Booster Heat Pump with Zeotropic Mixtures

3rd International Conference on Smart Energy Systems
and 4th Generation District Heating
12.09.2017 - Copenhagen

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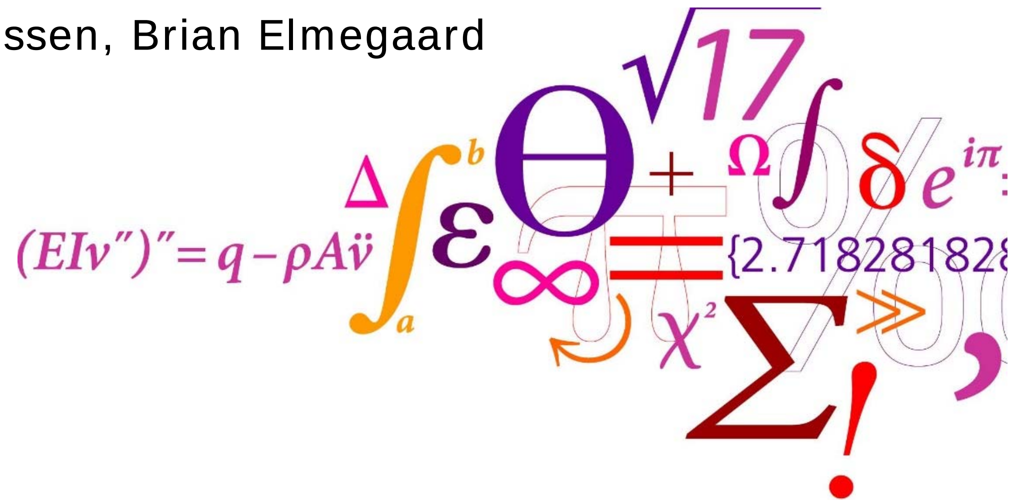
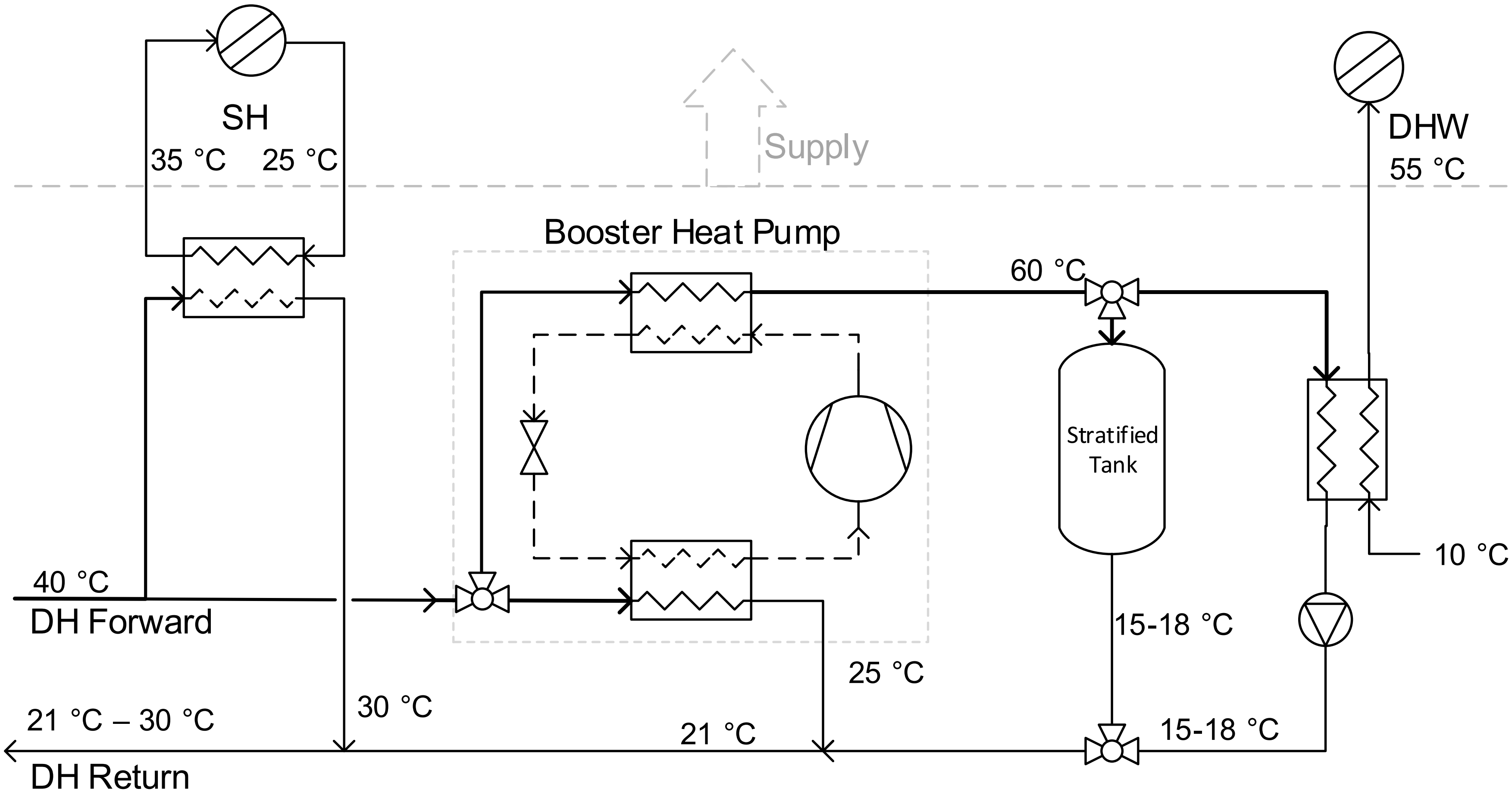


DTU Mechanical Engineering
Department of Mechanical Engineering

Agenda

- Introduction
- Motivation for using mixed working fluids
- Booster HP
  - Working fluid screening
  - Economic evaluation
- Ultra low temperature district heating mixtures
  - Off design analysis
  - System performance (incl. central HP with mixtures)
- Conclusions

