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Comparison of Conventional and CO_2 Power Generation Cycles for Waste Heat Recovery

1st European Seminar on Supercritical CO_2 (sCO_2) Power Systems
28.-30. September 2016 - Vienna - Austria

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Overview

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- Project partners
- Cement plant Hatschek
- Steam Rankine Cycle
- Organic Rankine Cycle
- sCO_2 - advantages
- sCO_2 - Brayton Cycle (sCO_2-BC)
- tCO_2 - Brayton Cycle (tCO_2-BC)
- tCO_2 - Rankine Cycle (tCO_2-RC)
- Cycle comparison and turbine efficiency
- Conclusions

Project partners

- FFG
- Klima und Energie Fonds
- Rohrdorfer Zement
- Maschinenfabrik Liezen
- Salzburg AG
- Firma Scheuch
- Firma Zauner GesmbH

Waste Heat Recovery

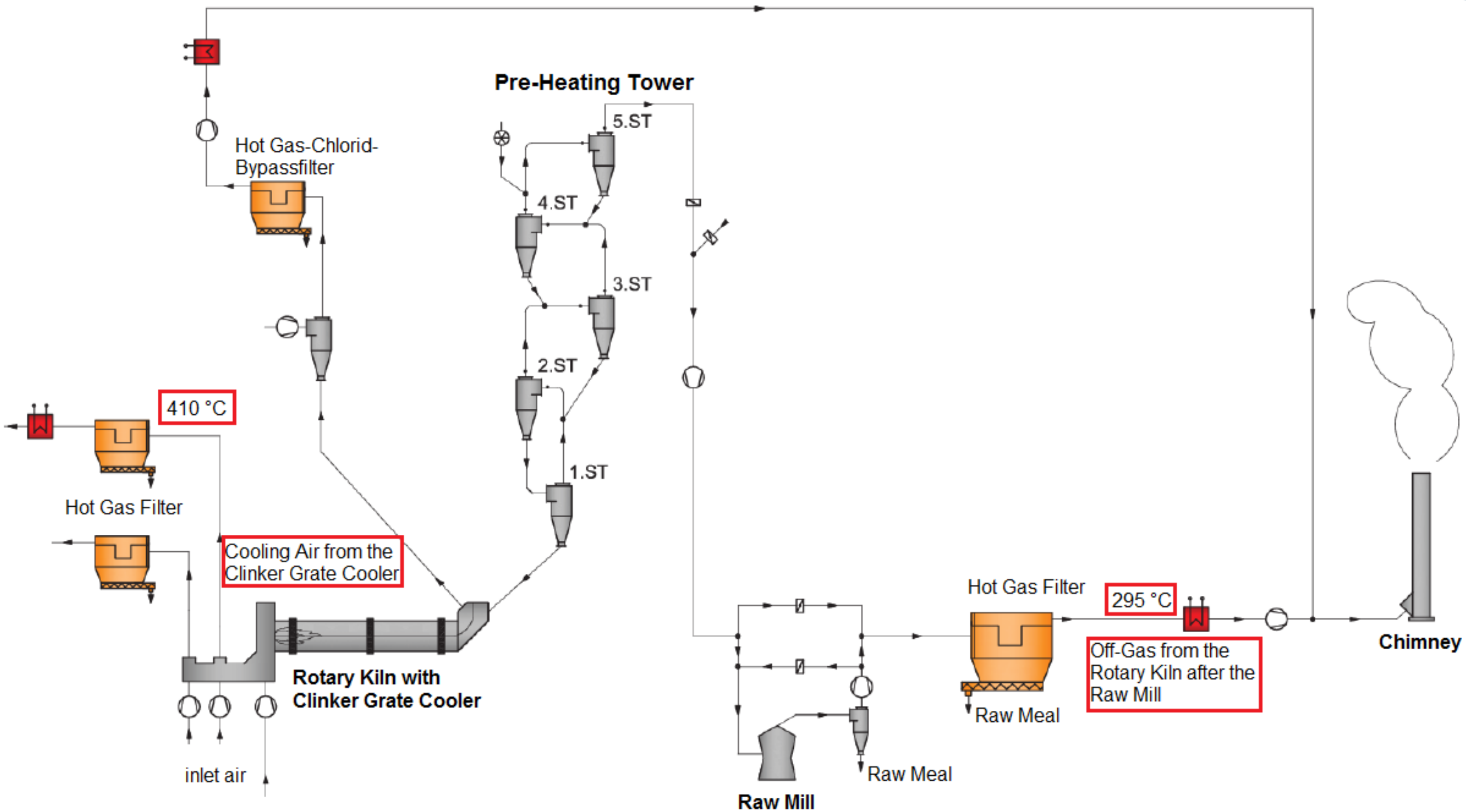
- waste heat recovery from industrial processes is of rising interest
  ➔ in terms of the Energy Efficiency Directive of the EU
  and Climate Change

