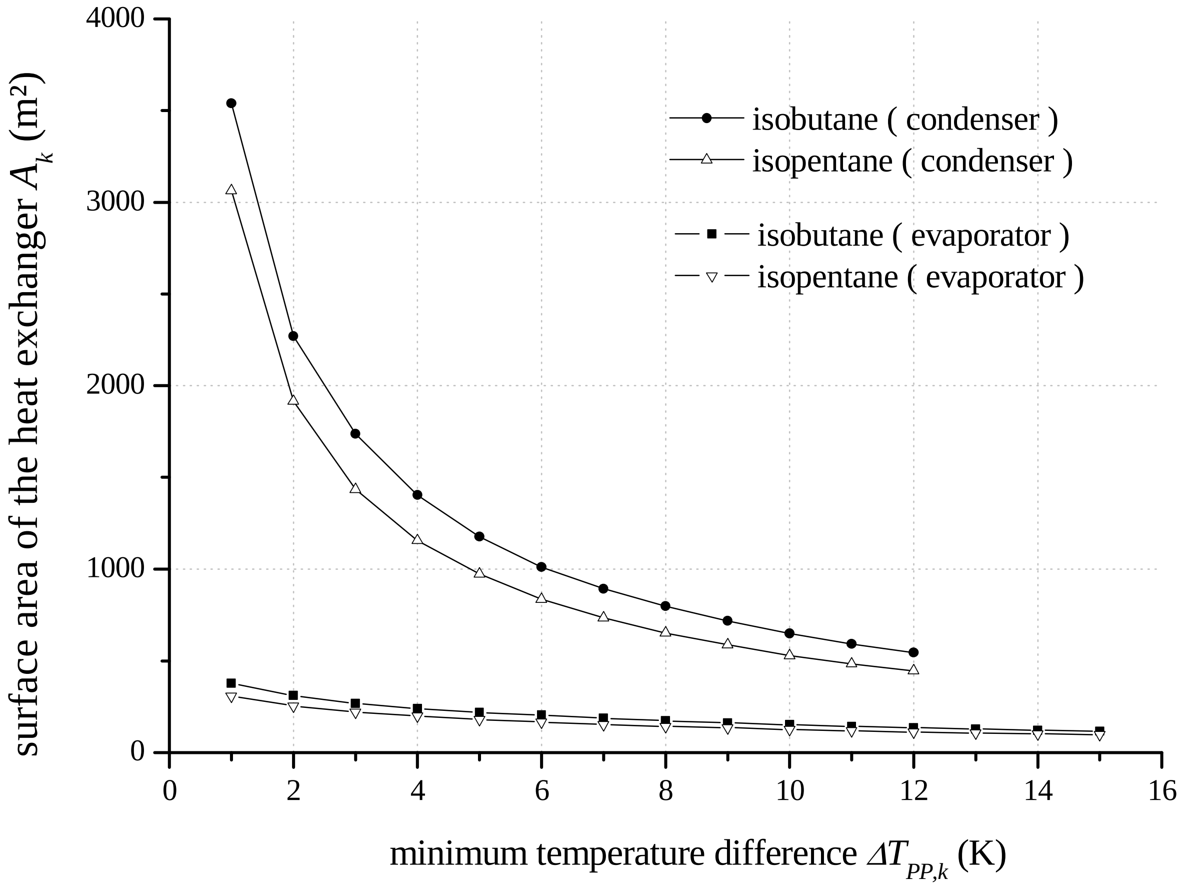

- → Higher heat exchange surface in case of the condenser
- → For isopentane about 23 % lower total surface
- → Lower amount of transferred heat and higher heat transfer coefficient due to transport properties

Methods
Exergoeconomic analysis

Cost rates

- Annual capital investment cost rate
- Annual expense concerning operation and maintenance

