Challenges in using fuel-fired heaters for sCO_2 closed Brayton Cycle

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6th International Supercritical CO_2 Power Cycle Symposium - Tuesday, March 27, 2018 - Pittsburgh USA

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 764690.

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R&D's AIMS

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new energy services
for customers

PREPARE
the electrical systems and
networks of the future

CONSOLIDATE AND DEVELOP
competitive and zero-carbon
production mixes

SUPPORT the Group's international
growth by developing research
partnerships

EDF R&D activies on supercritical sCO_2

The sCO_2 cycle is an opportunity to:

- Improve power plant efficiency
- Reduce the fossil plant impact
- Enhance renewable heat sources

Main goals about sCO_2 cycles are to:

- Scale-up the sCO_2 Brayton cycle maturity level
- Prove the sustainability of this technology
- Optimize processes at any load

2010
Review for nuclear power cycles (GenIV)

2012
Preliminary study: performance assessment with CCS

2014
sCO_2-BC for coal power plant – study + starting of PhD

2016
European project constitution: efficiency & flexibility

2018
Start of the sCO_2-Flex European project

Outline

1. Context
2. Adaptation of sCO_2 Brayton cycle to current coal-fired heater constraints
3. Methodology and results
4. Conclusion and Perspectives

The supercritical CO_2 Brayton cycle

- **Advantages**

Compactness

High performance at high temperature

No water consumption (if air cooled)

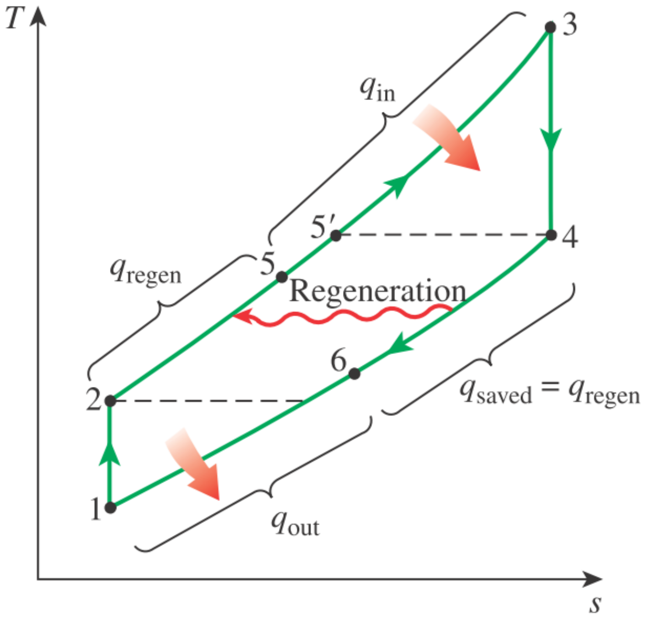
Simplified layout

Expected cost reduction

Expected to fit many heat sources

Expected to fit several heat sink technologies

- **Cycle characteristics**
  - ✓ Highly regenerative cycle (heat available at the turbine outlet)



Source : Cengel & Boles, 2015

  - ✓ Very sensitive to pressure drops, heat sink temperature

Literature review: sCO_2 Brayton cycle applications

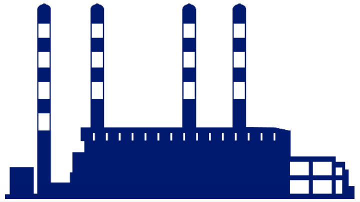
- Many publications on **nuclear applications** (non-exhaustive list):
  - ✓ Vaclav Dostal,
    A supercritical carbon dioxide cycle for next generation nuclear reactors,
    The MIT Center for Advanced Nuclear Energy Systems 2004 http://web.mit.edu/22.33/www/dostal.pdf
  - ✓ Yoonhan Ahn, Seong Jun Bae, Minseok Kim, Seong Kuk Cho, Seungjoon Baik, Jeong Ik Lee, Jae Eun Cha,
    Review of supercritical CO_2 power cycle technology and current status of research and development,
    Nuclear Engineering and Technology, Volume 47, Issue 6, 2015, Pages 647-661, ISSN 1738-5733,
    http://dx.doi.org/10.1016/j.net.2015.06.009

  and many many others…

- Prototypes/demo on several other applications:
  - ✓ Concentrated Solar: Sunshot, STEP
  - ✓ Direct fossil fuel cycles (Allam Cycle): NetPower
  - ✓ Waste Heat Recovery: ECHOGEN
  - ✓ …

Literature review: indirect coal-fired application?