- the efficiency of using waste heat is highly influenced by the used working fluid (e.g. Water, organic substances, CO_2 ,...) and certain components of the cycle (compressor, pump, turbine,...)

- 5 different cycles investigated: Steam Rankine Cycle (SRC), Organic Rankine Cycle (ORC), supercritical CO_2-Brayton Cycle (sCO_2-BC), transcritical CO_2-Brayton Cycle (tCO_2-BC) and transcritical CO_2-Rankine Cycle (tCO_2-RC)

- waste heat source is the cement plant Hatschek in Gmunden (Austria)

The cement plant Hatschek



2 major heat sources are available:

- the off-gas from the rotary kiln after the raw mill (295 °C, 78 kg/s)
- the cooling air from the grate cooler at the exit of the rotary kiln (410 °C, 14 kg/s)
- the hot gas from the chlorine bypass is not included (low mass flow)

Steam Rankine Cycle

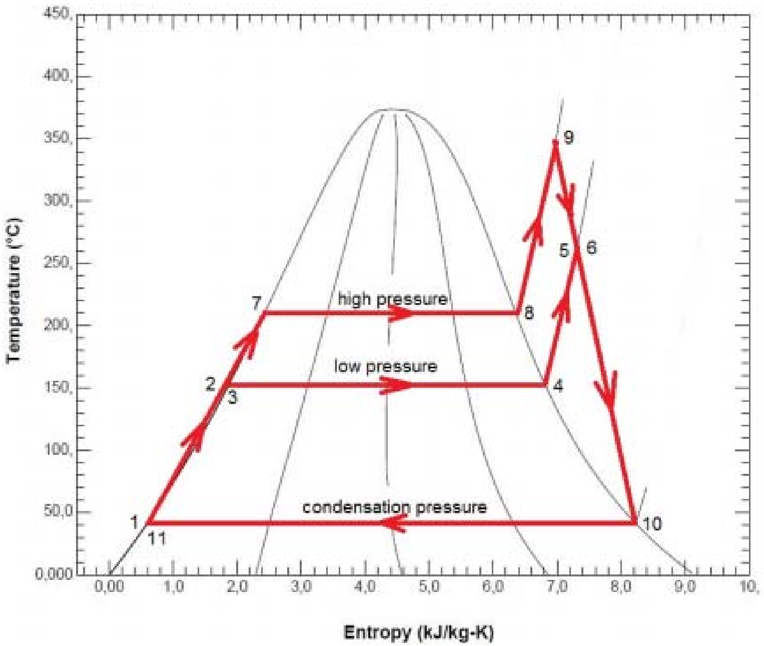
- \+ frequently used and well developed system
- \+ fluid characteristics
- \+ pump has low energy consumption

- − not suited for low temperature applications
- − size of steam turbines
- − water treatment system