Exergy costing

- Cost rate: $\dot{C}_i = c_i \cdot \dot{E}_i$
- Cost balance of each component: $\dot{C}_{P,k} = \dot{C}_{F,k} - \dot{C}_{L,k} + \dot{Z}_K$
- Total specific cost rate of the product: $c_{P,total} = \frac{\dot{C}_{P,total}}{\dot{E}_{P,total}} = \frac{(c_{Fuel,total} E_{Fuel,total} + \sum_K \dot{Z}_K)}{\dot{E}_{P,total}}$

Results

Total specific cost rate of the product - Pure working media

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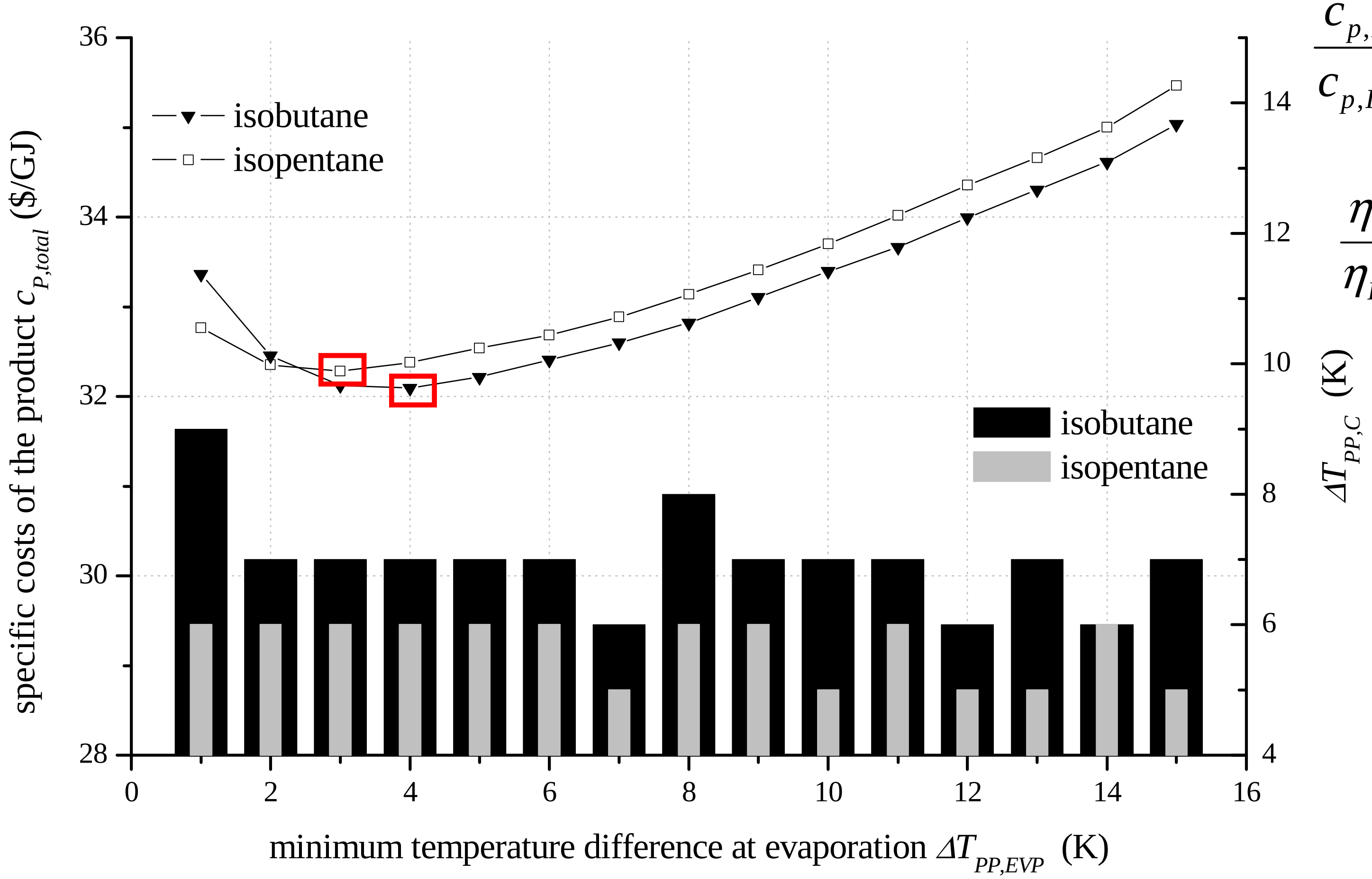