Booster HP System

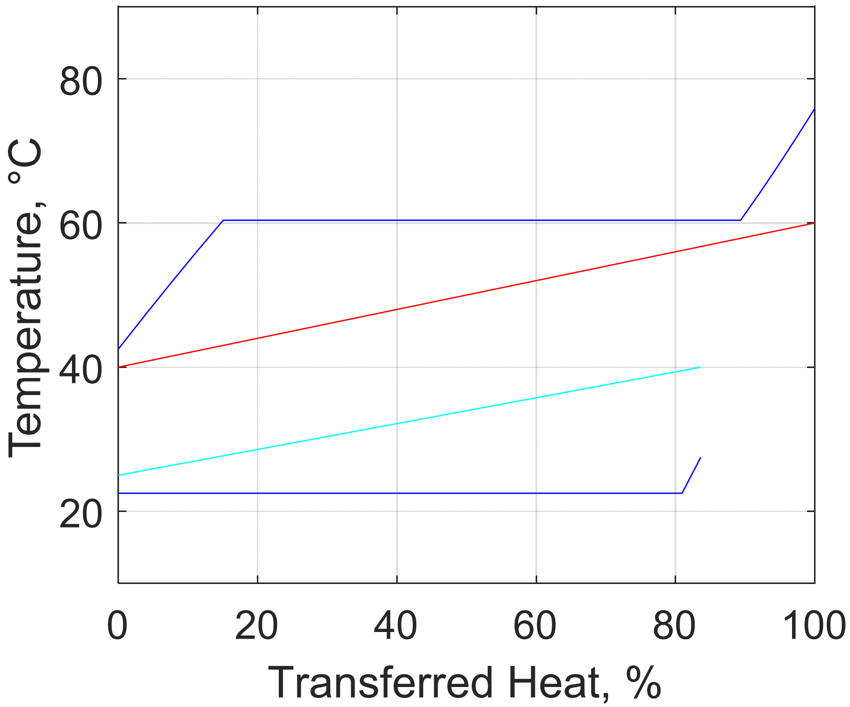


Motivation

<u>Heat Pump:</u>

Heat Source: 40 °C → 25 °C

Heat Sink: 40 °C → 60 °C



<u>R134a:</u>

$COP = 6.11$

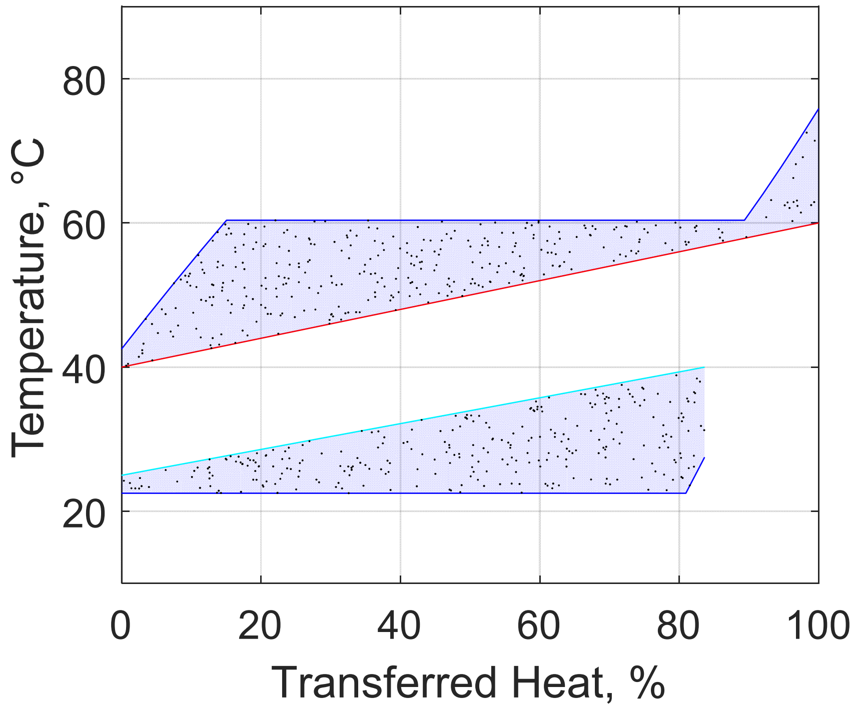
$p_{evap} = 6.17 \text{ bar}, p_{cond} = 16.97 \text{ bar}$

Motivation

<u>Heat Pump:</u>

Heat Source: 40 °C → 25 °C

Heat Sink: 40 °C → 60 °C



<u>R134a:</u>

$COP = 6.11$

$p_{evap} = 6.17$ bar, $p_{cond} = 16.97$ bar

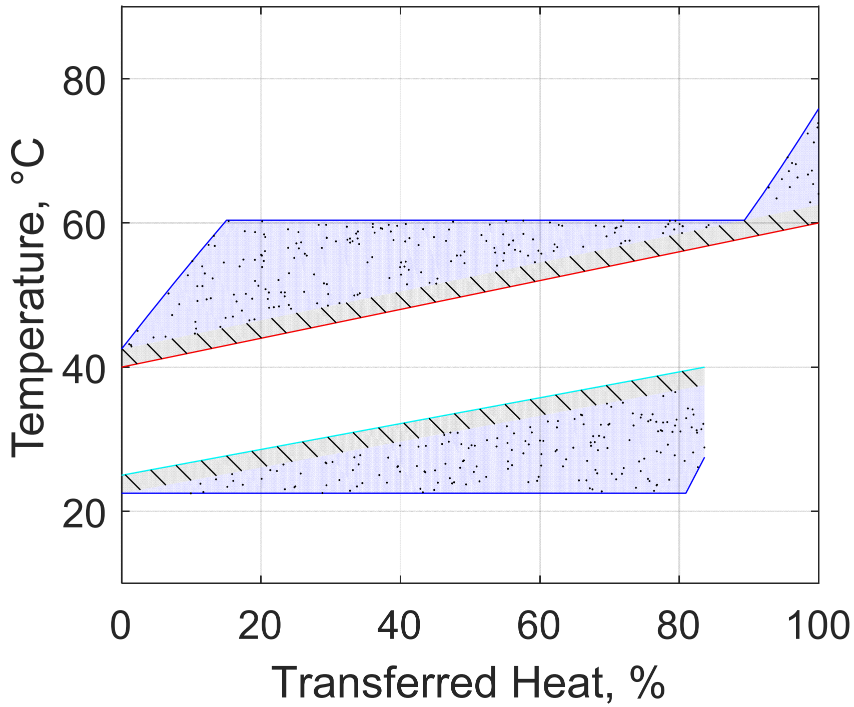
$y^*_{D,source} = 25\ \%,\ y^*_{D,sink} = 25\ \%$

