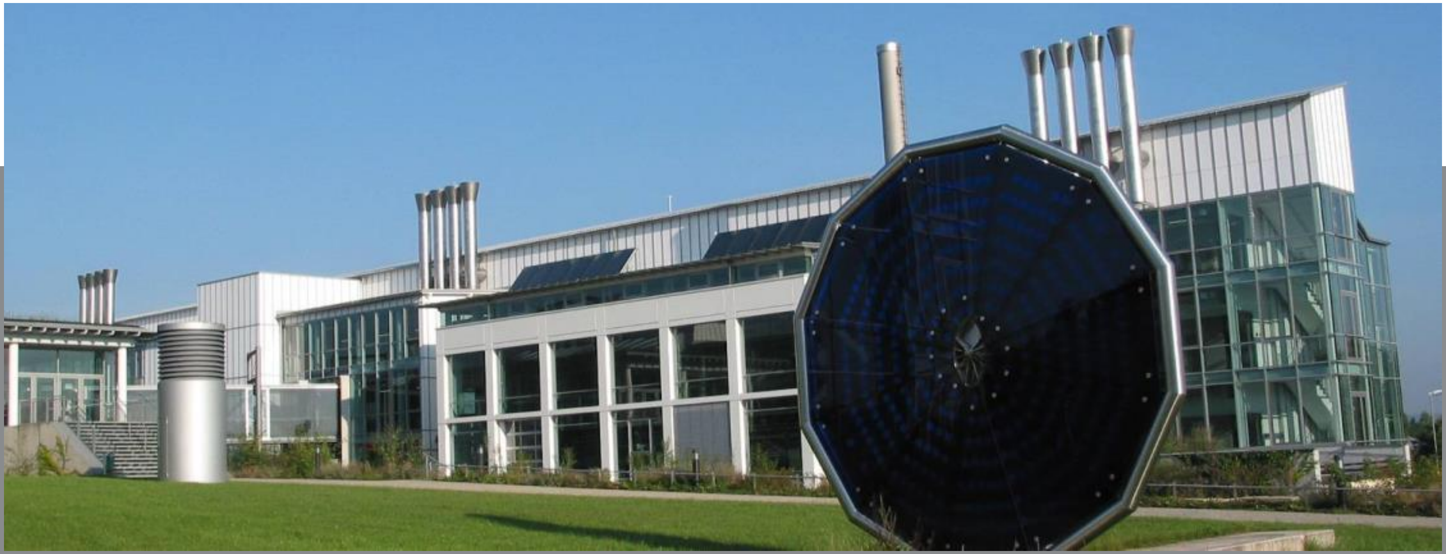

THERMO-ECONOMIC ANALYSIS OF ZEOTROPIC MIXTURES AND PURE WORKING FLUIDS IN ORGANIC RANINKE CYCLES FOR WASTE HEAT RECOVERY

3rd International Seminar on ORC Power Systems, Brussels (Belgium)

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Introduction

Zeotropic mixtures as working fluids in ORC power systems

- Zeotropic mixtures are potential working fluids for ORC power systems.
- The temperature-glide at phase change leads to temperature match with heat source and sink. Compared to pure components lower irreversibilities and higher efficiency is obtained.
- In the context of a thermo-economic evaluation, a reduction of heat transfer characteristics due to additional mass transfer resistance has to be taken into account for zeotropic mixtures.
- A comparison to pure working fluids is performed to clarify, if the efficiency increase overcompensates the additionally required heat transfer surface.

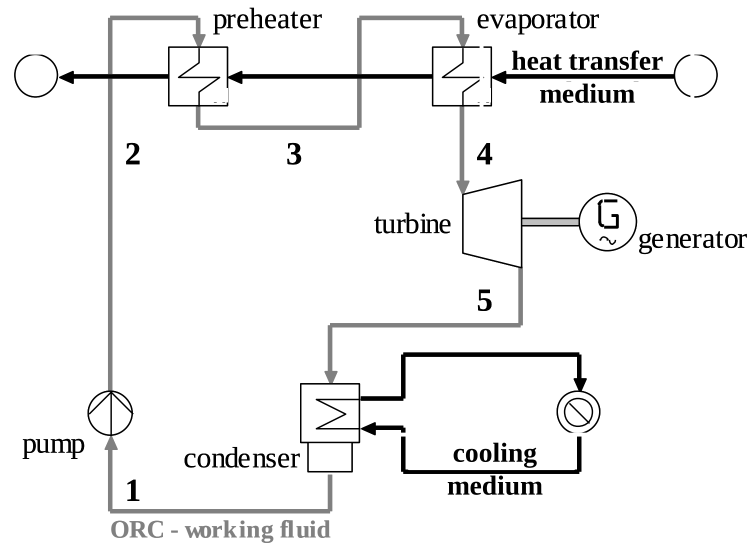
Introduction
General approach

- Boundary conditions / Fluid selection
- Simulations / Second law analysis
- Design of key components
- Cost estimation / Economic evaluation

Boundary conditions

- Subcritical and saturated cycle
- Heat input of 3 MW by pressurized water at 6 bar and 150 °C
- Additional boundary conditions:

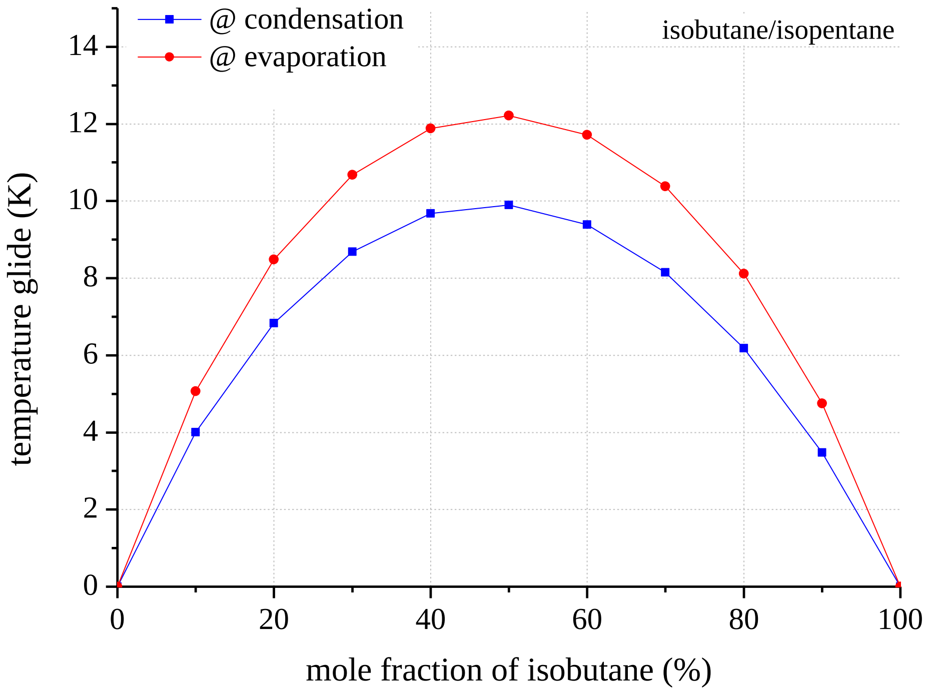
Parameter	Value
mass flow rate of heat source $\dot{m}_{HS}$	10 kg/s
outlet temperature of heat source $T_{HS,in}$	80 °C
inlet temperature of cooling medium $T_{CM,in}$	15 °C
temperature difference of cooling medium ΔT_{CM}	15 °C
maximal ORC process pressure p_2	$0.8 \cdot p_{crit}$
isentropic efficiency of feed pump $\eta_{i,P}$	75 %
isentropic efficiency of turbine $\eta_{is,T}$	80 %
efficiency of generator η_G	98 %



