Efficiency improvement in pre-combustion CO_2 removal units

ORC waste-heat recovery power plant

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Pre-combustion CO_2 capture

Technology

- Carbon Capture and Storage (CCS): Transitional technology to mitigate CO_2 emissions related to combustion of fossil fuels

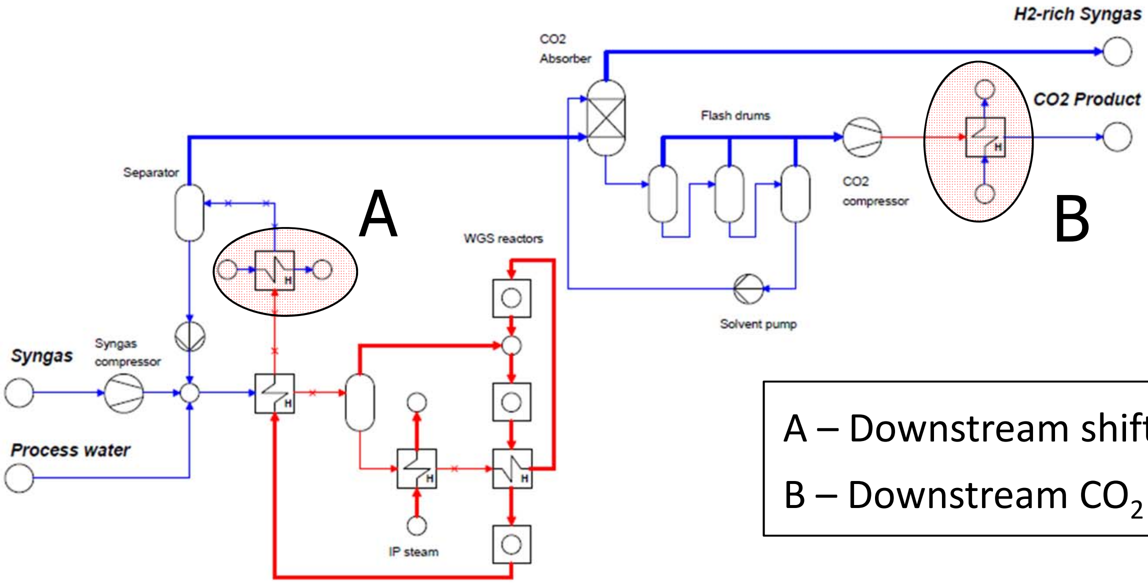
- IGCC with pre-combustion capture has greatest potential for high net power efficiency [2]

- Nuon/Vattenfall → "CO_2 Catch-up" research project including pilot plant at Buggenum IGCC power station

[2] K Damen, A comparison of electricity and hydrogen production systems with CO2 capture and storage, Prog Energy Combust Sci 2006

Pre-combustion CO_2 capture

Process / Objective



A – Downstream shifting section (137 °C/ 40 °C)

B – Downstream CO_2 compressor (140 °C/ 40 °C)

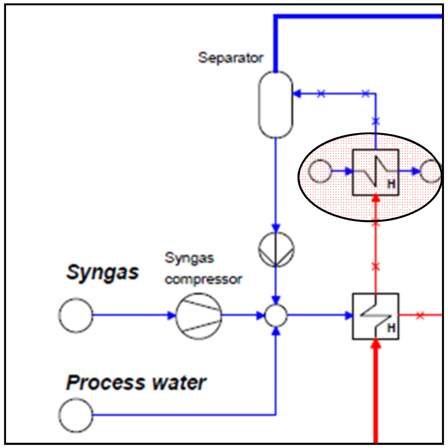
- Additional energy demand ($\eta_{capture}$ ≈80%): 8-10% -points of $\eta_{el,TOT}$
- Objective: Reduction of energy penalty
- Possibility: Recovering of low-grade thermal energy → ORC PP
- Advantage: base-load

Waste-heat recovery

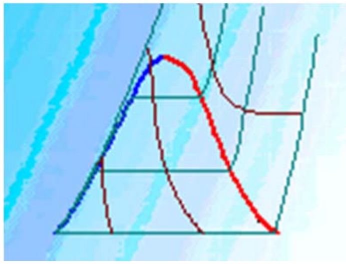
Process parameters

- Boundary conditions (A – Downstream shifting section):