(non-exhaustive list)



2013
- ✓ **Conceptual study of a high efficiency coal fired power plant with CO_2 capture using a supercritical CO_2 Brayton cycle**, Le Moullec

2015
- ✓ **Supercritical CO_2 Brayton cycles for coal-fired power plants**, Mecheri & Le Moullec

2017
- ✓ **Thermodynamic and economic investigation of coal-fired power plant combined with various supercritical CO_2 Brayton power cycle**, Park et al.

2018
- ✓ **A supercritical CO_2 Brayton cycle with a bleeding anabranch used in coal-fired power plants**, Bai et al.
- ✓ **300 MW Boiler Design Study for Coal-fired Supercritical CO_2 Brayton Cycle**, Bai et al.

→ Late interest for coal-fired power plant application ?

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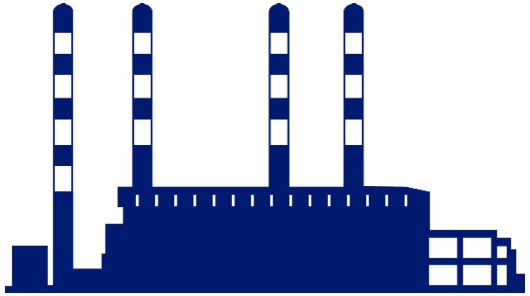
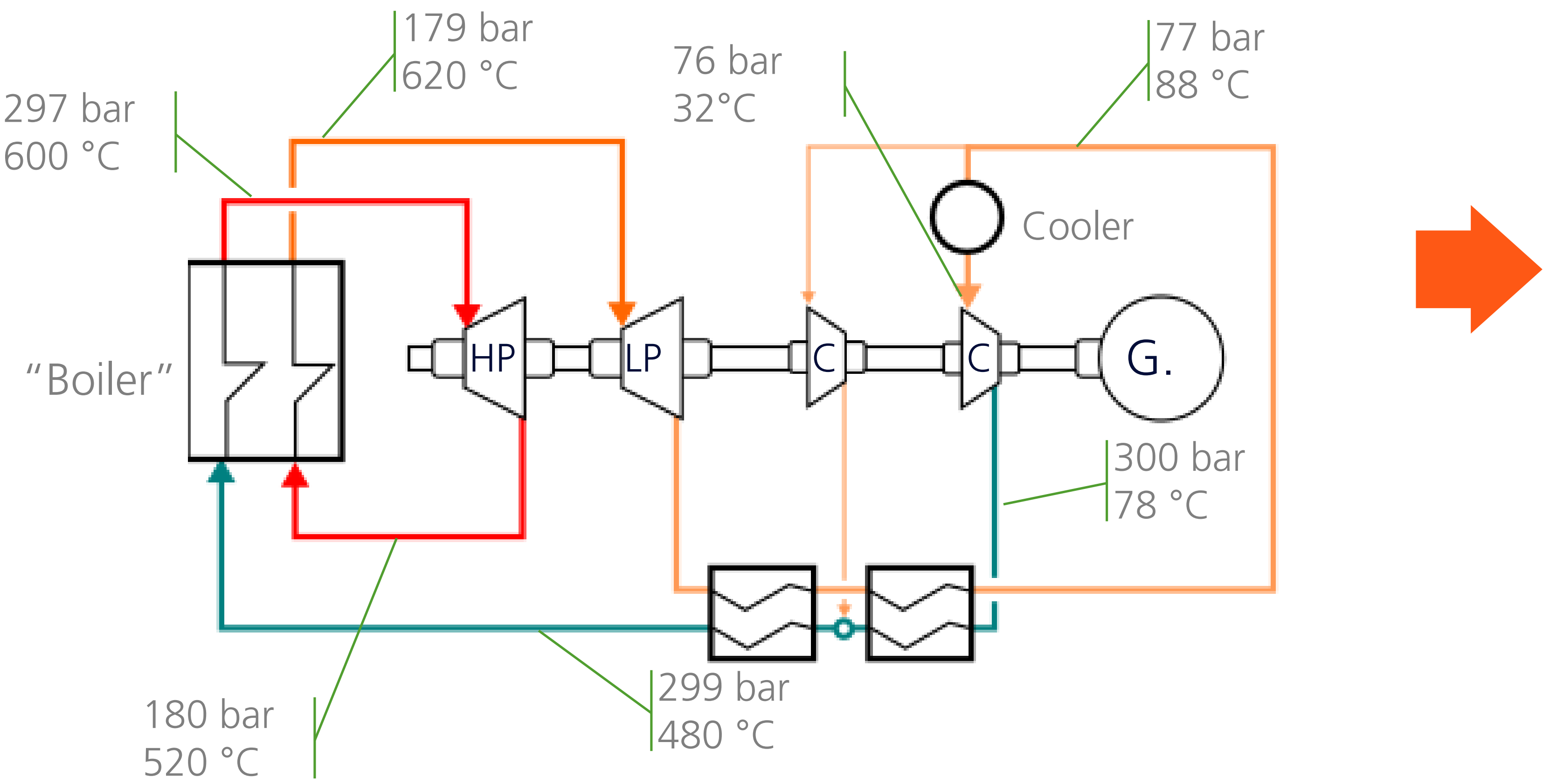
Current "steam coal-fired boiler" constraints