Fluid selection
Investigated working fluids

- Pure fluids: R245fa, isobutane, isopentane

- Zeotropic mixture: isobutane/isopentane
  → Composition is varied in discrete steps of 10 mole-%



Simulations / Second law analysis

- The minimal temperature difference in the evaporator and condenser are chosen as independent design variables in order to identify the most cost-efficient process parameters.

- Pressure and heat losses are neglected in the pipes and components.

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- Pressure and heat losses are neglected in the pipes and components.

- Second law efficiency: $$\eta_{II} = \frac{\left| P_G + P_{Pump} + P_{Fans} \right|}{\dot{E}_{HS}} = \frac{P_{net}}{\dot{m}_{HS} \cdot e_{HS}}$$

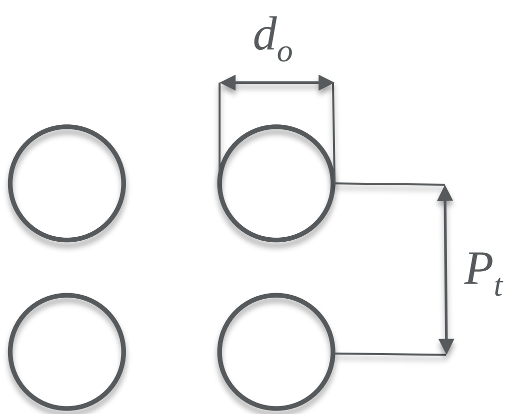
where $e_{HS} = h - h_0 - T_0(s - s_0)$

and T_0 = 15 °C; p_0 = 1 bar

Design of key components

Preheater and evaporator – Predefined design specification

- Shell and tube heat exchanger for preheater and evaporator (TEMA-E-type)
- Inner diameter of the tubes: d_i = 0.02 m
- Wall thickness of the tube: s = 0.002 m
- Maximum flow velocities (VDI Heat Atlas): u_l = 1.5 m/s and u_g = 20 m/s
- Squared layout:



$$\frac{P_t}{d_o} = 1.22$$

Design of key components

Preheater and evaporator – Heat transfer correlations

- Shell side (preheater, evaporator)
  Single phase; pressurized water: Kern (1950)

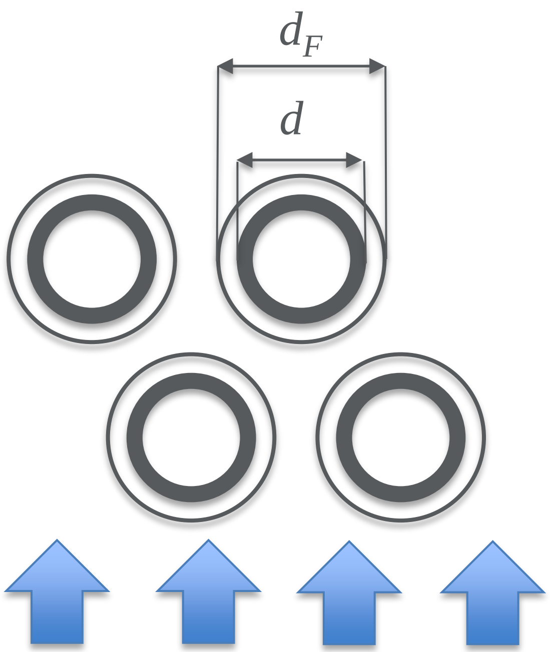
- Tubes side (preheater)
  Single phase; pure fluid & mixture: Sieder and Tate (1936)

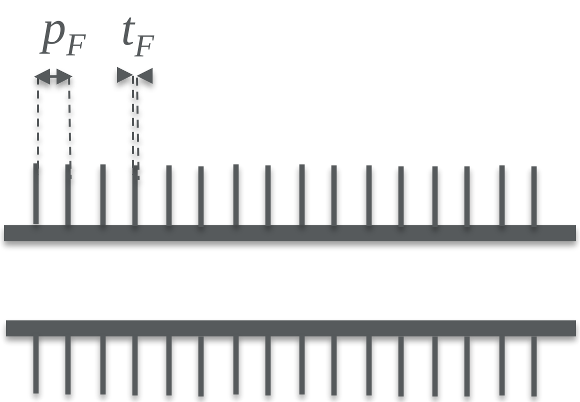
- Tubes side (evaporator)
  Two phase; pure working fluid: Steiner (2006)

  Two phase; zeotropic mixture: Schlünder (1983)

Design of key components
Air cooled condenser – Predefined design specification

- A tube bank staggered arrangement is considered.
- Cross-flow heat exchanger with finned tubes.
- Layout:





Design of key components
Air-cooled condenser – Heat transfer correlations

- Air side

Single phase; air:	Shah and Sekulic (2003)

- Tubes side

Single phase; pure fluid & mixture:	Sieder and Tate (1936)
Two phase; pure working fluid:	Shah (1979)
Two phase; zeotropic mixture:	Bell and Ghaly (1973), Silver (1964)

Cost estimation
Purchased equipment costs (PEC) of the major components

- *PEC* in US $ for ambient operating conditions and a carbon steel construction

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

- Equipment cost data according to Turton et al. (2003)

component	*Y*; unit	K_1	K_2	K_3
Pump (centrifugal)	kW	3.3892	0.0536	0.1538
Heat exchanger (floating head)	m^2	4.8306	-0.8509	0.3187
Heat exchanger (air cooler)	m^2	4.0336	0.2341	0.0497
Turbine (axial)	kW	2.7051	1.4398	-0.1776