Two-pressure system

- further cooling of the exhaust gas
- reduction of exergy losses

operating parameters	
high pressure level	20 bara
low pressure level	6.5 bara
max. steam temperature	395°C
min. allowed ΔT in HEX	15°C
turbine isentropic efficiency	75 %



results	
power output	3208 kW
thermal efficiency	23.74 %

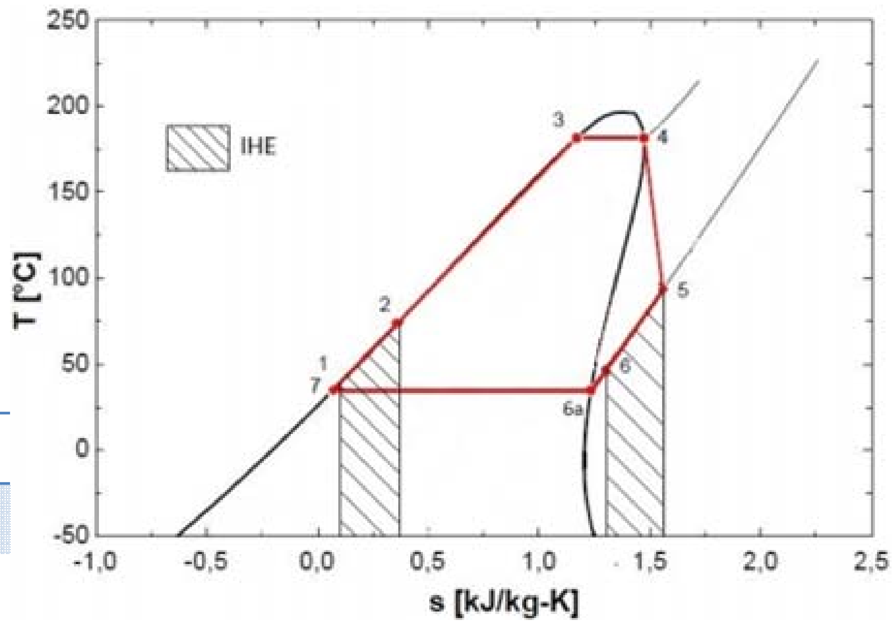
Organic Rankine Cycle

- ✚ suited for low temperature applications
- ✚ position of the critical point
- ✚ no superheating

- ▬ expensive working fluids
- ▬ flammable
- ▬ global warming potential

Fluid selection

- critical temperature appropriate to the heat source
- high heat transfer capacity
- best fit: cyclopentane (θ_{crit}=238°C)

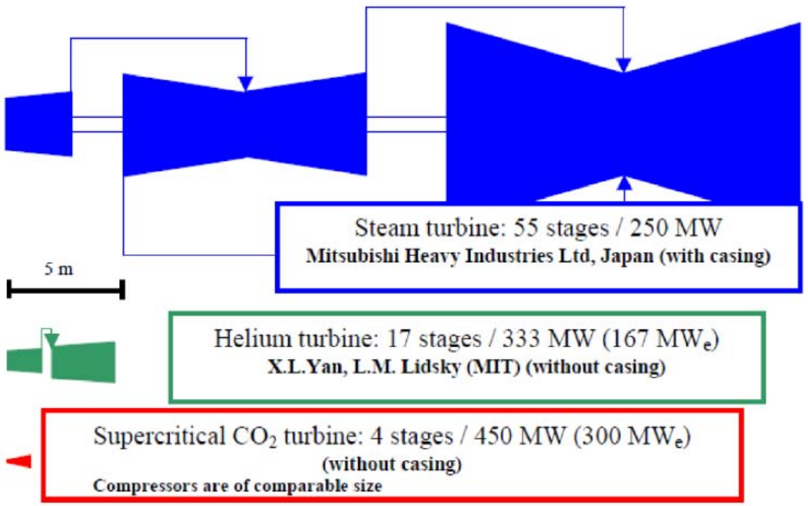


operating parameters	
operating pressure	34.6 bara
condensation pressure	0.7 bara
max. operating temperature	217°C
cooling water temperature	17°C
turbine isentropic efficiency	75 %