- Heat available:
  - ✓ Combustion chamber
  - ✓ Flue gases
- Boiler performances → depends on the heat recovered
- Limitations:
  - ✓ Combustion chamber → working fluid must protect material from very high temperatures
  - ✓ Flue gases → flue gas temperature at the stack > condensation temperature ~120°C (~248°F)
- Specificities of the "water steam Rankine cycle" (vs CO_2 Brayton cycle)
  - ✓ Phase change → low water temperature at the turbine outlet + latent heat (vaporization/condensation)
  - ✓ Low water temperature at the boiler inlet → use of low temperature heat of the boiler

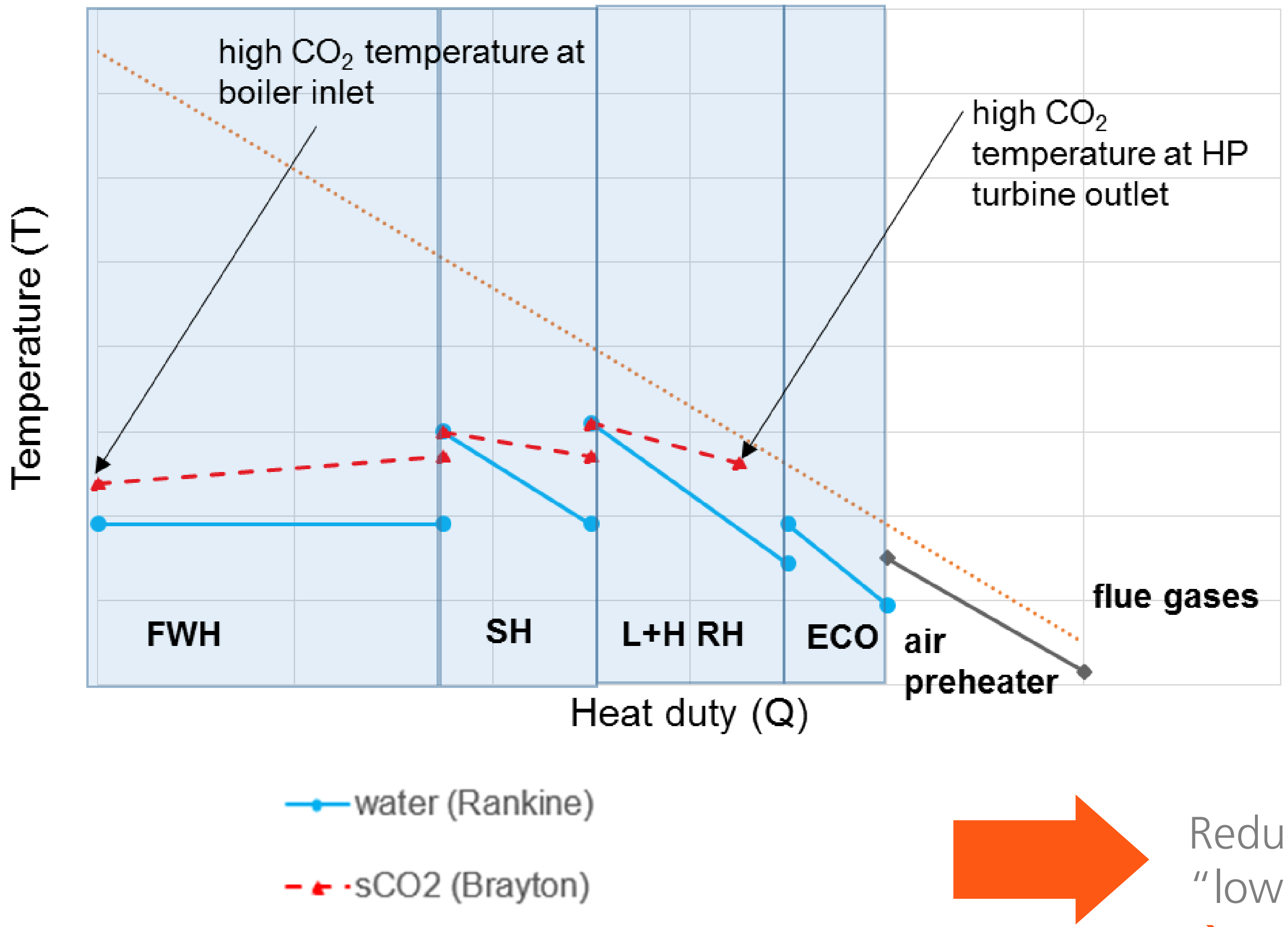
"Optimized" recompression sCO_2 Brayton Cycle

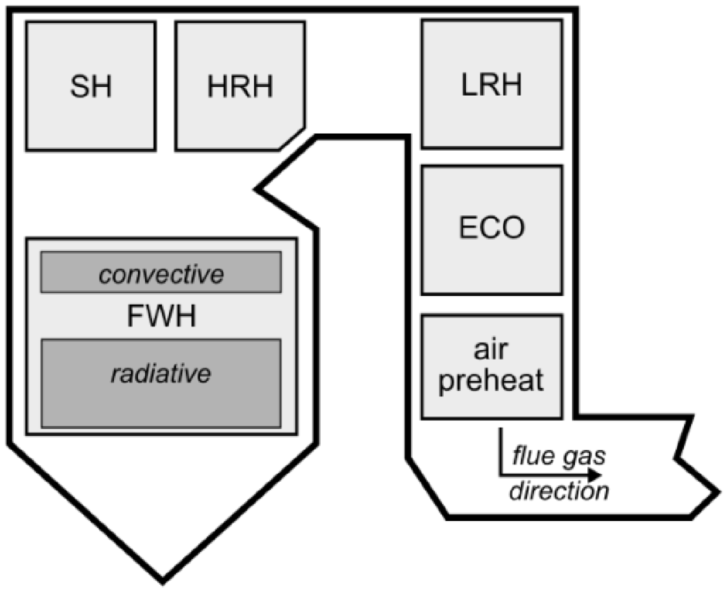
Note: approximate values



- ✓ High cycle performance
- ✓ Low enthalpy rise in the "boiler"
- ✓ Optimized cycle is not able to recover "low temperature heat" of the heat source

