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

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Overview

➤ Waste Heat Recovery

➤ 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
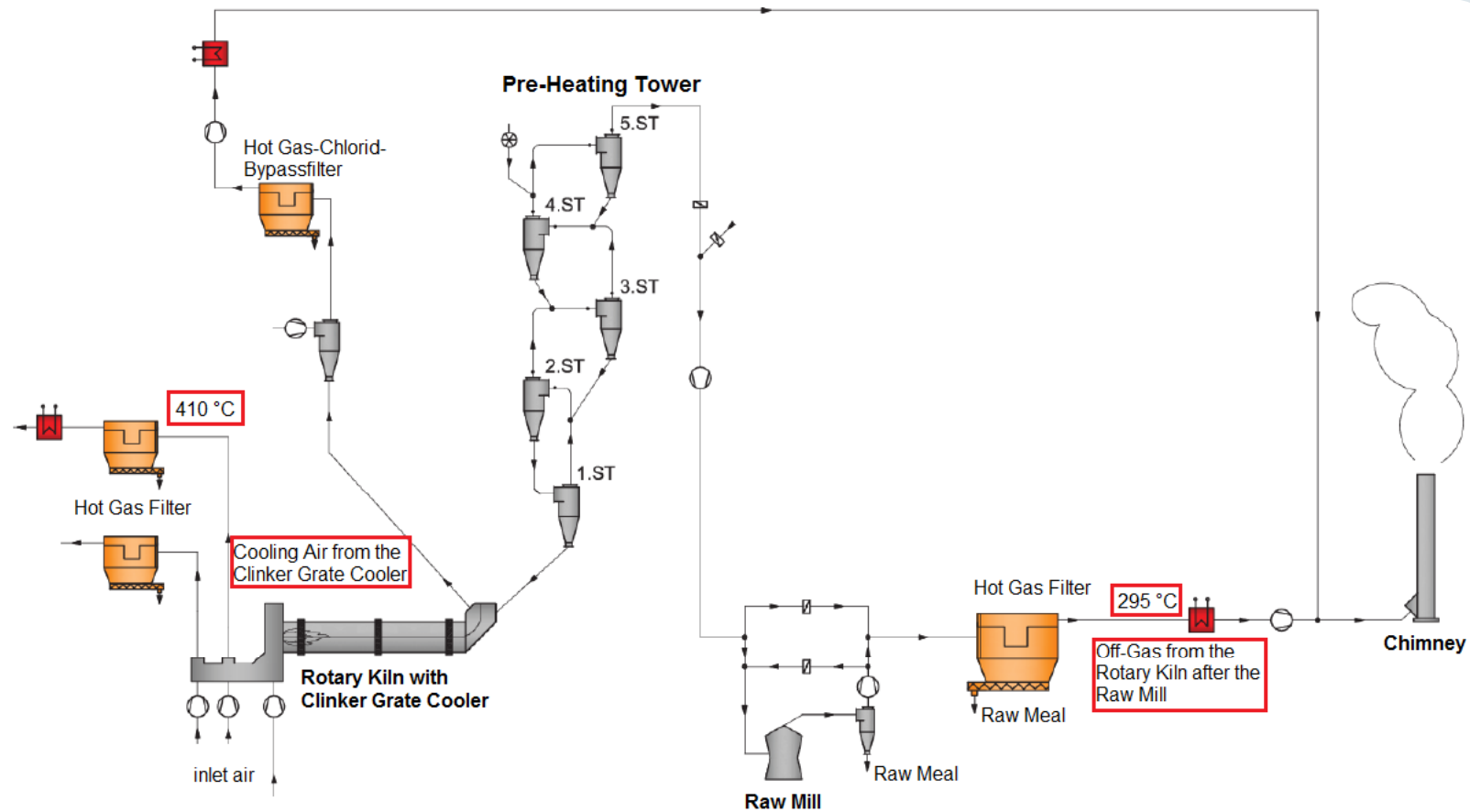
2 major heat sources are available:

- 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 %
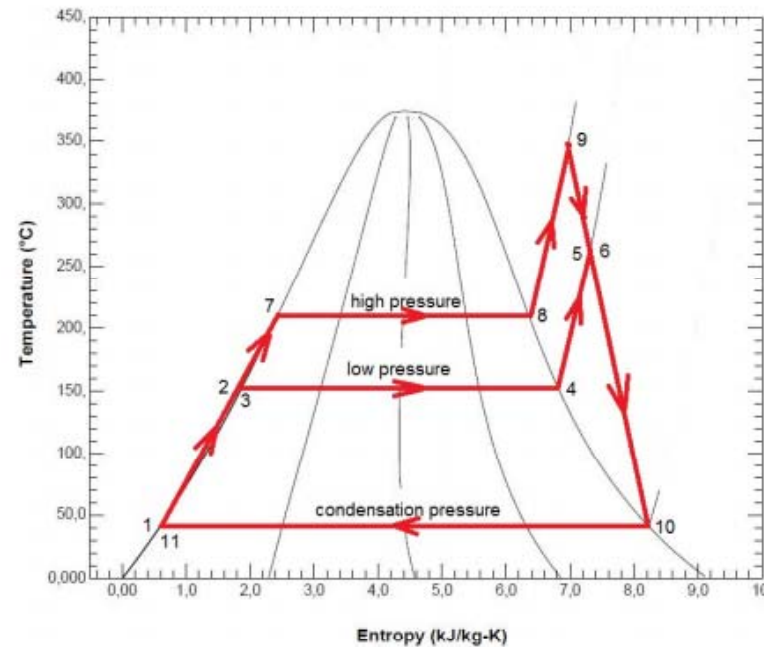
results	
power output	3208 kW
thermal efficiency	23.74 %

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

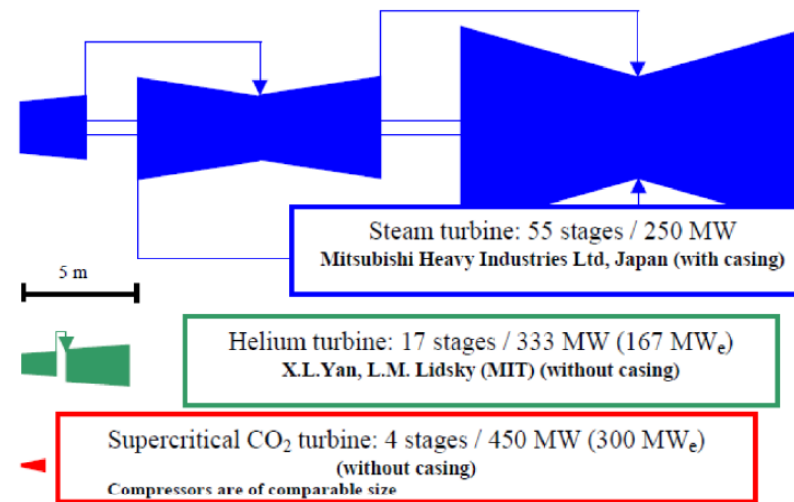| operating pressure	34.6 bara
condensation pressure	0.7 bara
max. operating temperature	217°C
cooling water temperature	17°C
turbine isentropic efficiency	75 %
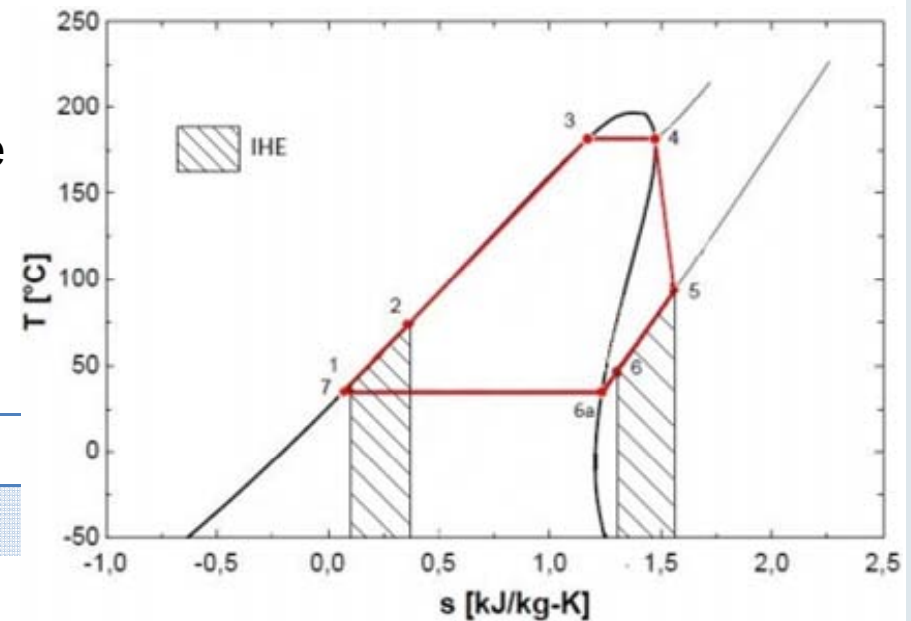
results

| 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$_2$

5 m

Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries Ltd, Japan (with casing)