Heat source		Syngas-Water
Pressure	bar	21.6
Mass flow	kg/s	72
Temperature IN	°C	137
Target Temperature OUT	°C	35-40
Fluid constituents		H_2, CO_2, H_2O, N_2, CO
Cooling medium		Water
Temperature IN	°C	10-25

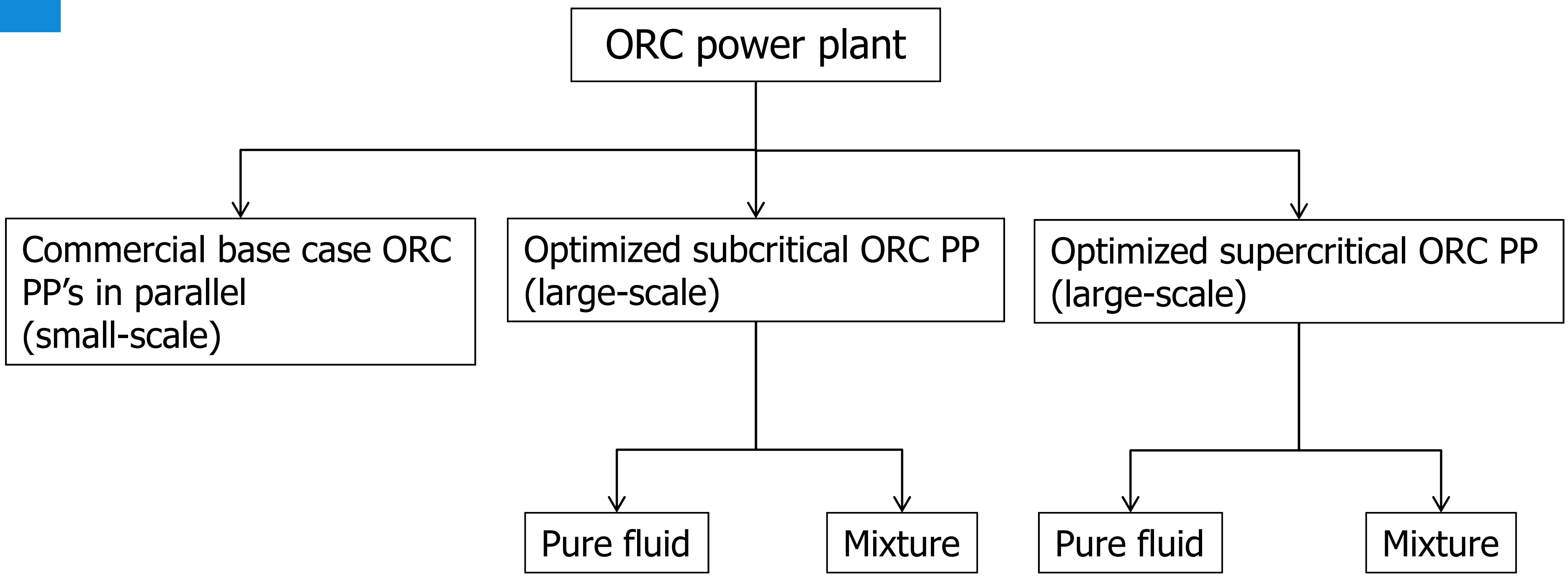


- Software:
  - Cycle Tempo – Thermodynamic cycle analysis & optimization
  - FluidProp – Thermophysical properties calculation