Motivation

<u>Heat Pump:</u>

Heat Source: 40 °C → 25 °C

Heat Sink: 40 °C → 60 °C



<u>R134a:</u>

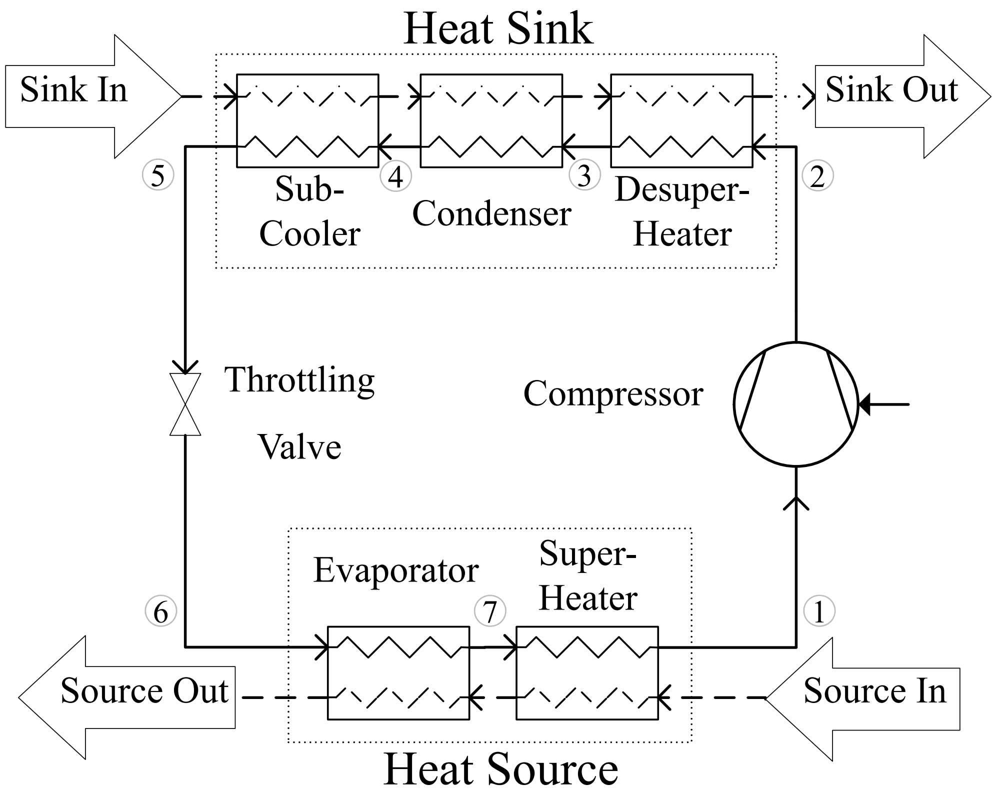
COP = 6.11

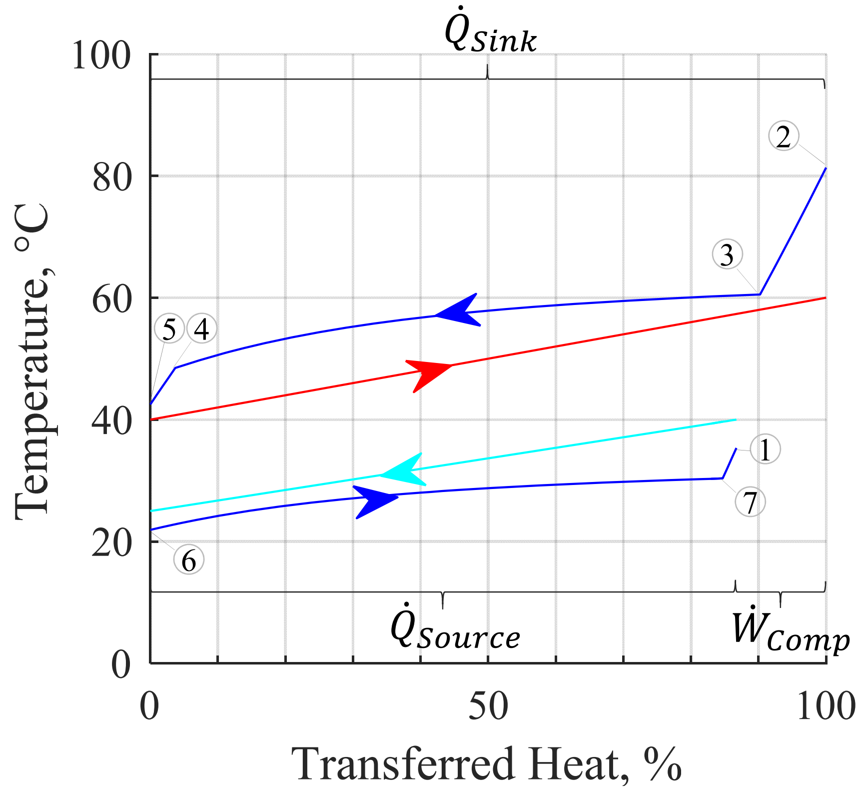
$p_{\text{evap}} = 6.17$ bar, $p_{\text{cond}} = 16.97$ bar

$y^*_{\text{D,source}} = 25\,\%$, $y^*_{\text{D,sink}} = 25\,\%$

$y^*_{\text{D,source,Fluid}} = \mathbf{19}\,\%$, $y^*_{\text{D,sink,Fluid}} = \mathbf{19}\,\%$

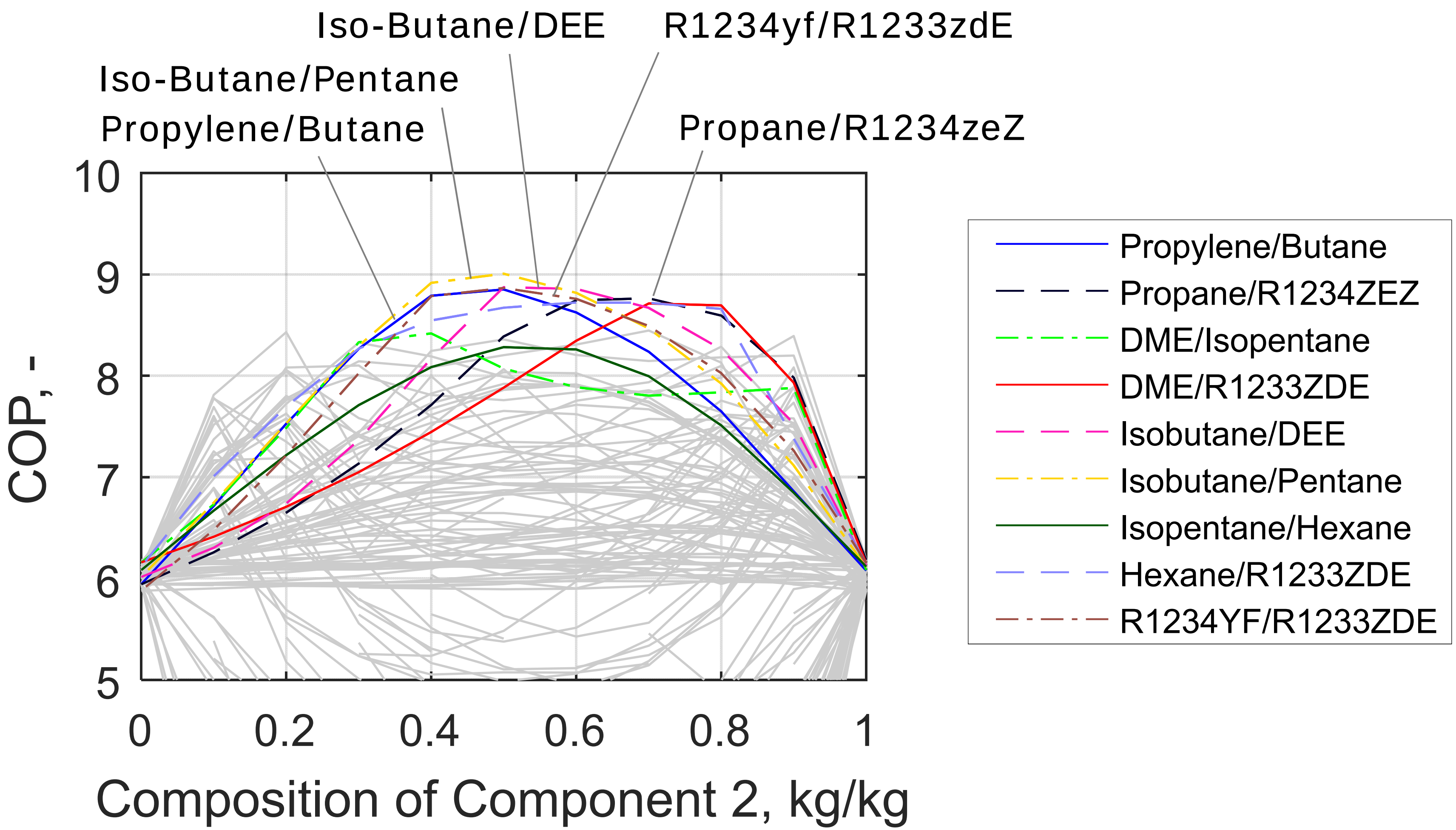
Working Fluid Screening: Thermodynamic Model