Helium turbine: 17 stages / 333 MW (167 MW$_e$)
X.L.Yan, L.M. Lidsky (MIT) (without casing)

Supercritical CO$_2$ turbine: 4 stages / 450 MW (300 MW$_e$)
(without casing)
Compressors are of comparable size

sCO₂-Brayton - Cycle (sCO₂-BC)

concept of a simple Brayton Cycle:

- 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
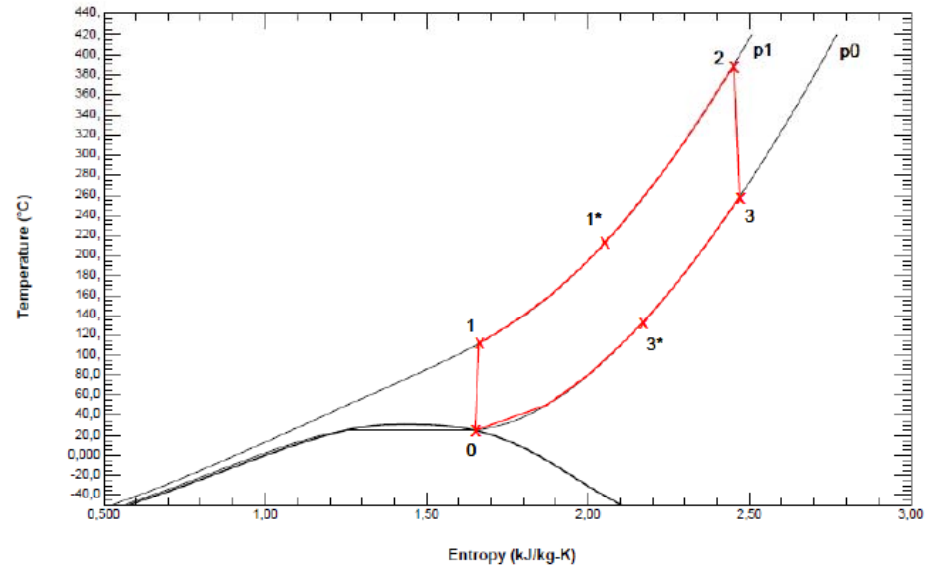- 3*-0: fluid runs through the cooler

results

net power output	2340 kW
thermal efficiency	12.88 %
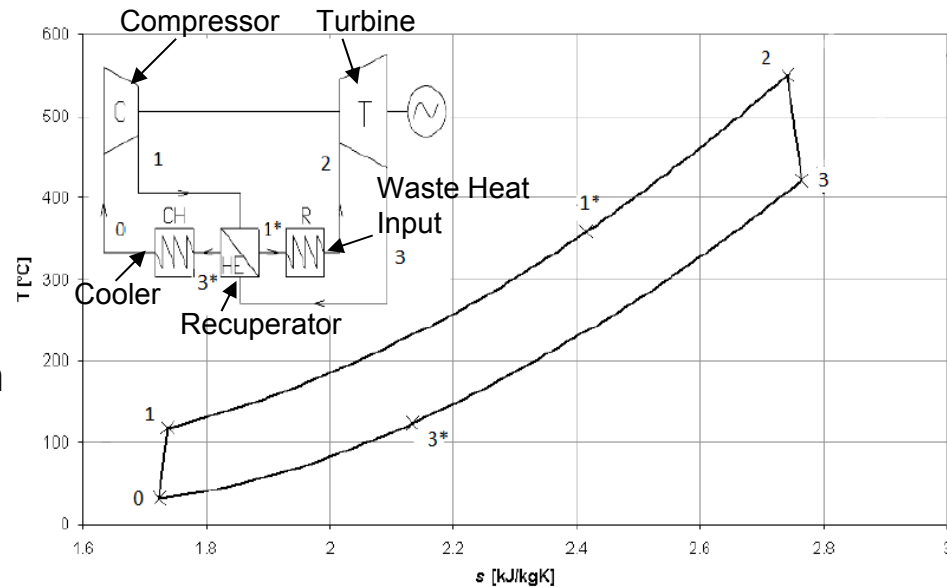
operating parameters