Waste-heat recovery

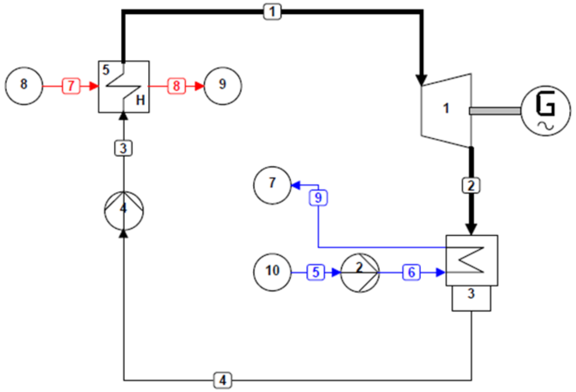
Analysis overview

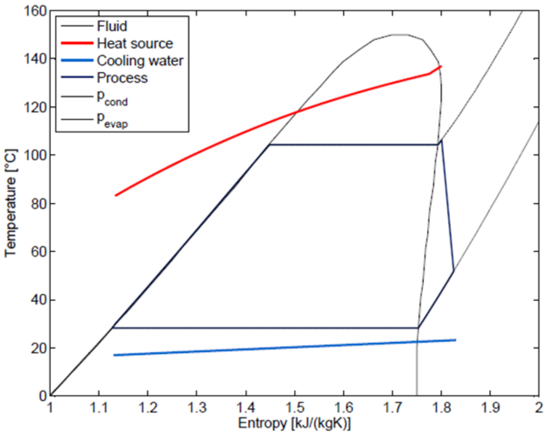


Waste-heat recovery

Base case

- Parallel configuration of 13 commercial small-scale ORC units





Parameters		Base case ORC
Working fluid	-	R245fa
T_{source} (in/out)	°C	137/83.0
$\dot{m}_{ORC}$	kg/s	8.3
$\dot{V}_{ORC}$ turbine in	m^3/s	0.10
Volume ratio β_v	-	9.2
$p_{evaporation}$	bar	13.9
TIT	°C	106.3
$p_{condensation}$	bar	1.67
$T_{condensation}$	°C	28.2
η_{th}	%	11.6
η_{ex} cycle	%	32.0
P_{net}	kW	231 (3003)
η_{ex} condenser	%	39.1
η_{ex} evaporator	%	55.2
η_{ex} pump	%	38.1
η_{ex} turbine	%	81.7

Waste-heat recovery
Optimized ORC PP

- Design parameters:
  - Working fluid
  - Cycle configuration (subcritical, superheated or supercritical)
  - Process parameters (evaporation & condensation conditions)
  - Recuperator $\eta_{th}\uparrow$ $\eta_{ex}\rightarrow$ $P_{net}\rightarrow$ $T_{source,out}\uparrow$
- Improvements in comparison to base case ORC PP
  - Choice of optimal design parameters
  - Increase in turbine efficiency (higher volume flow, lower gap losses)
  - Characteristic of HEX equipment comparable (different pressure profile)
  - Optimized ORC PP: financial/technical benefit?

Waste-heat recovery

Optimized ORC PP

- Constrained operating parameters:

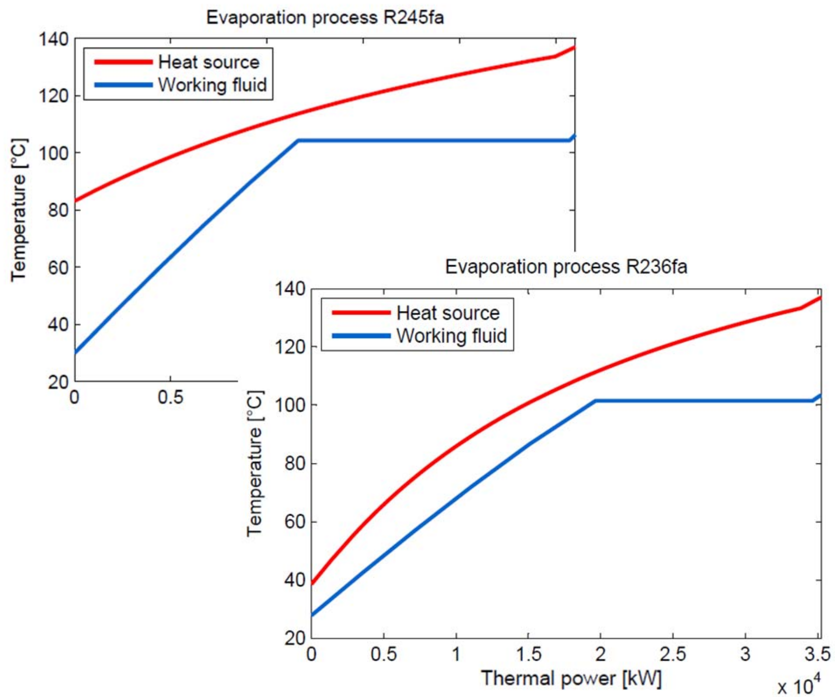
ΔT pinch point evaporator	K	10
Average cooling water temperature	°C	17
ΔT pinch point condenser	K	5
Cooling water temperature rise	K	5
Superheating of vapor	K	2
Isentropic efficiency of turbine	%	90
Isentropic efficiency of pump	%	65