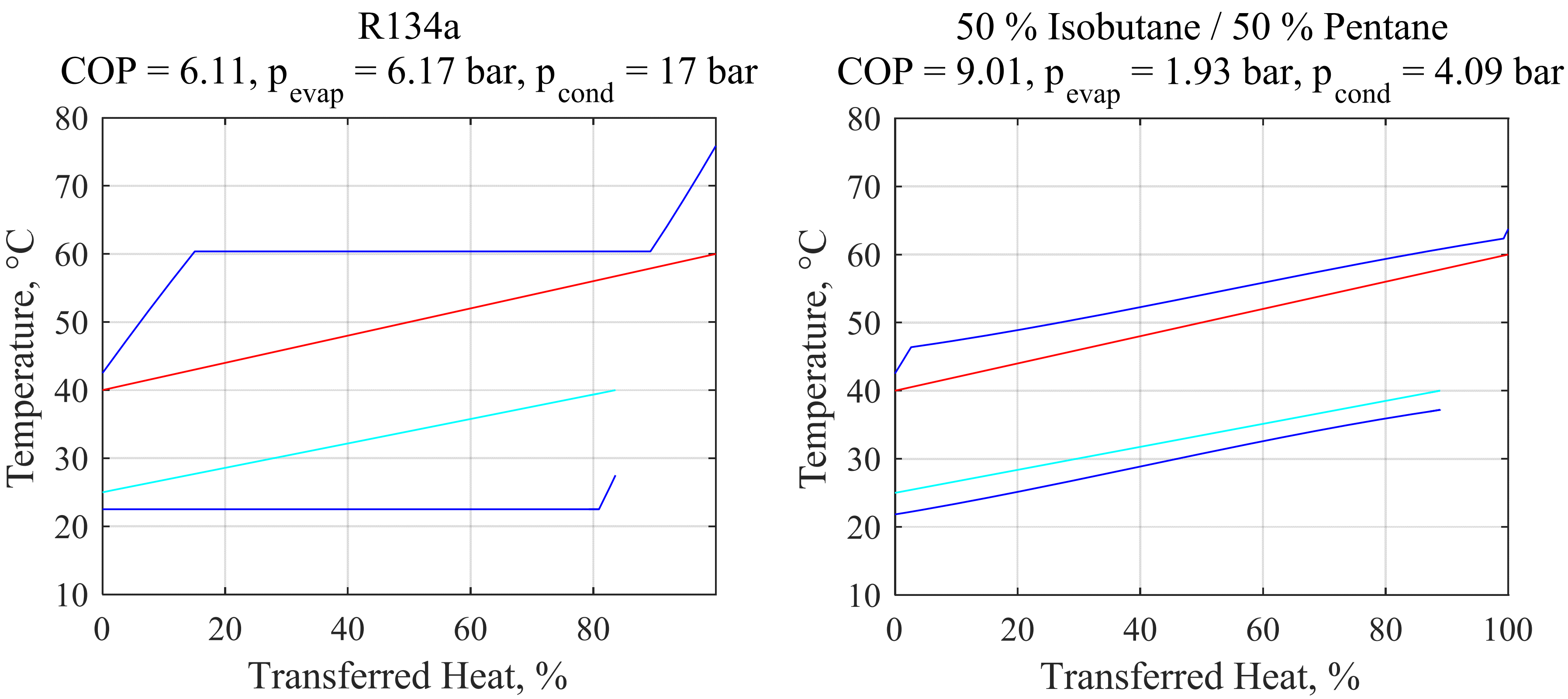


→ Simulation of all possible binary mixtures, considering 14 HCs + 4 HFOs

Working Fluid Screening: Results (0 K min. Super Heating)