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
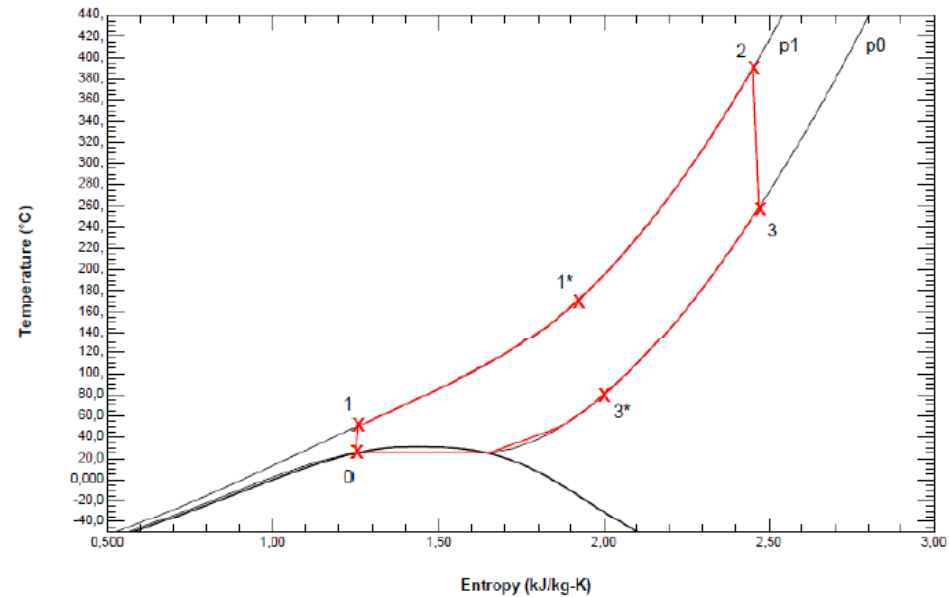

results

net power output	2565 kW
thermal efficiency	13.80 %

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 %

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)
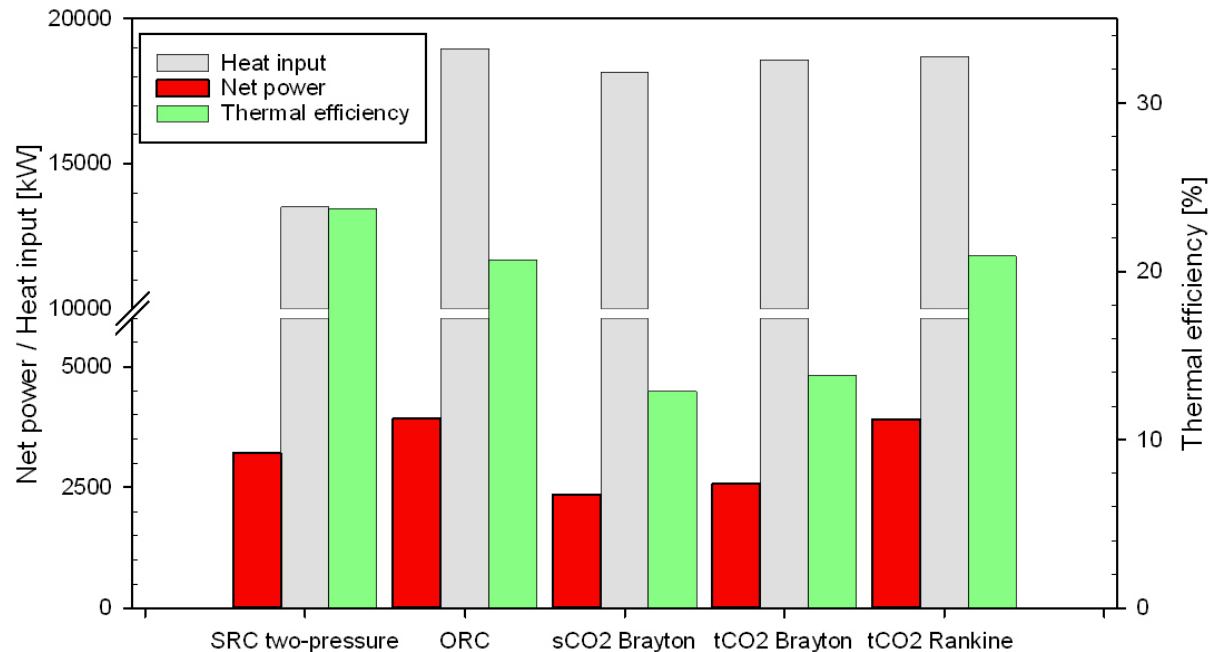

operating parameters

| 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	3910 kW
Thermal efficiency	20.92 %