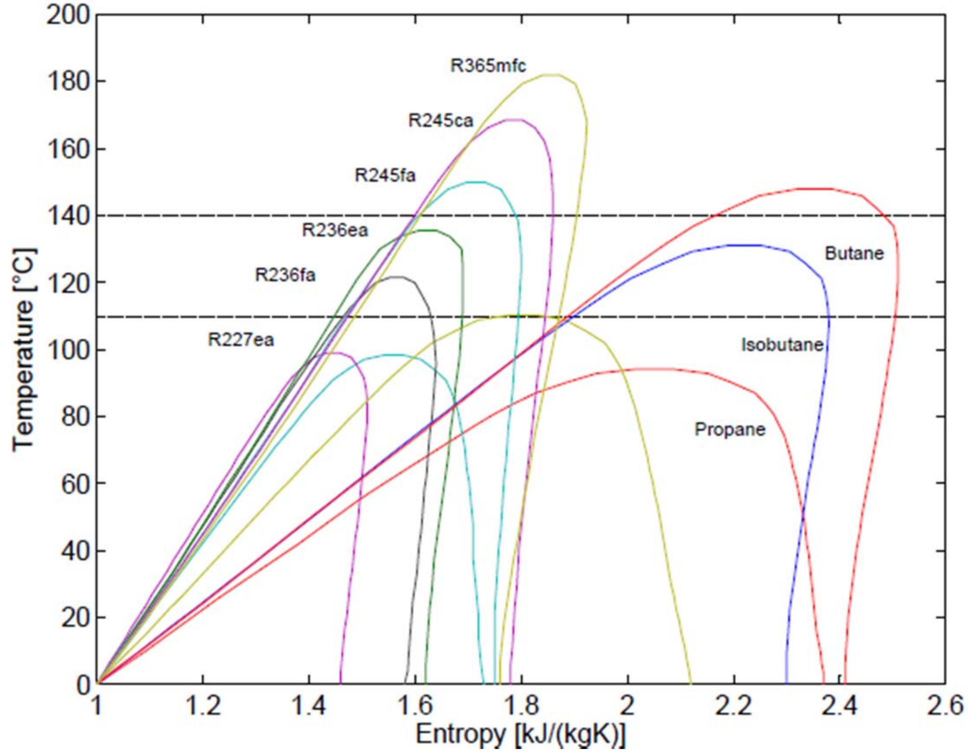
Volumetric ratio β_v : 7-13
Compression ratio β_c: 6-9

- Selection criteria for organic fluid:
  - Thermophysical properties (shape of saturation curve, critical properties, heat of evaporation, slope of dew line)
  - Environmental requirements (ODP, GWP, toxicity)

Waste-heat recovery
Subcritical ORC PP – pure fluid

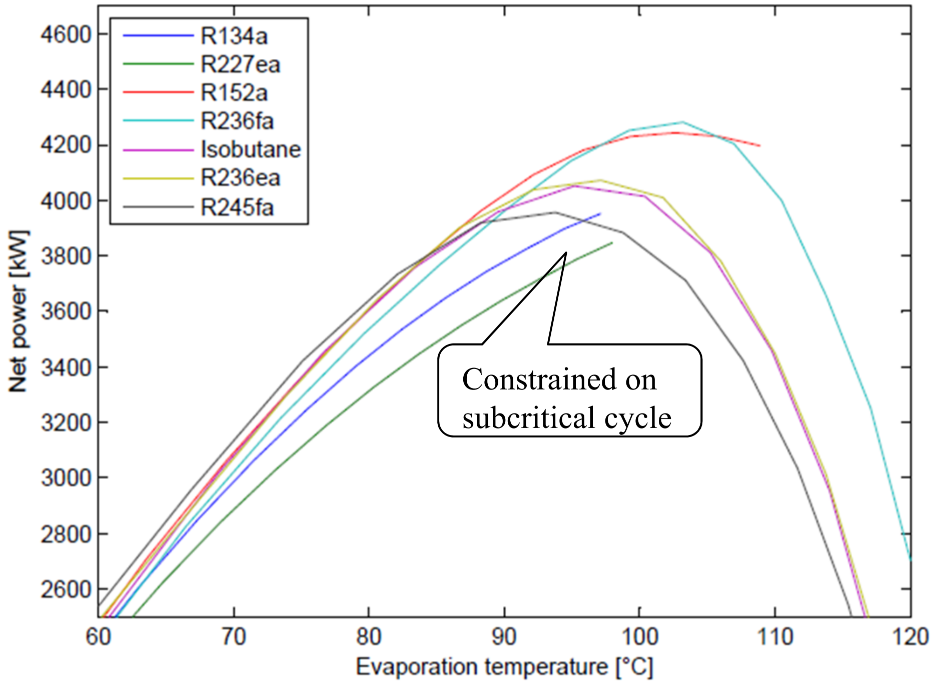
- Match evaporator temperature profile →pinch at inlet of evaporator
  → T_{crit} in range of T_{source}