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- Consideration of inflation and the development of raw material prices

$$PEC_{k,2014} = PEC_{k,2001} \cdot \left(CEPCI_{2014} / CEPCI_{2001}\right)$$

- Total investment costs (TCI) of the ORC modul according to Bejan et al. (1996)

$$TCI = 6.32 \cdot \sum PEC_{k,2014}$$

Economic evaluation

Economic boundary conditions and parameters

- Economic boundary conditions

parameter	
lifetime	20 years
interest rate *ir*	4.0 %
annual operation hours	7500 h/year
Cost rate for operation and maintenance	$0.02 \cdot \dot{Z}_{CI}$
Costs for process integration C_{PI}	$0.2 \cdot PEC_{total}$
Power requirements of the air-cooling system	$5\ kW_e/MW_{th}$
Electricity price	0.08 €/kWh

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- Calculated economic paramters

$$c_{P,tot} = \frac{\dot{C}_{P,tot}}{\dot{E}_{P,tot}} = \frac{(c_{F,tot}\dot{E}_{F,tot} + \sum_k \dot{Z}_k)}{\dot{E}_{P,tot}}$$

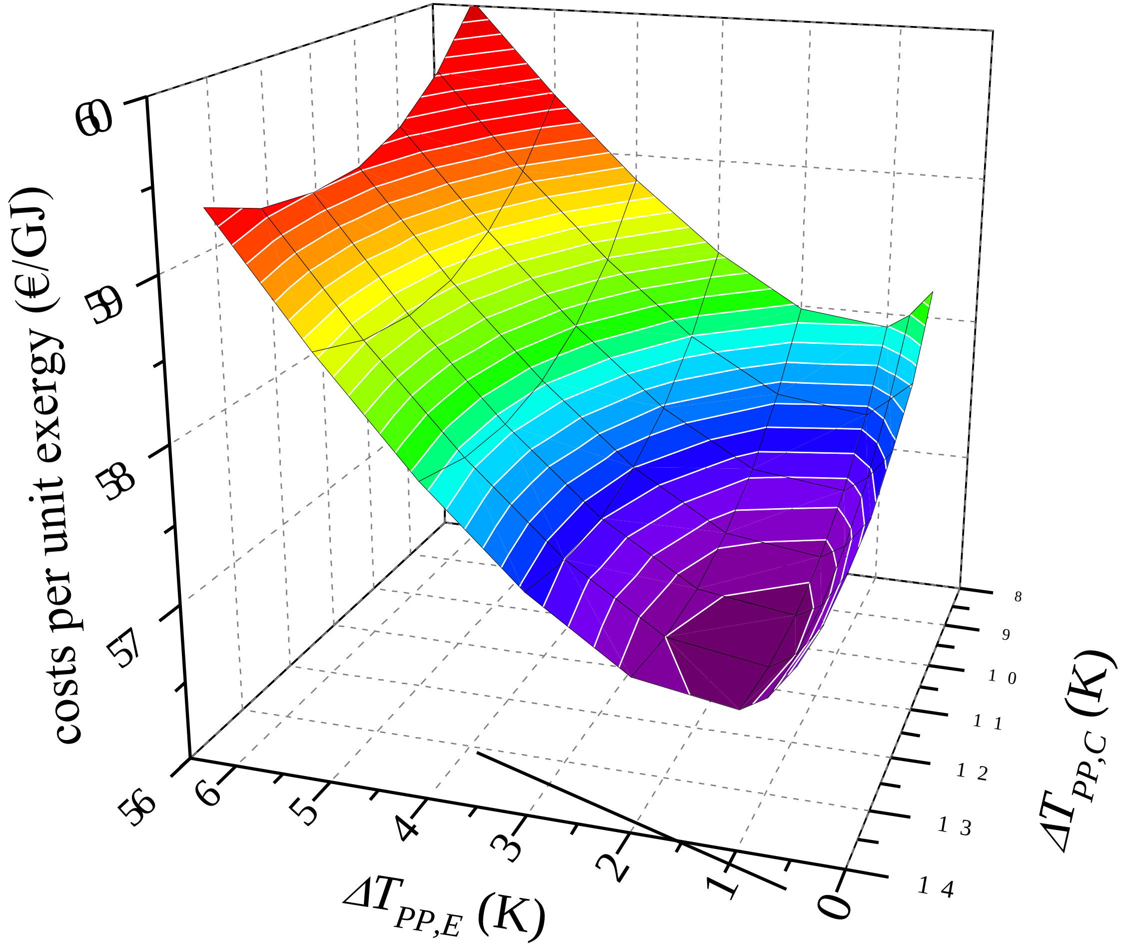
costs per unit exergy (Bejan et al.)

$$SIC = \frac{C_{tot,ORC}}{P_{net}}$$

specific investment costs

Results

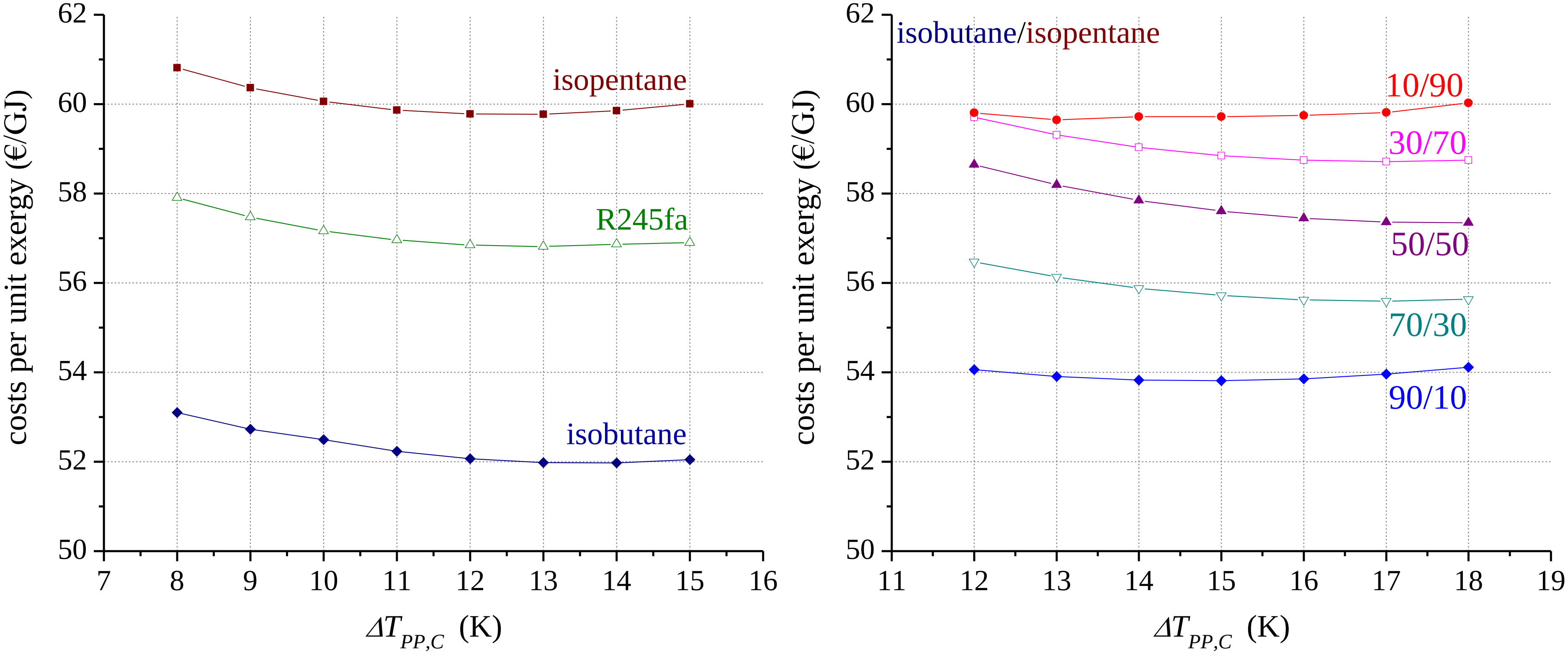
Minimization of costs per unit exergy – R245fa