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.

electrical power output
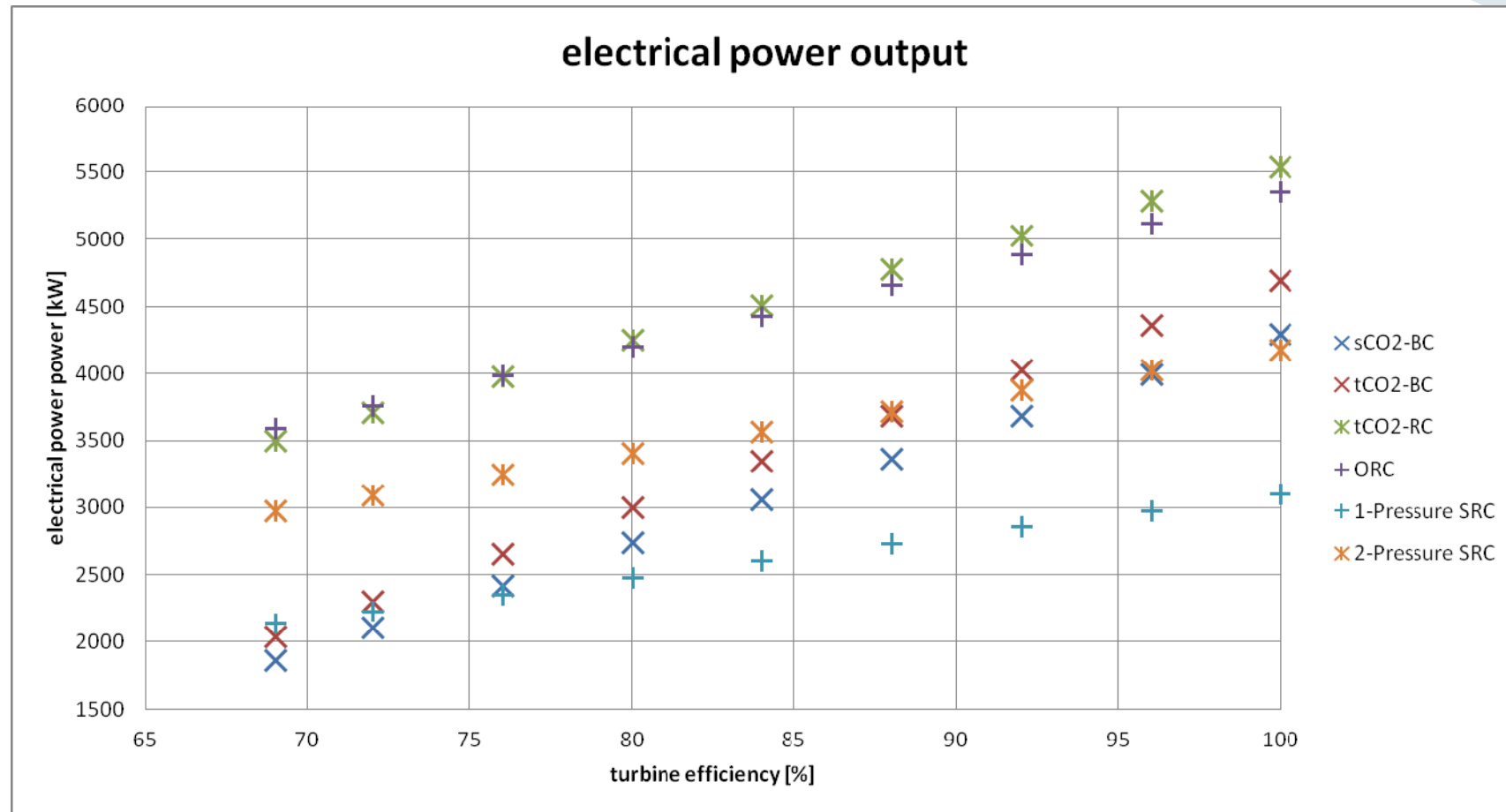
- ➢ the thermal efficiency of the cycles is strongly dependent on the turbine efficiency

- ➢ 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

Thank you very much for your attention !