results	
net power output	3915 kW
thermal efficiency	20.64 %

sCO_2 - advantages

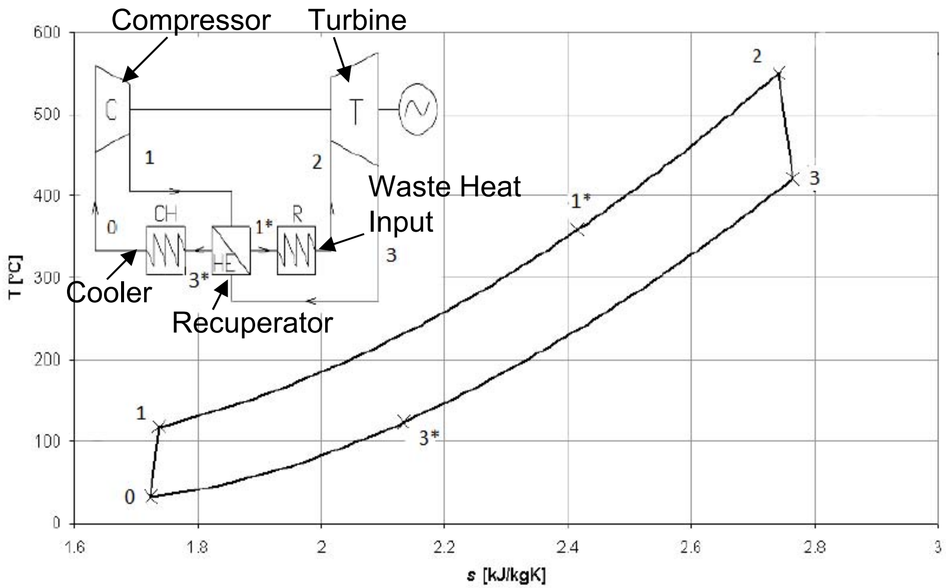
- sCO_2 cycles achieve high efficiencies at low temperatures
- the high operating pressure enables smaller size components
- well known thermodynamic properties
- stability, non-toxicity, non-flammable
- low critical temperature (31°C)
- high power density
- low surface tension (reduced effects of cavitation in the machinery)
- abundantly available
- low costs
- easy handling
- plant personnel accustomed to CO_2



sCO_2-Brayton - Cycle (sCO_2-BC)

<u>concept of a simple Brayton Cycle:</u>

- 0-1: compression of the fluid
- 1-1*: heating up in the recuperator
- 1*-2: heating up with the waste heat
- 2-3: expansion in the turbine section
- 3-3*: cooling in the recuperator
- 3*-0: fluid runs through the cooler



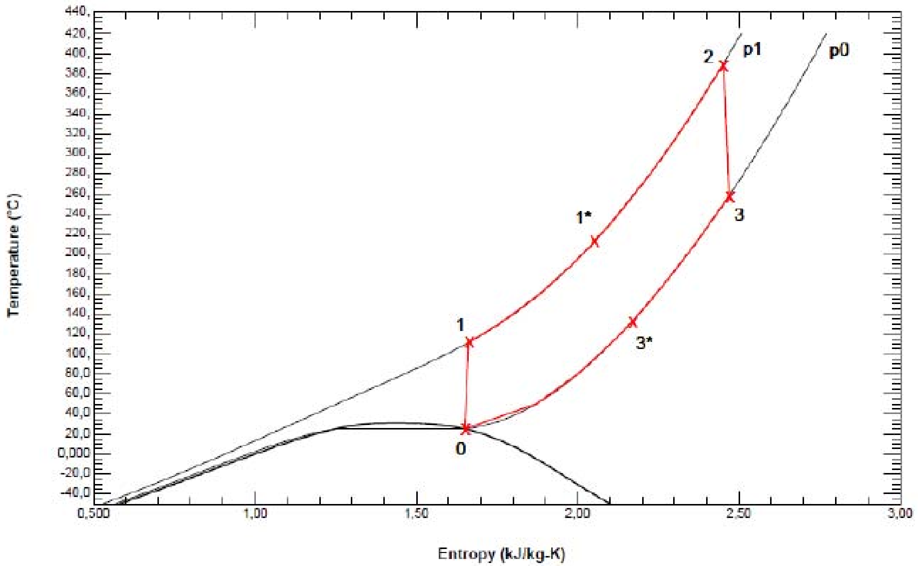
results	
net power output	2340 kW
thermal efficiency	12.88 %