$$\frac{c_{p,Isobutan}}{c_{p,Isopentan}} = -0.8\%$$

$$\frac{\eta_{II,Isobutan}}{\eta_{II,Isopentan}} = 2.5\%$$

Results
Total specific cost rate of the product - Fluid mixtures

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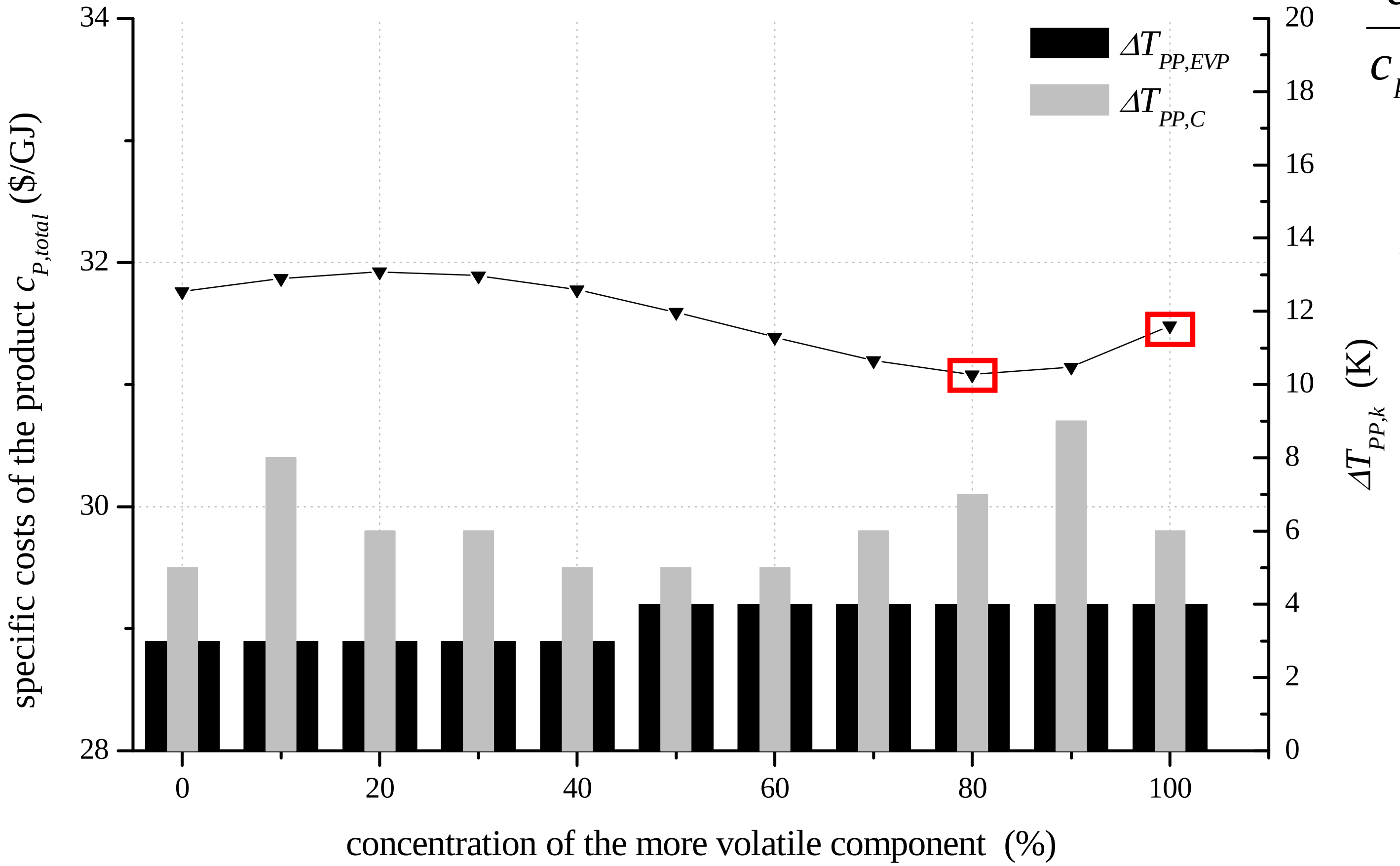