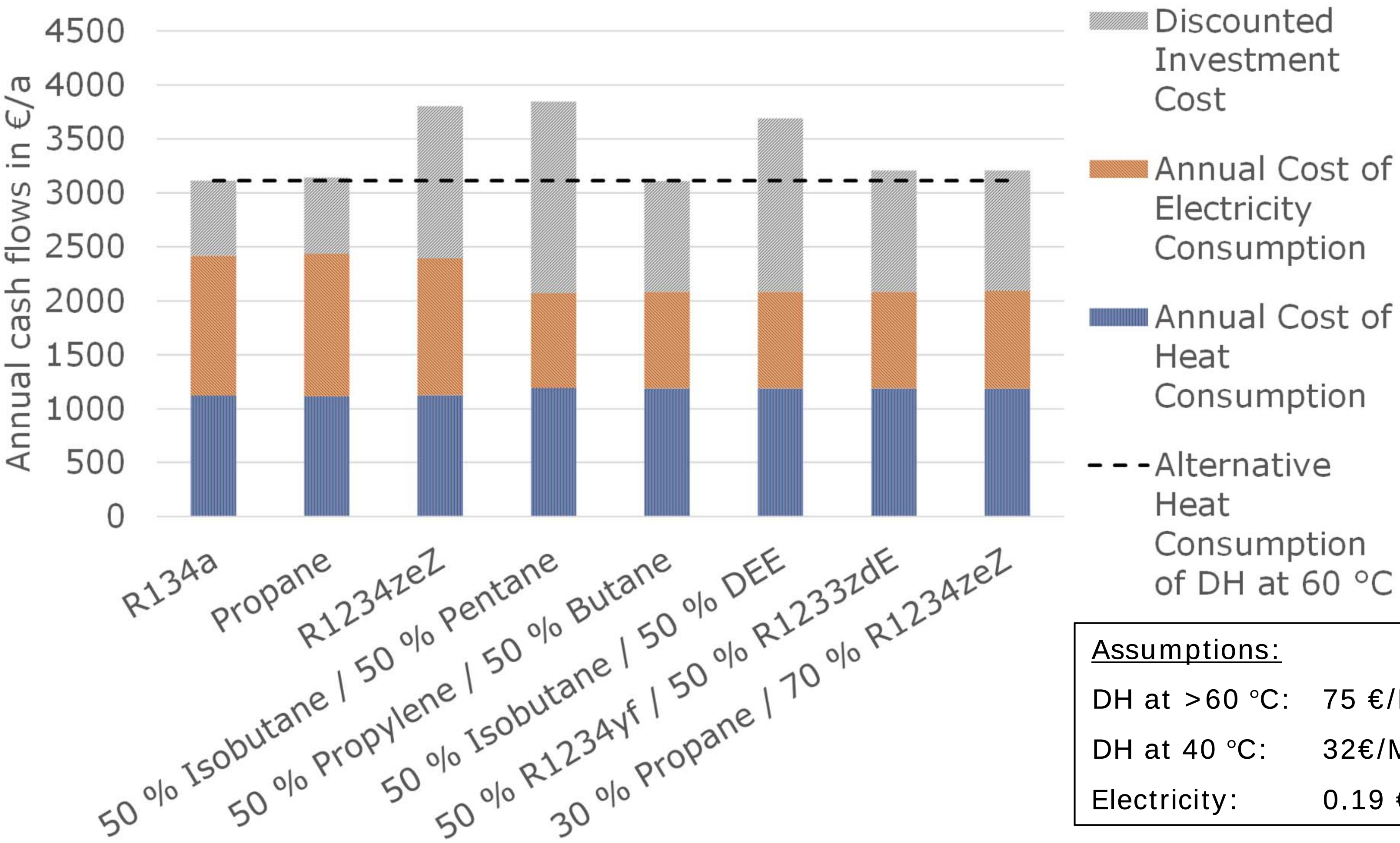
Working Fluid Screening: Results



Booster HP: Investment Cost

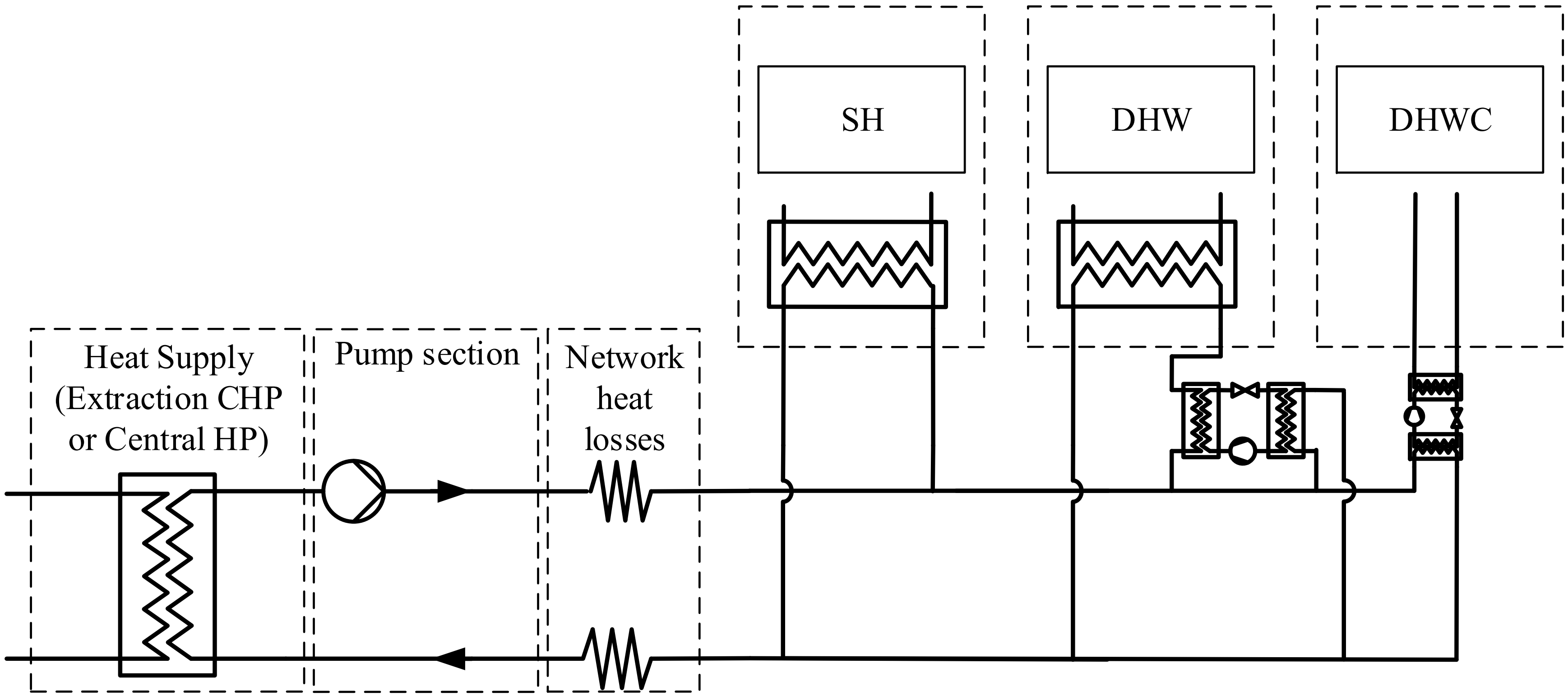
Working Fluid	COP [–]	A_{evap} [m²]	A_{cond} [m²]	$\dot{V}_{comp}$ [m³/h]	PEC_{evap} [€]	PEC_{cond} [€]	PEC_{comp} [€]	PEC_{total} [€]	TCI_{total} [€]
R134a	6.11	1.52	2.11	9.21	289.01	350.88	1,525.83	2,165.71	8,662.86
Propane	6.01	1.52	2.13	7.56	288.54	353.80	1,564.14	2,206.49	8,825.94
50 % Propylene – 50 % Butane	8.85	5.09	4.28	9.92	668.31	582.06	1,943.18	3,193.55	12,774.20
30 % Propane – 70 % R1234zeZ	8.76	4.41	4.62	12.00	596.30	618.07	2,263.86	3,478.23	13,912.92

Booster HP: Heat Generation Cost



Assumptions:	
DH at >60 °C:	75 €/MWh
DH at 40 °C:	32€/MWh
Electricity:	0.19 €/kWh

DH System: Layout



DH System:
Off Design Analysis

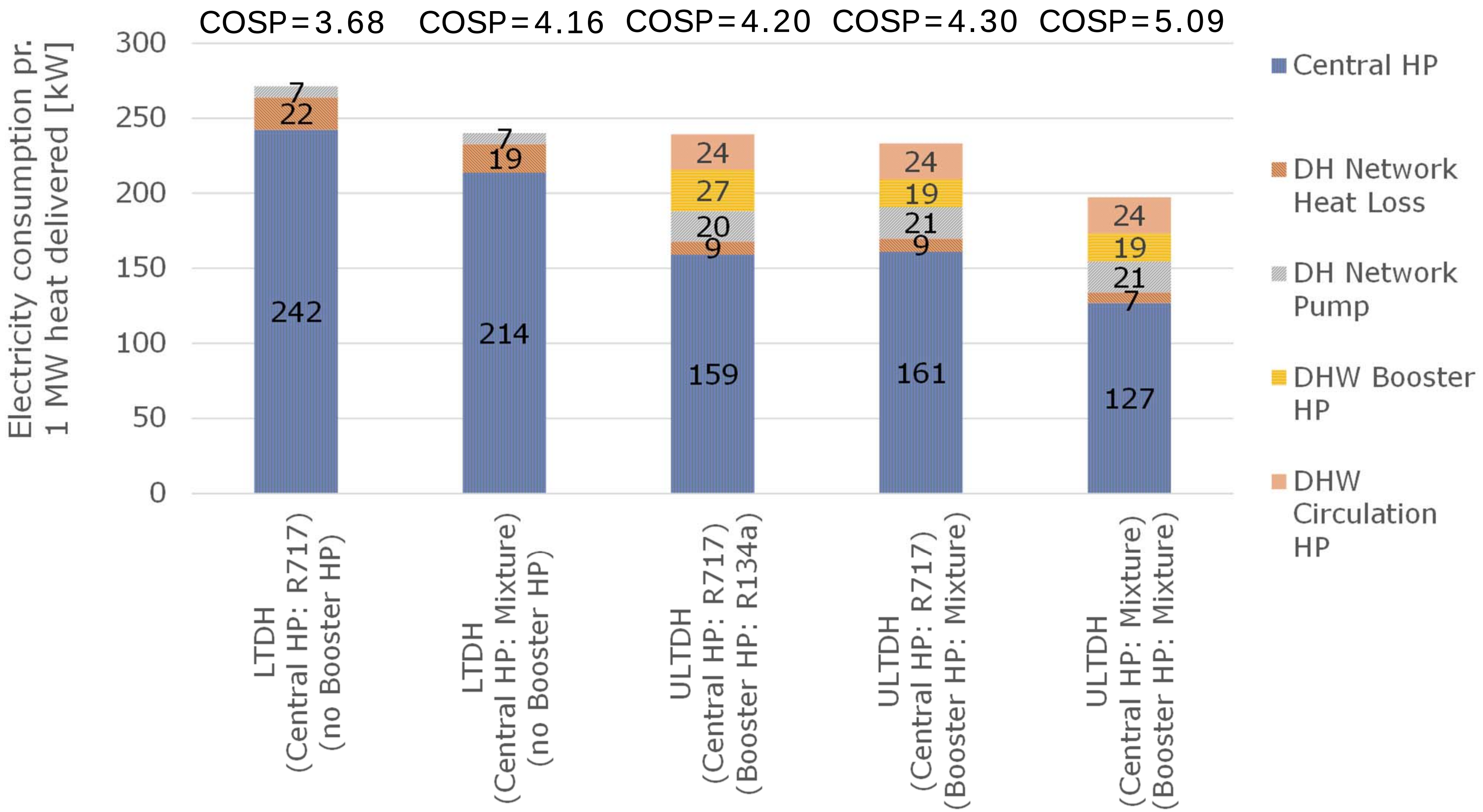
Varying forward temperature:
$T_{forward} = (35 \ldots \mathbf{40} \ldots 45 \ldots 50)$ °C