operating parameters	
high pressure level	221.4 bara
low pressure level	73.8 bara
lowest cycle temperature	34 °C
turbine inlet temperature	302 °C
cooling Water temperature	12 °C
turbine isentropic efficiency	75 %
compressor isentropic efficiency	86 %

tCO_2-Brayton - Cycle (tCO_2-BC)

- very similar to the sCO_2-BC, but entry in compressor below the critical point ➔ CO_2 still in gaseous state on the saturated vapor line

- less energy used for the compression because of lower pressure ➔ smaller compressibility factor



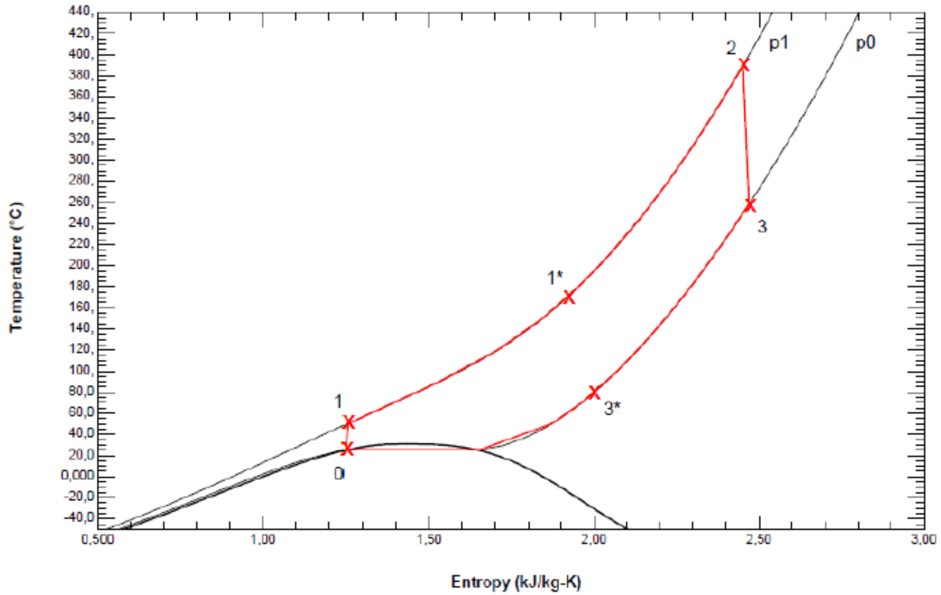
operating parameters	
high pressure level	221.4 bara
low pressure level	64.34 bara
lowest cycle temperature	25 °C
turbine inlet temperature	302 °C
cooling Water temperature	12 °C
turbine isentropic efficiency	75 %
compressor isentropic efficiency	86 %

results	
net power output	2565 kW
thermal efficiency	13.80 %

tCO_2-Rankine - Cycle (tCO_2-RC)

- is like the SRC a condensation process
➔two phase region is passed, CO_2 completely liquefied
- a pump is used (instead of a compressor)
- the entry in the pump is on the saturated liquid line, below critical point
- notable less energy for compression ➔ CO_2 in the liquid state (high density)
- possible problems with the cooling, depending on ambient conditions (e.g. water sources) ➔ high water mass flow is needed (346 kg/s)