Main issues (using CO_2 instead of water)

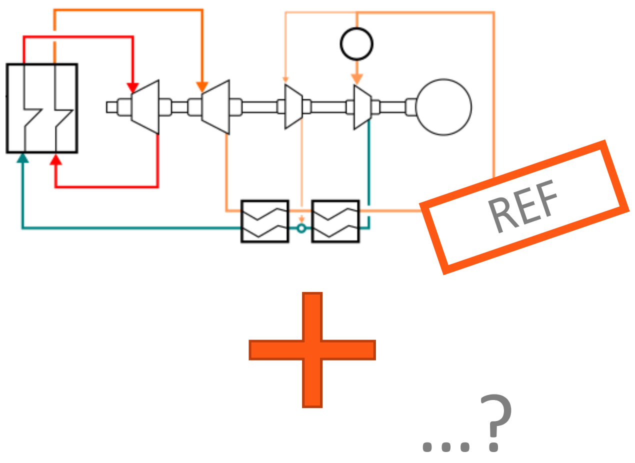




Reduction of the "Boiler" performance due to wasted "low temperature heat" available in flue gases

→ **How to recover "low temperature heat"?**

Foreseen solutions to keep high heater performance without impacting the "main" sCO_2 Brayton cycle



- Combination of an "optimized sCO_2 Brayton cycle" (denoted "**reference cycle**") with:
  - ✓ a sCO_2 bottom cycle (cascaded cycles) [Thimsen and Weitzel, 2016]
  - ✓ an Organic Rankine Cycle (ORC)
  - ✓ a very high temperature air-preheating process
  - ✓ low Temperature Recuperator (LTR Bypass) sCO_2 Brayton cycle configuration
  - ✓ high Temperature Recuperator (HTR Bypass) sCO_2 Brayton cycle configuration

Outline

Methodology

1 Inlet data (cycle configuration, study boundaries, models…) and assumptions (numerical values…)

2.1 Process flow simulation (thermodynamic simulation)

Cycle performances,
maximal temperature and pressure,
heat duty, power output…

2.2 Economic assessment (simplified economic model)

Power cycle CAPEX and specific cost

3 Flexibility qualitative assessment

Start/stop frequency
Part-load interval
Time-response

4 Comparison of each foreseen solution

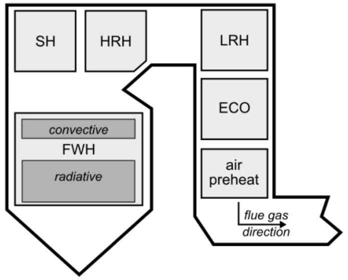


Table 1: heater main parameters

FIXED

Parameter	Value	Unit
Coal gross Low Heating Value (LHV)	20.15	MJ/kg
Coal consumption	102	kg/s
Combustion heat	2055	MW_{th}
Radiative losses	0.2	%
Ignition losses	1	%
Useful combustion heat	2031	MW_{th}
Heater efficiency	98.8	%
Furnace Wall Heater (FWH) duty: radiative heat	448	MW_{th}
Furnace Wall Heater (FWH) duty: convective heat	80	MW_{th}
SuperHeater (SH) duty	434	MW_{th}
High temperature Reheater (HRH)	237.6	MW_{th}
Low temperature Reheater (LRH)	551	MW_{th}
Economizer (ECO)	241	MW_{th}
Minimum flue gas temperature at the ECO outlet	320	°C
Heater exchanger pinch	20	K

Disclaimer: this study does not deal with sCO_2 coal-heater design purposes: only simplified assumption are made