- Minimal costs per unit exergy are identified for each working fluid.
- In case of R245fa $c_{p,total}$ minimal for $\Delta T_{PP,E}$ = 1 K and $\Delta T_{PP,C}$ = 13 K.
- Corresponding *LCOE* = 106.6 €/MWh

Results

Costs per unit exergy – Variation of working fluids



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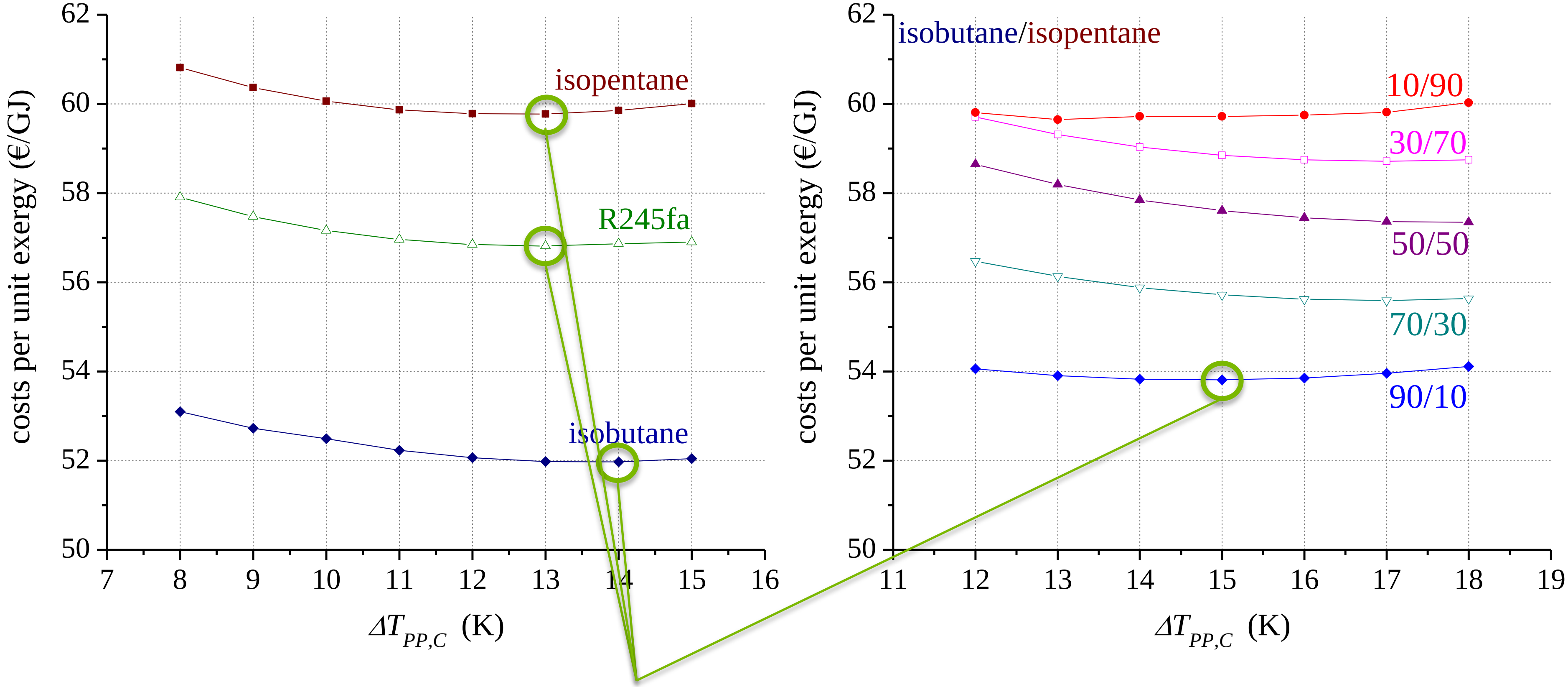

→ Most cost-efficient parameters for the investigated fluids and compositions.

→ Here, $\Delta T_{PP,E}$ is chosen according to the cost minimum.

Results
Most cost-effective parameters depending on fluid selection

parameter	isobutane	R245fa	isopentane	isobutane/isopentane (90/10)
A_{total} (m^2)	1043.4	1039.8	1065.4	1005.9
$\Delta T_{PP,E}$ (K)	1.2	1.0	1.0	2.0
$\Delta T_{PP,C}$ (K)	14.0	13.0	13.0	15.0
P_G (kW)	387.8	345.9	331.0	366.4
P_{Pump} (kW)	60.1	21.6	12.1	41.4
η_{II} (%)	30.3	30.0	29.4	30.0
$PEC_{total,ORC}$	450,585	439,328	442,292	440,779
SIC (€/kW)	1,162	1,270	1,336	1,203
$c_{p,tot}$ (€/GJ)	52.0	56.8	59.8	53.8