Constant T_{return}:
$T_{return} = 25$ °C

Constant ΔT_{source}:
$\Delta T_{source} = 15$ K

<table>
<tr><th rowspan="4"></th><th colspan="7">$T_{\text{forward}} = T_{sink,in}$</th></tr>
<tr><th colspan="2">35 °C</th><th>40 °C</th><th colspan="2">45 °C</th><th colspan="2">50 °C</th></tr>
<tr><th colspan="7">$T_{return} = T_{\text{source,out}}$</th></tr>
<tr><th>20 °C</th><th>25 °C</th><th>25 °C</th><th>30 °C</th><th>25 °C</th><th>35 °C</th><th>25 °C</th></tr>
<tr><td>Medium</td><td colspan="7">COSP [-]</td></tr>
<tr><td>R134a</td><td rowspan="8">- 7 %</td><td rowspan="8">- 13 %</td><td>4.18</td><td rowspan="8">± 0 %</td><td rowspan="8">± 0 %</td><td rowspan="3">- 2 %</td><td rowspan="3">- 3 %</td></tr>
<tr><td>R290</td><td>4.17</td></tr>
<tr><td>R1234zeZ</td><td>4.18</td></tr>
<tr><td>50 % IsoButane – 50 % Pentane</td><td>4.30</td><td rowspan="5">- 3 %</td><td rowspan="5">- 4 %</td></tr>
<tr><td>50 % Propylene – 50 % Butane</td><td>4.29</td></tr>
<tr><td>50 % IsoButane – 50 % DEE</td><td>4.29</td></tr>
<tr><td>50 % R1234yf – 50 % R1233zdE</td><td>4.29</td></tr>
<tr><td>30 % Propane – 70 % R1234zeZ</td><td>4.29</td></tr>
</table>

DH System:
System Performance



Conclusions

- Thermodynamic performance of Booster HP:
  - R134a: COP = 6.11
  - 50 % Isobutane / 50 % Pentane: COP = 9.01 (+47 %)

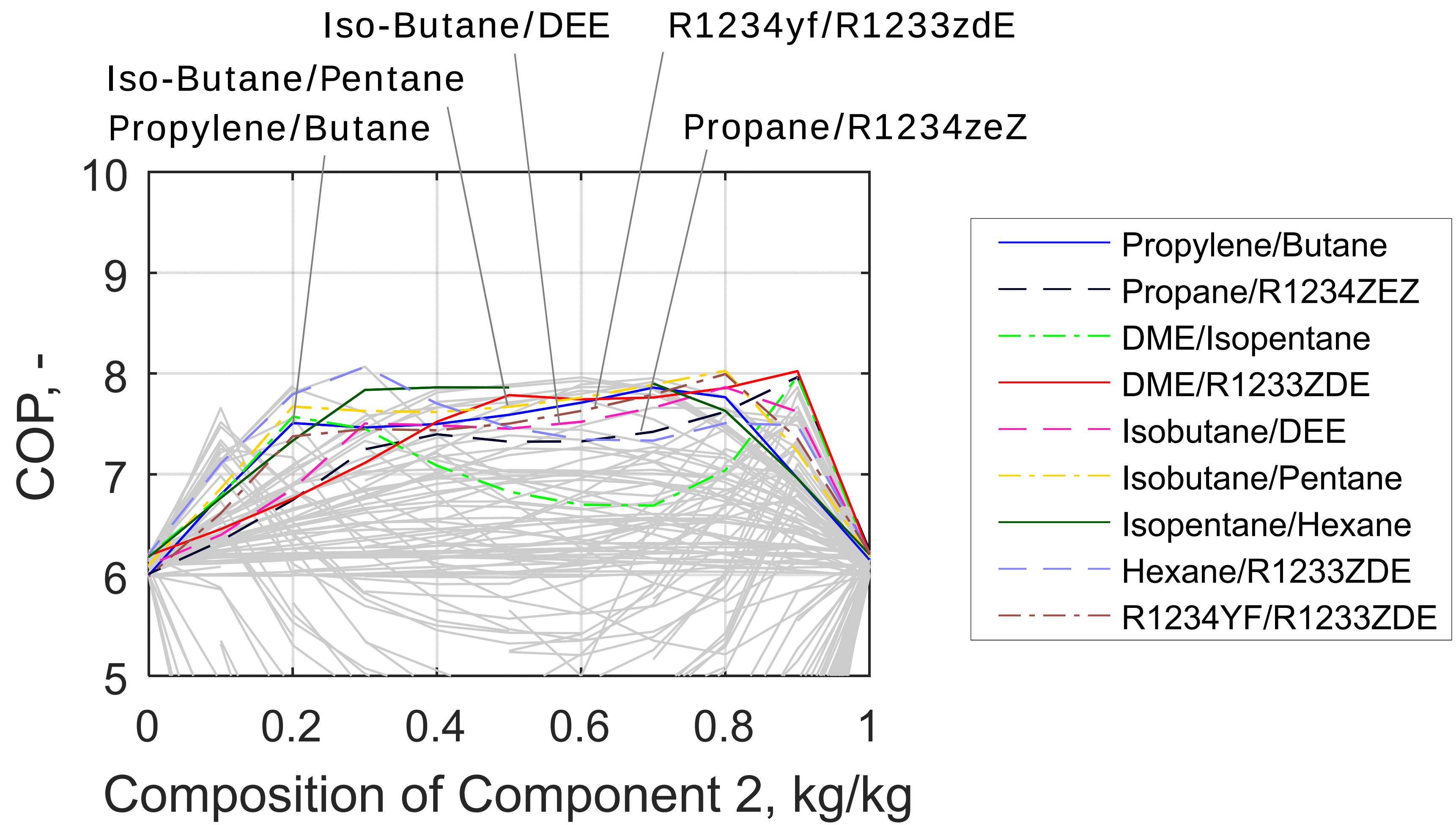
- Economic performance of best mixtures similar to best pure fluid
  - Economic performance strongly dependent on boundary conditions
- Off Design of mixtures similar to pure fluids
- Temperature difference between forward and return should be maintained during off design
- Thermodynamic performance of DH System:

Working Fluid of HPs	Pure Fluid	Mixture	
LTDH	COSP=3.68	COSP=4.16	(+13 %)
ULTDH	COSP=4.20	COSP=5.09	(+21 %)
	(+14 %)	(+22 %)	

Working Fluid Screening: Considered Fluids

No.	Name of Fluid	Ref. No.:	Type	ODP -	GWP -	Normal Boiling Point, ° C	Crit. Temp. ° C	Crit. Pressure bar	Safety Class
1	Methane	R-50	HC	0	25	-161.5	-82.6	46.0	A3
2	Ethylene	R-1250	HO	0	6.8	-103.8	9.2	50.4	A3
3	Ethane	R-170	HC	0	2.9	-88.6	32.2	48.7	A3
4	CO_2	R-744		0	1.0	-	31.0	73.8	A1
5	Propylene	R-1270	HO	0	3.1	-47.6	91.1	46.7	A3
6	Propane	R-290	HC	0	3.0	-42.0	96.7	42.5	A3
7	Dimethyl ether (DME)	R-E170	HC	0	1.0	-24.0	127.3	53.4	A3
8	Iso-Butane	R-600a	HC	0	3.0	-11.7	134.7	36.3	A3
9	n-Butane	R-600	HC	0	3.0	-0.5	152.0	38.0	A3
10	Iso-Pentane	R-601a	HC	0	4.0	27.8	187.3	33.8	A3
11	Ethyl ether (DEE)	R-610	HC	0	4.0	34.6	193.7	36.4	A3
12	Pentane	R-601	HC	0	4.0	36.1	196.6	33.7	A3
13	n-Hexane		HC			68.7	234.5	30.3	
14	Heptane		HC			98.4	267.0	27.4	
15		R1234yf	HFO	0	4.0	-26.0	94.7	33.8	A2L
16		R1234ze(E)	HFO	0	7.0	-19.0	109.4	36.4	A2L
17		R1234ze(Z)	HFO	0	<10.0	9.8	150.1	35.3	A2L
18		R1233zd(E)	HFO	0	4.5	17.9	166.5	36.2	A1

Working Fluid Screening: Results (5 K min. Super Heating)



Working Fluid Screening: Results

No.	Working Fluid	COP $[-]$	p_{evap} [bar]	p_{cond} [bar]	$\frac{p_{cond}}{p_{evap}}$ [bar]	$\dot{m}$ [kg/s]	$\dot{V}$ $[m^3/h]$	ε [%]	η_{Lor} [%]
1	R134a	6.11	6.17	16.97	2.75	0.075	9.2	41.9	33.0
2	Propane	6.01	10.84	21.28	2.38	0.039	7.6	41.3	32.5
3	DME	6.19	5.49	14.60	2.66	0.032	10.2	42.3	33.5
4	Butane	6.15	2.25	6.64	2.95	0.036	23.1	42.1	33.2
5	R1234yf	5.99	6.36	16.79	2.64	0.093	9.8	41.1	32.4
6	R1234zeE	6.08	4.62	13.11	2.84	0.080	12.1	41.7	32.9
7	R1234zeZ	**6.24**	1.63	5.32	3.27	0.063	28.5	42.7	33.7
8	R1233zdE	6.21	1.19	4.07	3.43	0.068	37.7	42.5	33.6
9	50 % IsoButane – 50 % Pentane	**9.01**	1.93	4.08	2.12	0.038	26.7	58.1	48.7
10	50 % Propylene – 50 % Butane	8.85	6.29	11.83	1.88	0.037	9.9	57.3	47.8
11	50 % IsoButane – 50 % DEE	8.87	2.27	4.81	2.12	0.039	23.0	57.4	48.0
12	50 % R1234yf – 50 % R1233zdE	8.87	3.67	7.54	2.06	0.080	15.0	57.4	47.9
13	30 % Propane – 70 % R1234zeZ	8.76	4.84	9.60	1.98	0.055	12.0	56.8	47.4

Investment Cost

Assumptions:

- Heat Exchanger: Danfoss C62 micro plate HX
  - Fixed average heat transfer coefficients (aligned to prototype)
- Compressor: Danfoss MLZ scroll compressors
  - + 20 % investment cost for flammable refrigerants
  - $\eta_{vol} = 90\ \%$
- Component cost interpolated to catalogue prices
- HP Cost ≈ 4 x Component Cost
- No additional cost for safety measures for flammability

Investment Cost

Working Fluid	COP [−]	A_{evap} [m²]	A_{cond} [m²]	$\dot{V}_{comp}$ [m³/h]	PEC_{evap} [€]	PEC_{cond} [€]	PEC_{comp} [€]	PEC_{total} [€]	TCI_{total} [€]
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R1234zeZ	6.24	1.53	1.96	28.47	289.21	335.76	3,764.74	4,389.70	17,558.80
50 % IsoButane – 50 % Pentane	9.01	4.83	4.37	26.69	641.05	591.75	4,290.02	5,522.81	22,091.25
50 % Propylene – 50 % Butane	8.85	5.09	4.28	9.92	668.31	582.06	1,943.18	3,193.55	12,774.20
50 % IsoButane – 50 % DEE	8.86	4.09	4.72	23.05	562.20	628.67	3,815.08	5,005.95	20,023.79
50 % R1234yf – 50 % R1233zdE	8.86	4.58	4.80	14.97	614.45	637.06	2,251.00	3,502.50	14,010.01
30 % Propane – 70 % R1234zeZ	8.76	4.41	4.62	12.00	596.30	618.07	2,263.86	3,478.23	13,912.92