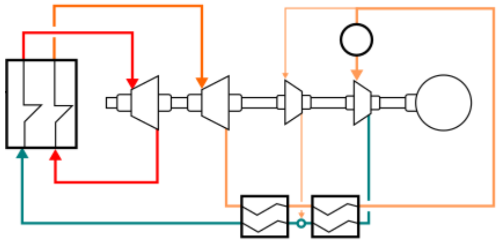


Table 2: Supercritical Brayton cycle (sCO_2-BC) reference case parameters

REF

Parameter	Value	Unit
Turbine isentropic efficiency (HP and LP)	92	%
HP Turbine inlet temperature	600	°C
HP Turbine inlet pressure	294.9	bar
HP Turbine outlet pressure	175	bar
LP Turbine inlet temperature	620	°C
LP Turbine inlet pressure	173.9	bar
LP Turbine outlet pressure	77.5	bar
Compressors isentropic efficiency	85	%
Main compressor inlet temperature (cooling temperature)	32	°C
Main and recompression compressors inlet pressure	76.5	bar
Main compressor outlet pressure	300	bar
Recompression inlet temperature	88	°C
Recompression compressor outlet pressure	299	bar
High and Low Temperature Recuperators (HRT and LRT) pinch	10	K
Reference case **cycle net** efficiency	51.36	%

2.1. Performances assessment (thermodynamic simulations)

- Process simulator : Aspen Plus v8.6 (aspentech)
- Simplified "heater" construction: heat duty at given temperature level for each "heater heat exchanger"
- Thermodynamic models:
  - ✓ **NIST RefProp** for modeling CO_2
  - ✓ SRK for hydrocarbons (ORC)
  - ✓ Water steam table for water
- Indicator: **net cycle efficiency** defined as:

$$\eta_{power\ cycle} = \frac{Turbine\ work - Compressor\ (or\ pump)\ work\ (MW_{el})}{Recovered\ heater\ duty\ (MW_{th})}$$

Main components:
- *turbines/compressors,*
- *heat exchangers (recuperators, coolers)*
- *pump (ORC)*

"a" and "b" empirical parameters that depend on component

Impact of the pressure and temperature on the costs (material aspects)

$$Component\ cost\ (\$) = a \times (electrical\ power\ or\ duty\ in\ MW)^b \times f_p \times f_T$$

$$f_p = \begin{cases} 1\ if\ P_{max} < 100\ bar \\ \alpha \times P_{max} + \beta \end{cases}$$

$$f_T = \begin{cases} 1\ if\ T_{max} < 400\ °C \\ \gamma \times T_{max}^2 + \delta \times T_{max} + \varepsilon \end{cases}$$

CAPEX ($)

- **Direct costs** → *purchased equipment, piping, electrical, civil work, transport, direct installation, auxiliary services, instrumentation and control, site preparation*
- **Indirect costs** → *mainly engineering, supervision, start-up*

$$Direct\ costs = 1.26 \times \sum Component\ cost$$

$$Indirect\ costs = 8\% \times direct\ costs$$

CAPEX ($)

$$= 1.3608 \times \sum Component\ cost$$

$$\times \frac{1}{Net\ power}$$

Specific costs ($/kW$_e$)

Sources : [Caputo et al., 2004], [Park et al. 2017], [Kumar et al, 2015]

3. Flexibility qualitative assessment

- Complete and accurate flexibility analysis requires specific dynamic calculations ! Not achieved here
- This study is only given an qualitative assessment of the flexibility of the foreseen solutions regarding 3 criteria:
  - ✓ Start/stop
  - ✓ Part-load range (maximal and minimal acceptable load)
  - ✓ Time-response
- The final results table is qualitatively assessing these 3 criteria within "positive", "neutral" or "negative" impact on the global power plant flexibility compared to the reference cycle

Criteria	-	=	+
Start/Stop	Not recommended : only if no other option	Usual frequency	Adapted to high frequency
Part-load range	Narrow range	Usual range	Wide range
Time response	Slow	Usual	Rapid