Results

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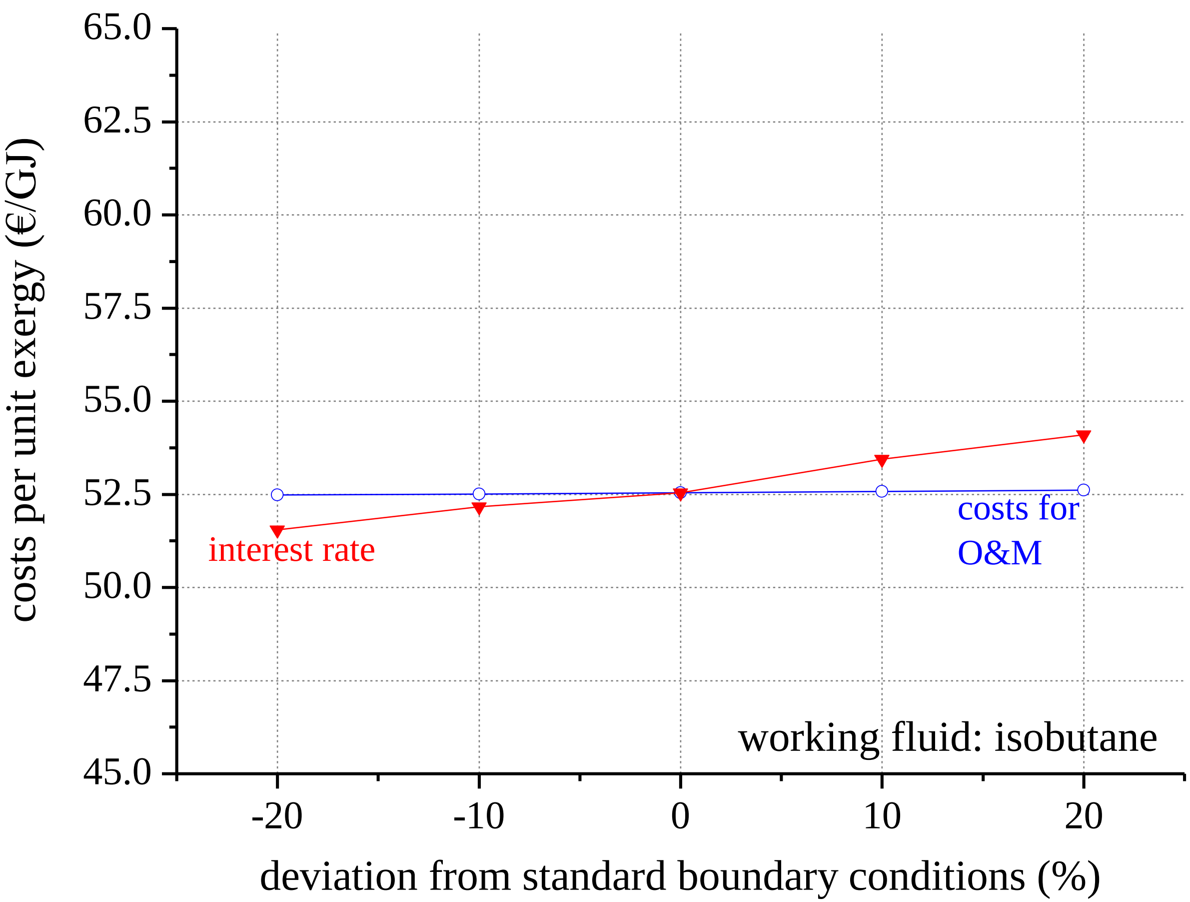
Results

Sensitivity analysis regarding thermodynamic and economic parameters



- Low influence of *ir* and $C_{O\&M}$ (maximal deviation: 2.9 %)

Results

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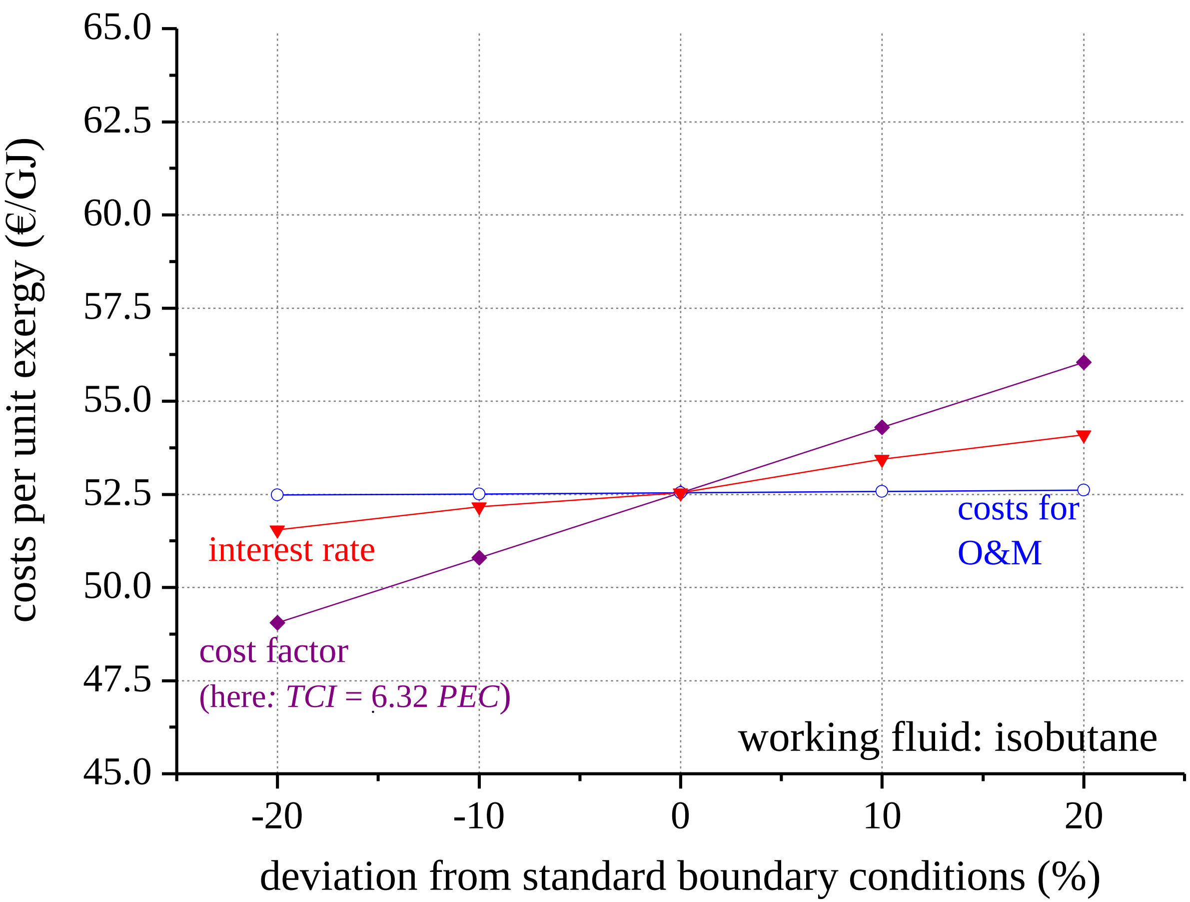