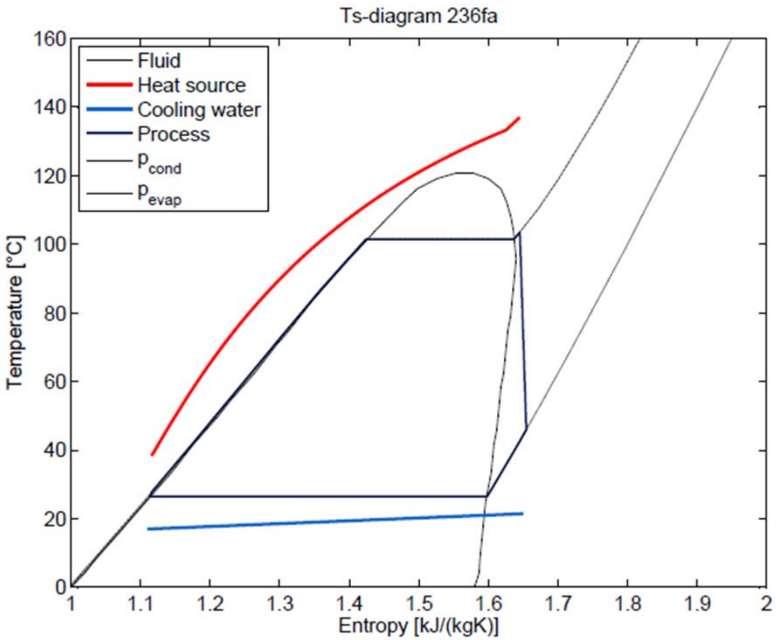


Waste-heat recovery

Subcritical ORC PP – pure fluid



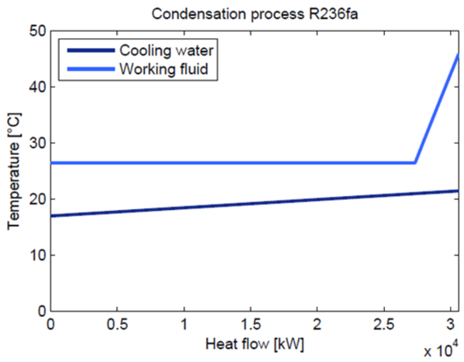
Fluid	T_{crit} [°C]	p_{evap}[bar]	η_{th} [%]	P_{net} [kW]	η_{ex}[%]
R236fa	124.9	20.0	12.5	4415	38.6
Isobutane	134.7	17.6	12.3	4174	37.0
R236ea	139.3	14.3	12.4	4251	37.6

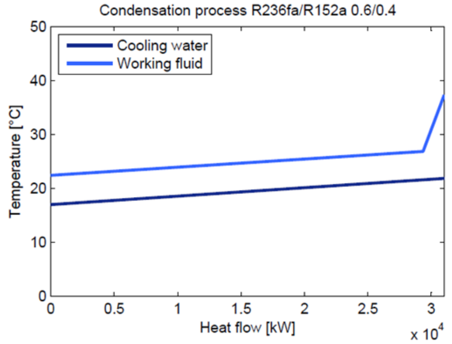


Waste-heat recovery

Subcritical ORC PP – mixture

- Better match of temperature profile → decrease irreversibility especially in condenser (evaporator → less advantageous)
- Mixtures selection criteria:
  - ΔT glide = cooling water temperature glide (5K)
  - Pure fluids with optimal sat. curve shape
  - Pinch at inlet of evaporator