results	
Net power output	3910 kW
Thermal efficiency	20.92 %



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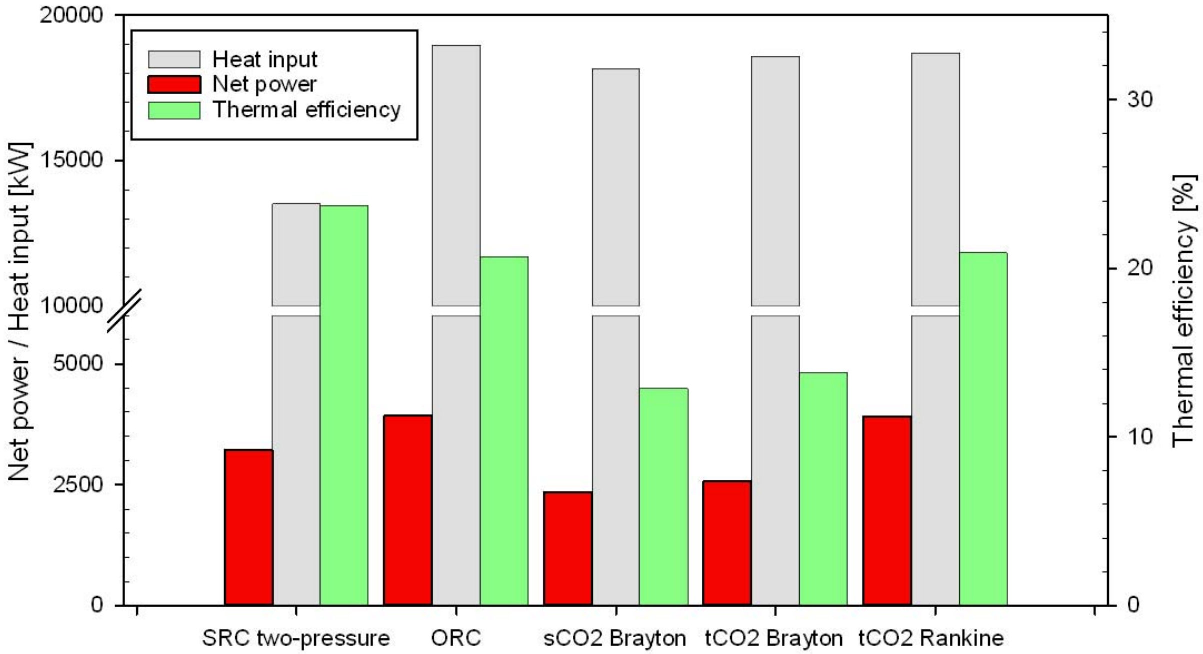
Cycle Comparison