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- Cost factor for estimation of *TCI* with medium relevance (maximal deviation: 6.7 %)

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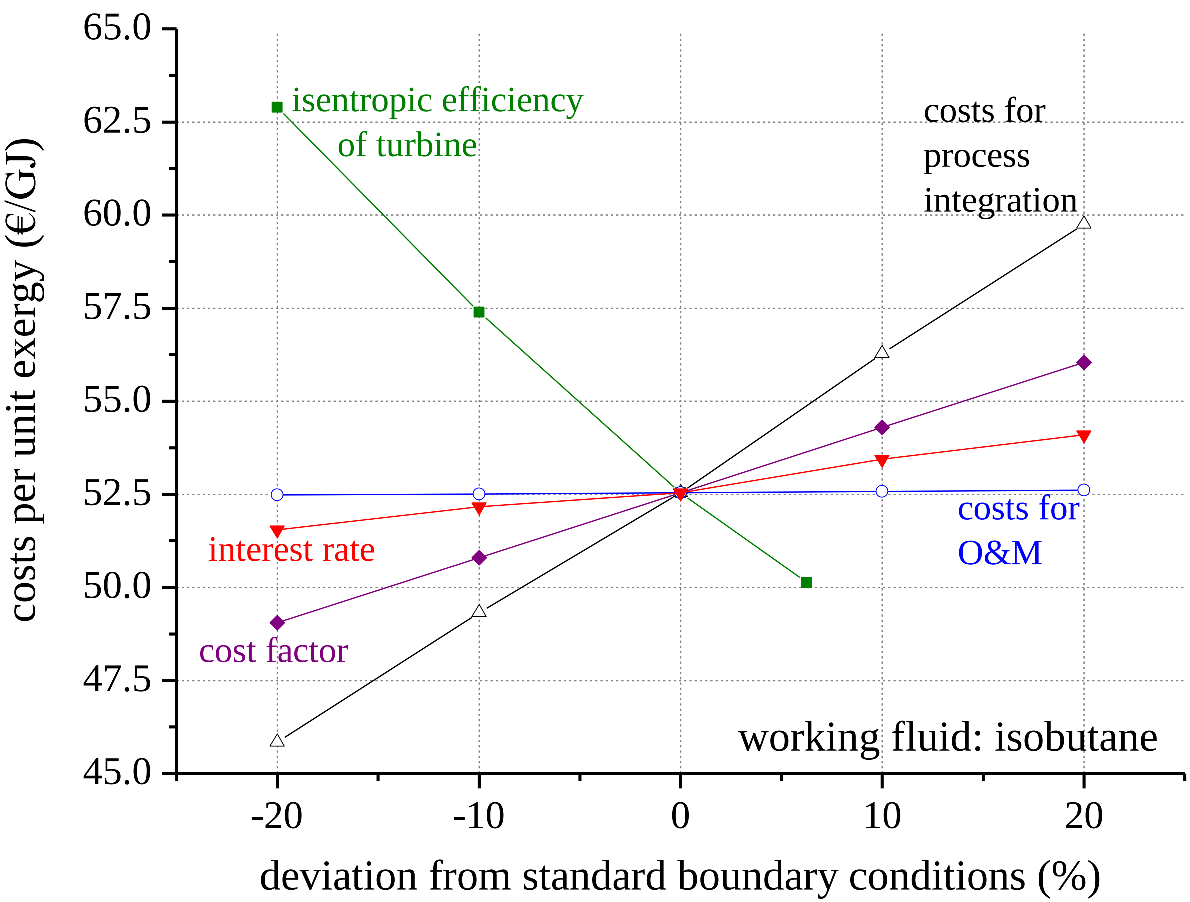

- Low influence of *ir* and $C_{O\&M}$ (maximal deviation: 2.9 %)
- Cost factor for estimation of *TCI* with medium relevance (maximal deviation: 6.7 %)
- High sensitivity for $\eta_{i,T}$ and C_{PI} (maximal deviation: 19.7 %)

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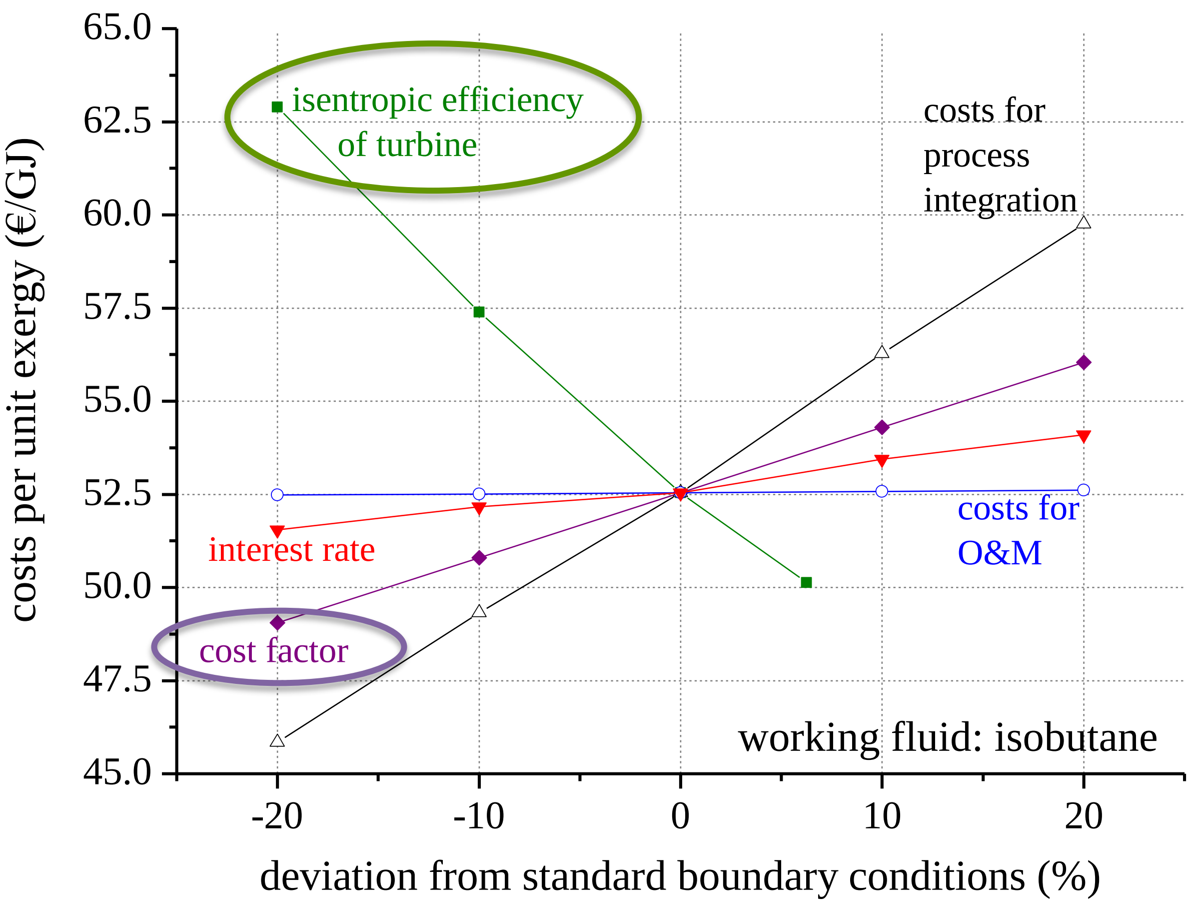