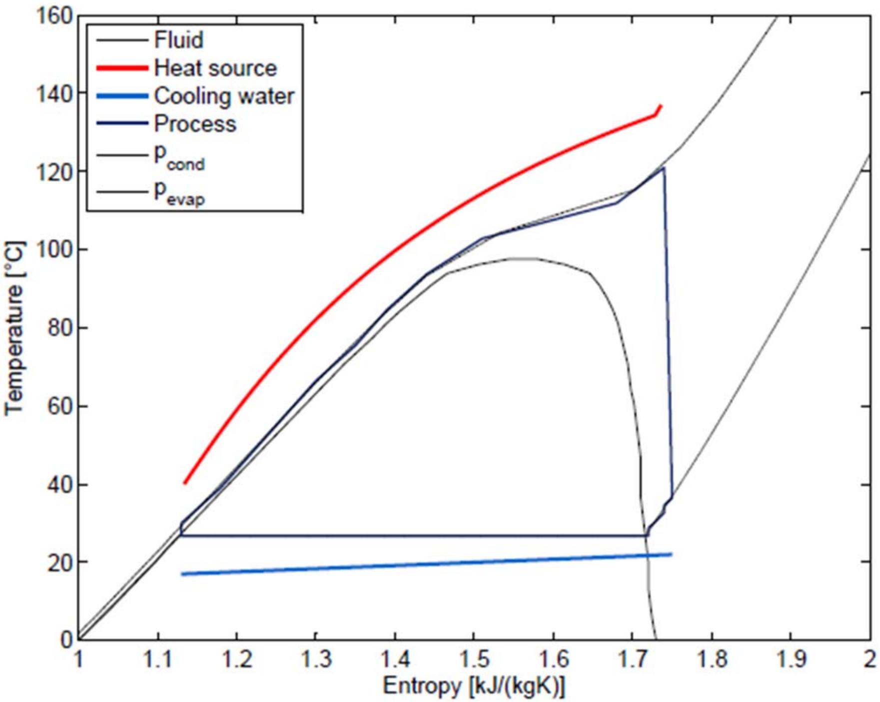


Fluid	T_{crit} [°C]	p_{evap}[bar]	η_{th} [%]	P_{net} [kW]	η_{ex}[%]
R236fa, R134a, 0.8, 0.2	120.1	27.5	12.8	4608	40.0
R236fa, R152a, 0.6, 0.4	120.3	27.4	12.9	4626	40.2
R236fa, R245ca, 0.7, 0.3	139.8	13.7	12.4	4469	38.8
R236fa	*124.9*	*20.0*	*12.5*	*4415*	*38.6*

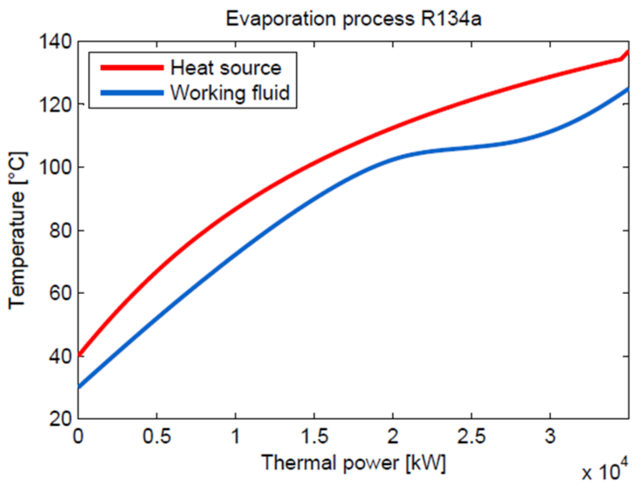
Waste-heat recovery

Supercritical ORC PP – pure fluid

- Suitable fluids: $T_{crit} < T_{source}$ (<137°C)
- Operational conditions: $p = 1.1\,p_{crit}$, $T > 1.1\,T_{crit}$