Off Design Analysis: Booster HP

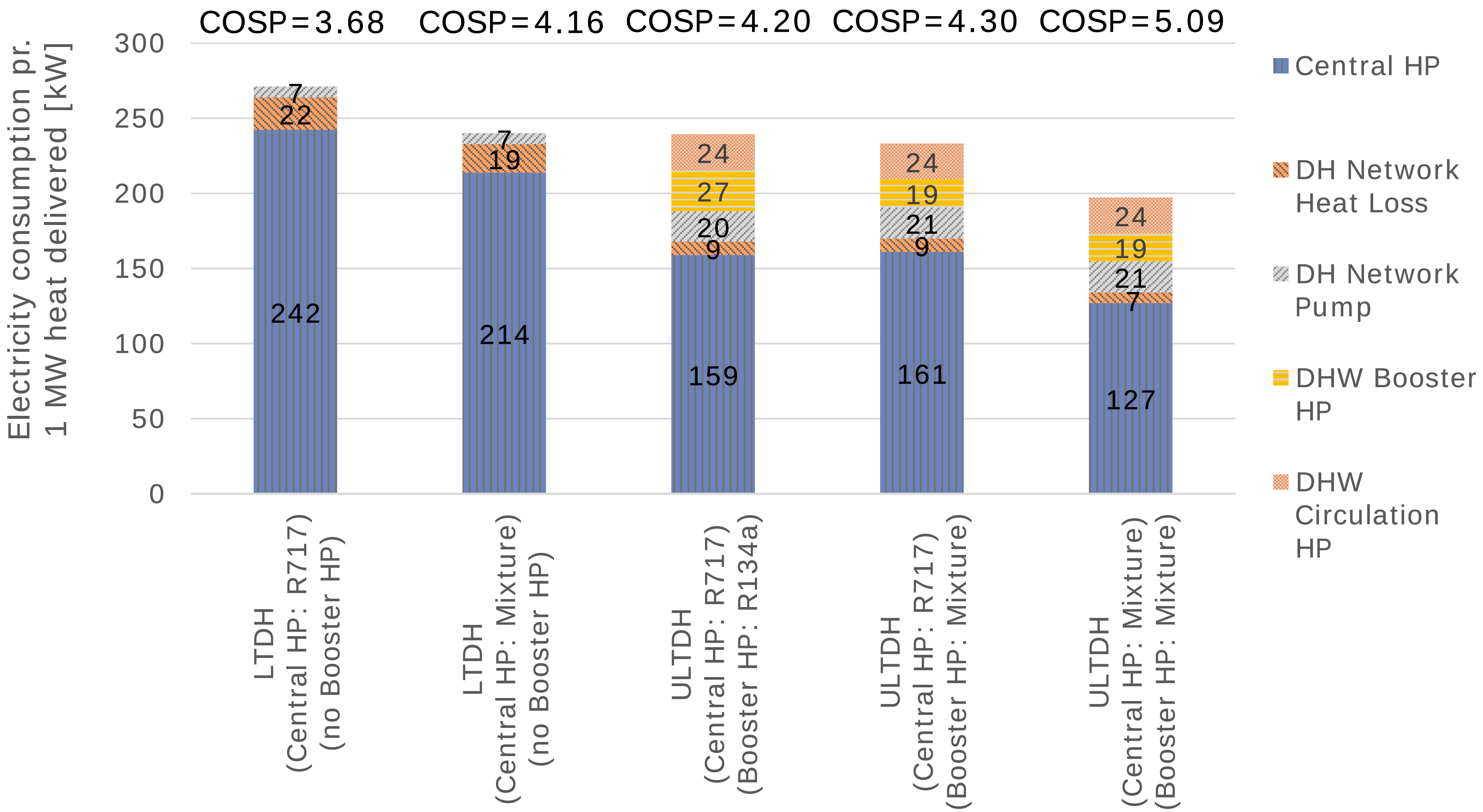
Varying forward temperature:
$T_{forward} = (35 \dots \mathbf{40} \dots 45 \dots 50)\ °C$

Constant T_{return}:
$T_{return} = 25\ °C$

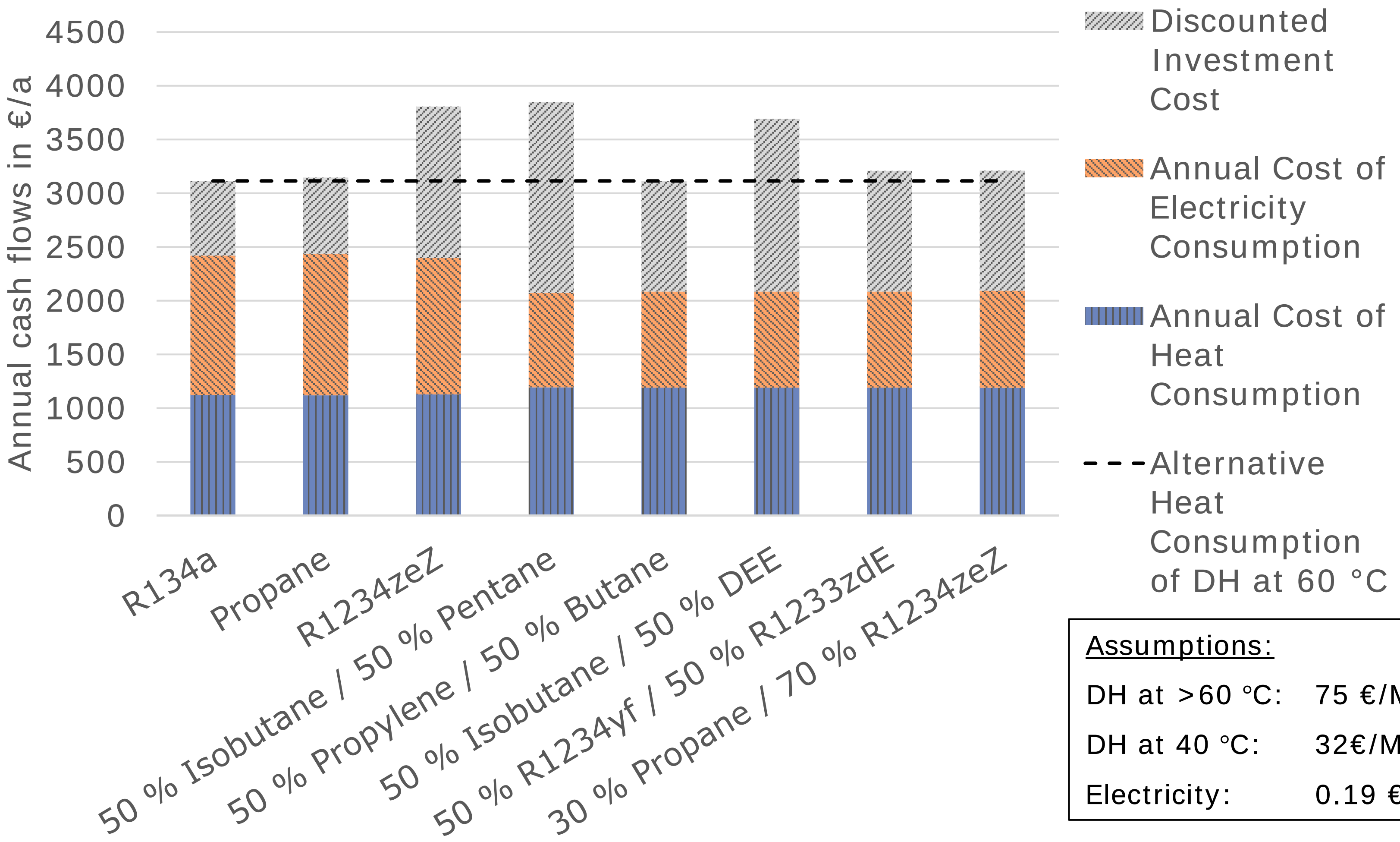
Constant ΔT_{source}:
$\Delta T_{source} = 15\ K$

	$T_{forward} = T_{sink,in}$: 35 °C		**40 °C**	45 °C		50 °C	
	$T_{return} = T_{source,out}$: 20 °C	25 °C	**25 °C**	30 °C	25 °C	35 °C	25 °C
Medium	COP [-]						
R134a			**6.11**				
R290	- 6 %	- 2 %	**6.01**	+ 5 %	- 3 %	+ 8 %	- 7 % … - 9 %
R1234zeZ			**6.24**				
50 % IsoButane – 50 % Pentane			**9.01**				
50 % Propylene – 50 % Butane			**8.85**				
50 % IsoButane – 50 % DEE	- 9 %	- 4 % … - 5 %	**8.86**	+ 7 %	- 3 % … - 5 %	+ 12 %	- 12 % … - 14 %
50 % R1234yf – 50 % R1233zdE			**8.86**				
30 % Propane – 70 % R1234zeZ			**8.76**				

DH System:
System Performance



Investment Calculation



Assumptions:	
DH at >60 °C:	75 €/MWh
DH at 40 °C:	32€/MWh
Electricity:	0.19 €/kWh