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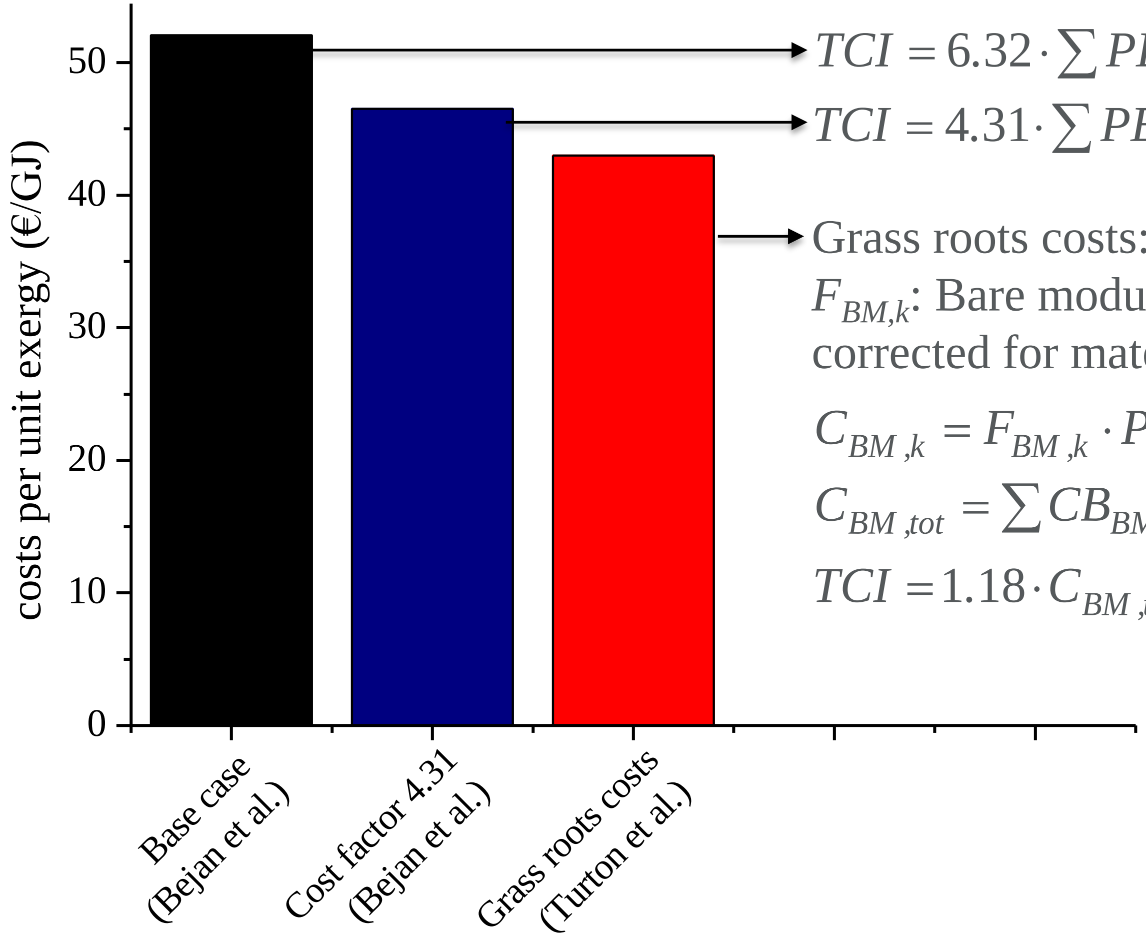
Results

Ongoing refinements of the thermo-economic model

- **Cost estimation - method for *TCI***



$$TCI = 6.32 \cdot \sum PEC_{k,2014}$$

$$TCI = 4.31 \cdot \sum PEC_{k,2014}$$

Grass roots costs:

$F_{BM,k}$: Bare module cost factor corrected for material and pressure > 1 atm

$$C_{BM,k} = F_{BM,k} \cdot PEC_{k,2014}$$

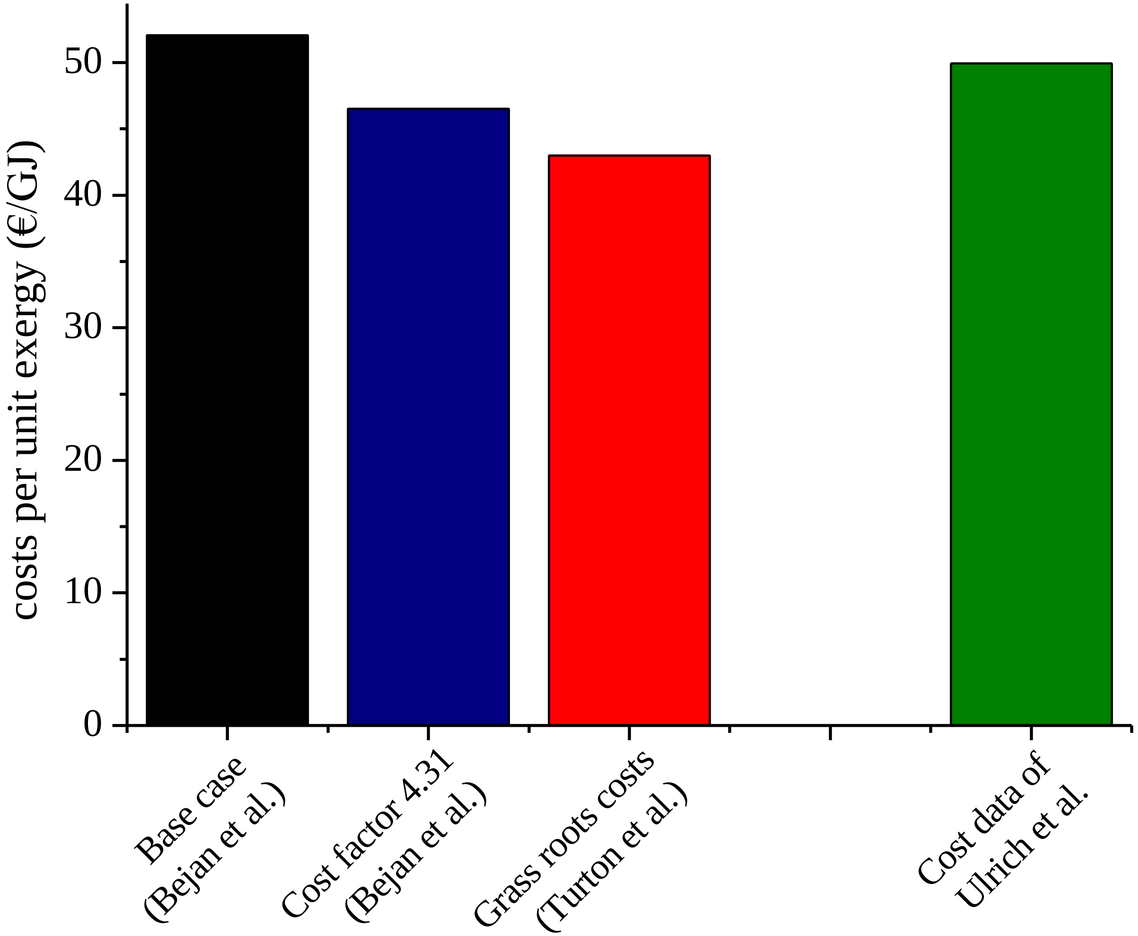
$$C_{BM,tot} = \sum CB_{BM,k}$$

$$TCI = 1.18 \cdot C_{BM,tot} + 0.5 \cdot C_{BM,tot}$$

working fluid: isobutane

Results
Ongoing refinements of the thermo-economic model

- Cost estimation - method for *TCI*
- **Cost estimation - database**



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Chemical Engineering Process Design and Economics, A Practical Guide. 2nd Edition, G. D. Ulrich and P. T. Vasudevan, 2004; Process Publishing.

Results

Ongoing refinements of the thermo-economic model

• Cost estimation - method for *TCI*	• Cost estimation - database
• **Turbine model**	

parameter	isobutane	R245fa	isopentane	isobutane/isopentane
$\eta_{i,T}$ (%)	78.5	80.6	80.2	78.8
$rd_{\eta_{i,T}}$ (%)	-1.88	0.75	0.25	-1.50
SP (-)	0.0486	0.082	0.0729	0.0508
N_S (-)	0.0759	0.0768	0.0767	0.076
D_{mean} (mm)	130.5	220.1	195.7	136.7
$c_{p,tot}$ (€/GJ)	52.20	59.05	56.69	54.02
$rd_{c_{p,tot}}$ (%)	0.38	-1.25	-0.19	0.41

→ Tool for prediction of the performance of low reaction, axial turbine stages

→ P. Klonowicz, F. Heberle, M. Preißinger, D. Brüggemann: *Significance of loss correlations in performance prediction of small scale, highly loaded turbine stages working in Organic Rankine Cycles*. Energy, vol. 72, pp. 322-330, 2014

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- **Turbine model**
- Consideration of pressure losses

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Input for cost estimation

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Conclusions

- In this study, isobutane leads to the lowest specific costs of the product.
- For the mixture (isobutane/isopentane) a mole fraction of 90 % isobutane leads to the lowest specific costs of the product.
- In contrast to geothermal applications, where the exploitation plays the major cost role, the mixture does not lead to the most cost efficient system for the considered WHR case study.
  (cf., F. Heberle and D. Brüggemann: Thermoeconomic Analysis of Hybrid Power Plant Concepts for Geothermal Combined Heat and Power Generation. Energies 2014, vol. 7, Issue 7, pp. 4482-4497, 2014)
- The isentropic efficiency of the turbine and the cost for process integration are the most sensitive parameters concerning the economic evaluation.
- More detailed cost estimation for the axial turbine and a consideration of pressure losses will be implemented.

Acknowledgements

The authors gratefully acknowledge financial support from

DFG

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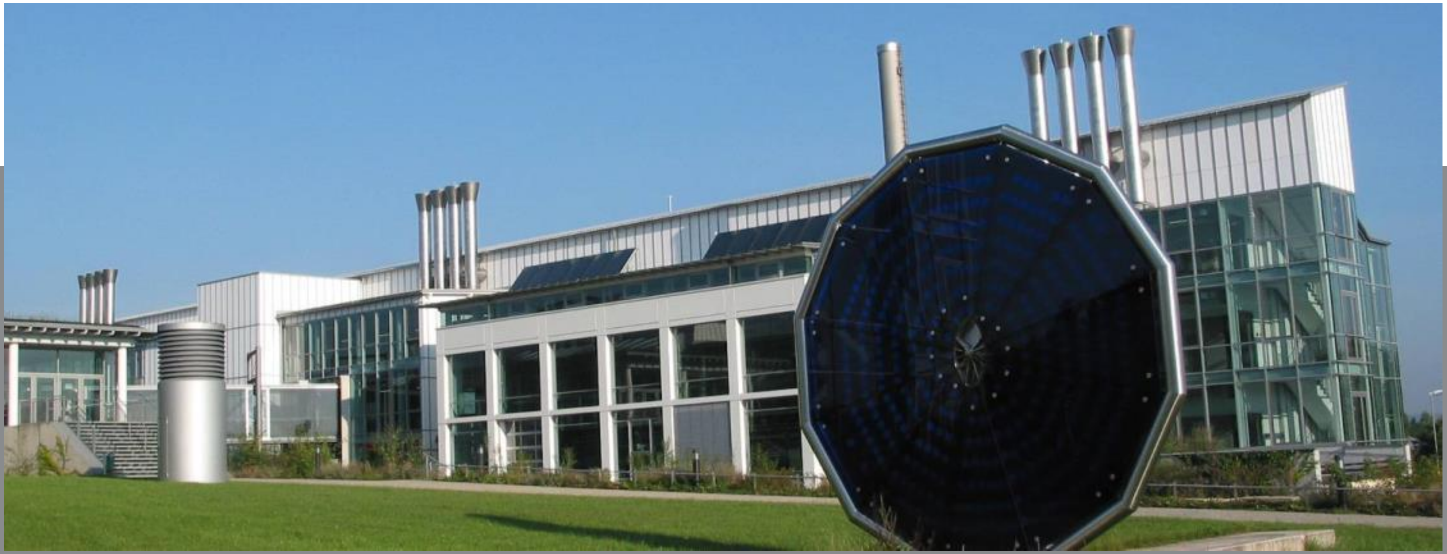

Thank you

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