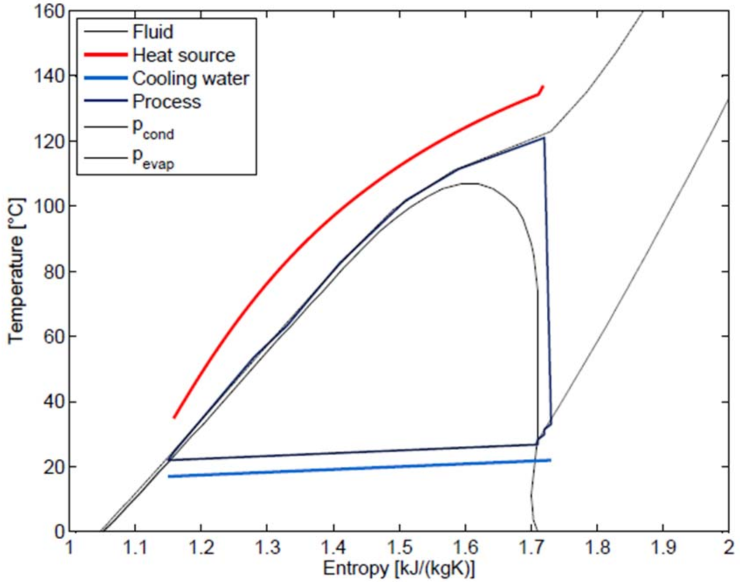
Fluid	T_{crit} [°C]	p_{evap}[bar]	η_{th} [%]	P_{net} [kW]	η_{ex}[%]
R134a	101.1	44.7	13.2	4592	40.3
R236fa, R152a, 0.6, 0.4	*120.3*	*27.4*	*12.9*	*4626*	*40.2*

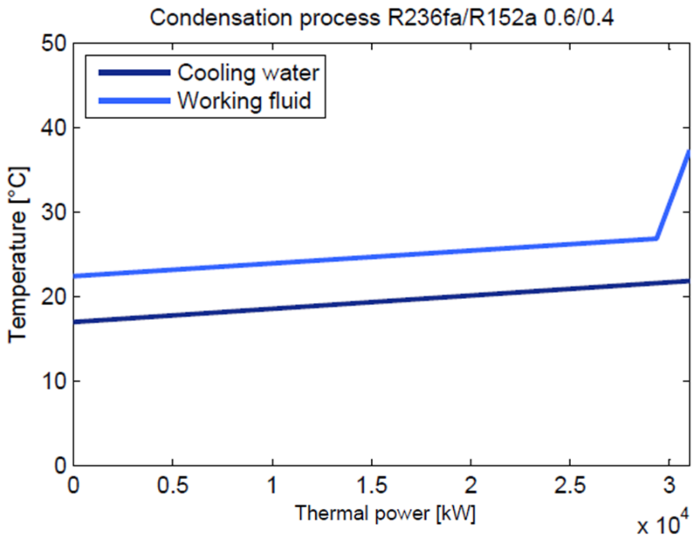


Waste-heat recovery

Supercritical ORC PP – mixture

- Selection criteria: ΔT glide = cooling water temperature glide (5K)





Fluid	T_{crit} [°C]	p_{evap} [bar]	η_{th} [%]	P_{net} [kW]	η_{ex} [%]
R134a, R236fa, 0.6, 0.4	110.6	42.7	13.1	4689	40.8
R134a	*101.1*	*44.7*	*13.2*	*4592*	*40.3*