$$\frac{c_{p,80/20}}{c_{p,Isobutan}} = -1.8\%$$

$$\frac{\eta_{II,80/20}}{\eta_{II,Isobutan}} = 1.3\%$$

Summary

Summary

- A case study of a geothermal ORC power plant was performed.
- Exergoeconomic analysis permits the identification of optimal process parameters.
- Isobutane leads to 0.8 % lower specific costs compared to isopentane.
- The use of zeotropic mixture decreases the specific costs up to 1.8 %.
- Results would differ significantly, if a constant temperature difference was assumed.

Further work

- Calculation of shell and tube heat exchanger (according to VDI-Wärmeatlas)
- Using EconExpert for economic data
- More detailed analysis concerning turbine design and costs.
- Thermoeconomic evaluation each component

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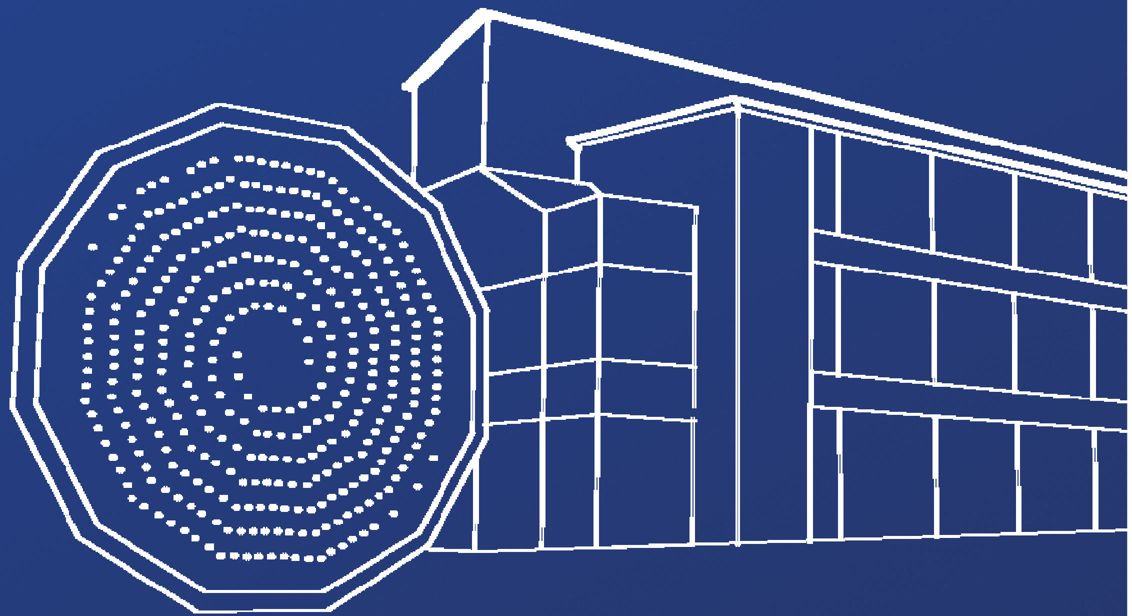

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