4. Results

		Reference (R)	R + Air preheating	R + LTR bypass	R + HTR bypass	R + ORC	R + Cascaded
Performances and costs	**Cycle Efficiencies (%)**	***51.36***	**51.36**	**49.88**	**51.12**	**51.36 and 35.8**	**49.9 and 36.6**
	Net Production (MW_e)	*899*	*899*	*994.6*	*1018.2*	*899*	*480.3*
	Secondary net Production (MW_e)	-	-	-	-	*86*	*377*
	Total net production (MW_e)	***899***	**899 (=)**	**994.6 (+95.6)**	**1018.2 (+119.2)**	**985 (+86)**	**857.3 (-41.7)**
	CAPEX (M€)	*789*	789 (=)	823 (+34)	851 (+62)	857 (+68)	711 (-78)
	Specific cost ($/$kW_e$)	*878*	878 (=)	827 (-51)	835.5 (-42.5)	870 (-8)	829.4 (-48.6)
Fired-heater	CO_2 temperature at the FWH inlet (°C)	*477*	477 (=)	488 (+11)	497 (+20)	477 (=)	415 (-62)
	Recovered heat (%)	*87.9 %*	100 %	100 %	100%	100 %	100 %
	Ratio (%) : Power / Recovered heat	*43.74*	43.74 (=)	48.39 (+4.7)	49.54 (+5.8)	47.92 (+4.2)	41.71 (-2)
Flexibility	Start/stop		=	=	=	=	-
	Load range		=	+	+	+	+
	Time-response		=	=	=	+	+

Outline

Conclusions of this study

AIR PRHEATING

LTR / HTR BYPASS

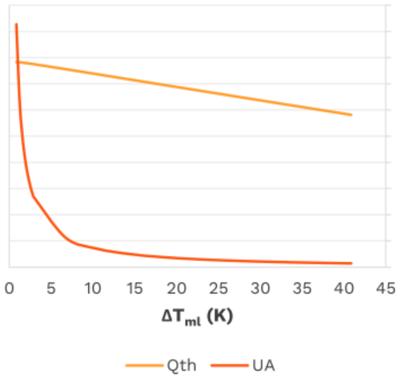
ORC

CASCADED CYCLES

Limitations and perspectives

Many **boiler design** challenges to heat CO_2 are not taken into account here (pressure drops management, furnace cooling, material choice, high mass flow rate, structural support…) see [Thimsen and Weitzel, 2016]

Simplified cost model: work in progress to **improve these correlations** (to go from "flux based" correlations to "characteristic parameter design" correlations *(e.g. : for heat exchangers: "UA" instant of "heat duty")…*



Flexibility of the sCO_2 – Brayton cycle: necessitate accurate dynamic models and simulations. One of the objectives of the sCO_2 Flex project

Thank you for your attention

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Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 764690.

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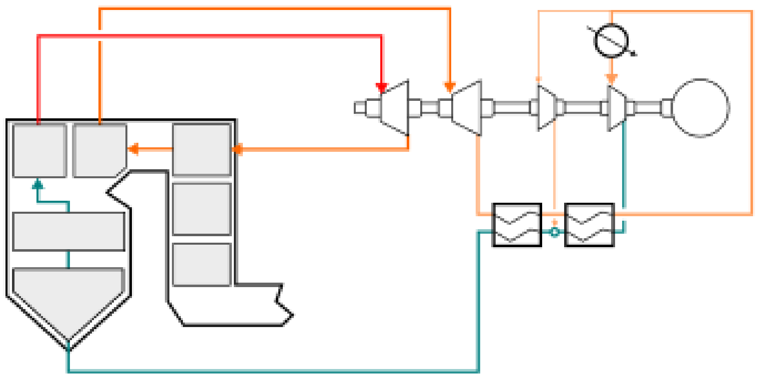
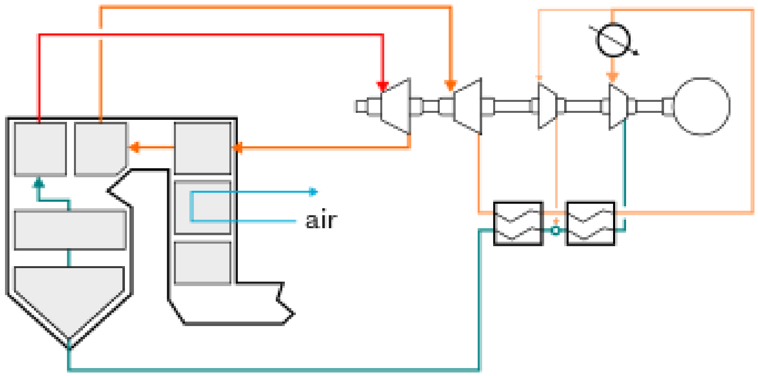
Simplified diagrams of tested configurations