Results comparison

Overview

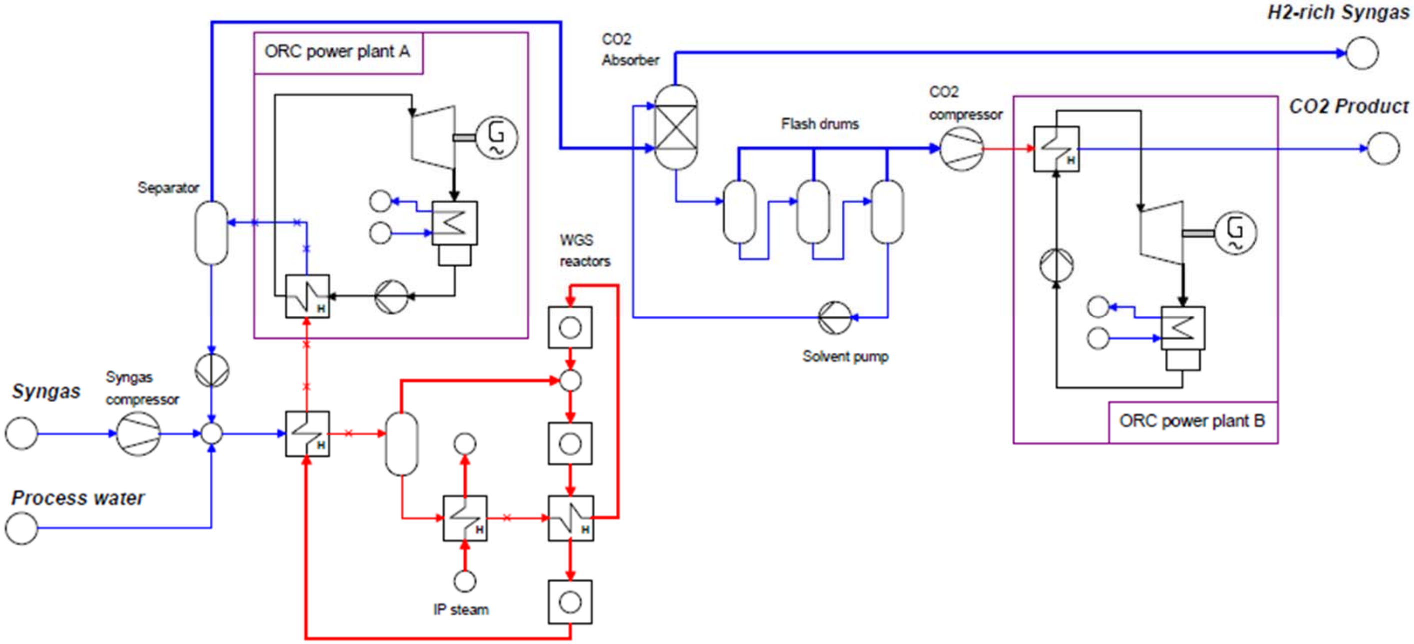
Parameters		Base case ORC	ORC subcrit.	ORC subcrit. (mixture)	ORC supercrit.	ORC supercrit. (mixture)
Working fluid	-	R245fa	R236fa	R236fa, R152a, 0.6, 0.4	R134a	R134a, R236fa, 0.6, 0.4
T_{source} (in/out)	°C	137/83.0	137/38.3	137/34.2	137/39.9	137/35.1
$\dot{m}_{ORC}$	kg/s	8.3	188.6	169.3	156.9	184.8
$\dot{V}_{ORC}$ turbine in	m^3/s	0.10	1.19	0.91	0.68	0.54
Volume ratio β_v	-	9.2	9.0	9.3	7.4	12.8
$p_{evaporation}$	bar	13.9	20.0	27.4	44.7	42.7
TIT	°C	106.3	103.5	106.9	125.0	122.5
$p_{condensation}$	bar	1.67	2.86	3.86	7.00	4.89
$T_{condensation}$	°C	28.2	26.5	22.4/26.9	26.7	22.1/26.9
η_{th}	%	11.6	12.5	12.9	13.1	13.1
η_{ex} cycle	%	32.0	38.6	40.2	40.3	40.8
P_{net}	kW	231 (3003)	4415	4626	4592	4690
ΔP_{net}	kW	-	1112	1623	1589	1687
η_{ex} condenser	%	39.1	37.0	46.6	38.0	48.9
η_{ex} evaporator	%	55.2	56.9	57.3	60.3	59.0
η_{ex} pump	%	38.1	66.5	66.0	66.7	66.1
η_{ex} turbine	%	81.7	90.8	90.5	90.7	90.4

Summary
Outlook

- ≈45% increase of P_{net} for subcritical ORC with pure fluid (T_{crit} in range of T_{source} → pinch moves to evaporator inlet)
- Use of mixture allows optimal match of temperature profiles (P_{net} increase: ≈5%)
- Supercritical ORC (pure fluid) similar P_{net} as subcritical ORC (mixture) (p↑, irreversibility of evaporator↓, $P_{turbine}$↑, P_{pump}↑, P_{net}→)
- ≈2% increase of P_{net} for supercritical ORC with mixture

Summary
Outlook

- Integration of optimized ORC power plant downstream of shifting section and within compression section → <u>≈10% reduction of power consumption</u>



Thank you for your attention!