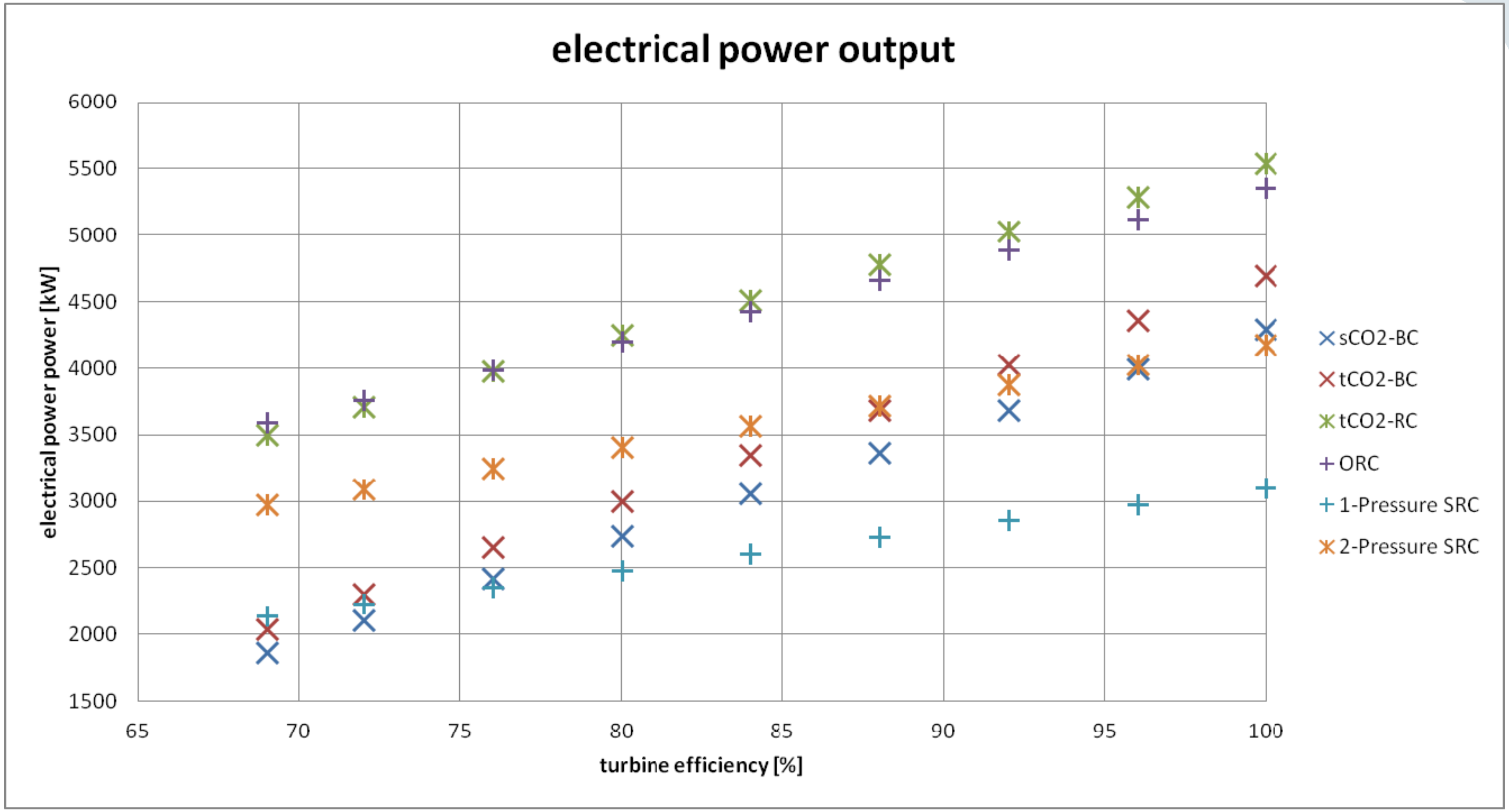


- the sCO_2-BC and the tCO_2-BC have low electrical power outputs under the mentioned circumstances

- SRC has significantly less heat input (5000 kW) than the other processes and therefore it reaches the highest thermal efficiency

- even under the assumption of a turbine efficiency of 75 % the t-CO_2-RC energy output is comparable to the standard ORC process.

Dependance on Turbine Efficiency



- the thermal efficiency of the cycles is strongly dependent on the turbine efficiency
- high efficiency turbines allow the tCO_2-RC to offer a greater power output

Conclusions

- potential waste heat recovery system of the cement plant was analysed
- different power cycles were simulated, aim was comparison between current used cycles and new supercritical CO_2 concepts
- transcritical CO_2 Rankine cycle delivers good results, but possible problems with cooling
- the sCO_2-BC and the tCO_2-BC are not as effective as the tCO_2-RC
- the turbine is a key component in all CO_2 cycles
- ORC approaches the results of the CO_2 cycles, but organic working fluids have several disadvantages (flammable, expensive, thermal oil, harmful to the climate,…)
- supercritical/transcritical power cycle technology should be further developed, but also economic efficiency has to be considered in the future

Acknowledgements

- SuCritDioCyc „(s)-CO_2-Prozesse zur Abwärmenutzung“ (FFG, Projektnummer 848889, duration 01.04.2015-31.03.2016)

- sCO_2-Phase 1 „CO_2 als Arbeitsmedium in der Energierückgewinnung“ (FFG, Projektnummer 853568, duration 01.03.2016-28.02.2019)

Thank you very much for your attention !