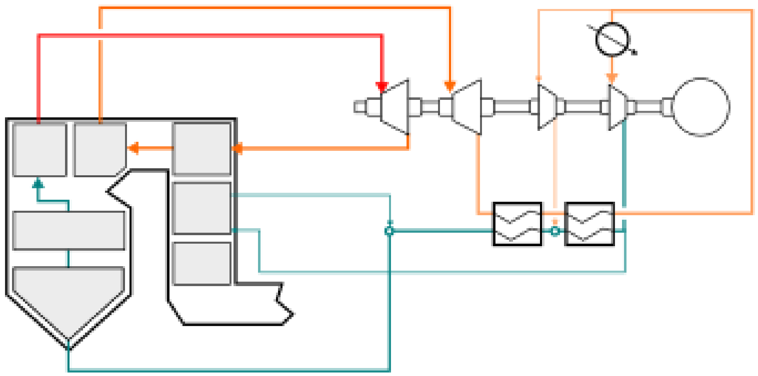
reference case



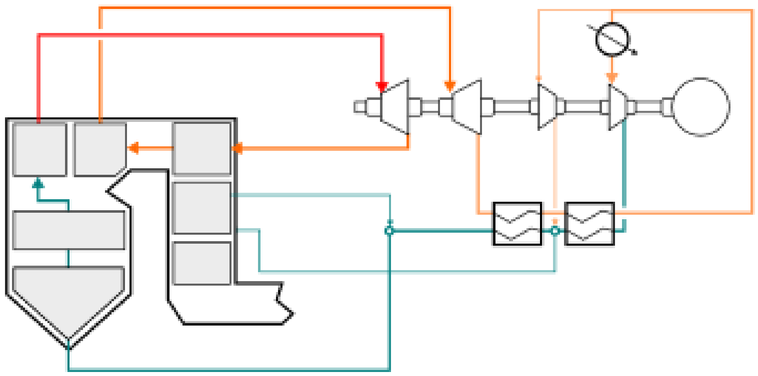
ref + air high pre-heating



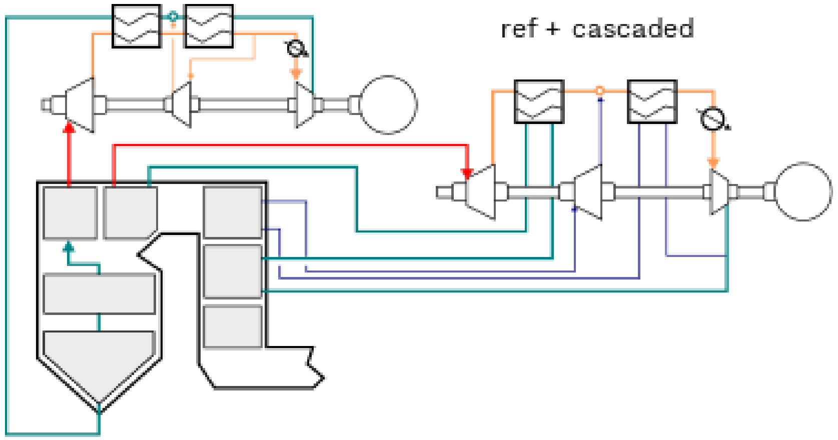
ref + LTR bypass



ref + HTR bypass



ref + cascaded



ref + ORC