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

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ABSTRACT

Supercritical CO_2 closed Brayton cycle (sCO_2-BC) represents a possible solution to enhance fuel-fired power plant performances. However, current fuel-fired boiler (heater) are mainly designed to fit the “water steam power cycle” specificities. Many challenges have been identified to adapt these current steam fuel-fired heaters (state of the art for water Rankine process) to sCO_2 heating applications (closed Brayton cycles). Indeed, compared to steam Rankine cycle, the sCO_2 Brayton cycle is a highly regenerative cycle (leading to high sCO_2 temperature at the heater inlet) and is very sensitive to pressure drops (due to low cycle pressure ratio, to high CO_2 mass flow rate and to the use of compressors instead of pumps). In these conditions, the heater design constraints for sCO_2-BC to ensure good overall power plant performances are significantly different compared to “water steam” power plants, specifically in terms of thermal integration (cooling of the furnace, use of available heat in the heater economizer). In this context, preliminary screening study has been conducted to analyze the combination of a sCO_2 Brayton cycle with cascaded sCO_2 cycle to provide sufficient cooling protection for the furnace enclosure. Other suggestions such as combination with organic Rankine cycle or the use “Recuperator (HTR or LTR) by-pass layout” or “high temperature air-preheating” configurations can also be considered.

Based on previous works done on this topic, this paper intends to compare the performances of different solutions that both provide sufficient furnace enclosure cooling and a high “heat recovery rate”.

Key words: supercritical CO_2 Brayton cycles, fuel-fired heater, thermal integration, economic assessment, flexibility assessment.

INTRODUCTION AND CONTEXT

Recent years have seen renewed interest for the study of supercritical CO_2 closed Brayton cycles (sCO_2-BC) for power production applications. Indeed, it has been theoretically demonstrated that this thermodynamic cycle could replace the steam Rankine cycle in electricity production for high temperature heat source applications, due to many advantages such as compactness, high performances, simplified layout and applicability to different heat sources (especially to high “quasi-constant temperature” heat sources like nuclear or solar energy) **[1]**. The high effectiveness of the sCO_2-BC is partially due to its high regenerative aspect: indeed, thermal energy is available at the turbine outlet and can be used to pre-heat the CO_2 before it enters the heater (see from point 4 to 6 on Figure 1).

Depending on the sCO_2-BC layout, the CO_2 temperature at the heater inlet is around 500°C when the CO_2 maximum temperature reaches 700°C at the heater outlet **[3]**. This specificity means that the heater only warm up the CO_2 from 500°C to 700°C (i.e. low CO_2 enthalpy rise in the heater). It also means that the CO_2 cannot recover low temperature heat from the heater (for example, the flue gas heat after combustion).

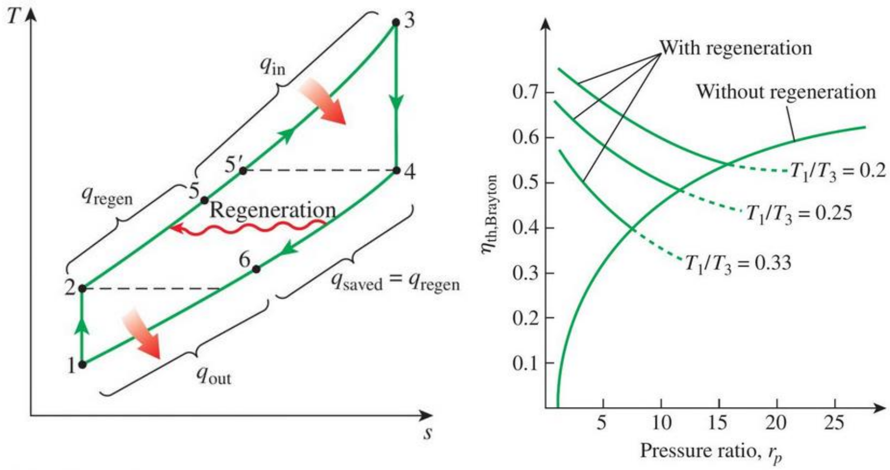


Figure 1: Regenerative sCO2 Brayton Cycle ***[2]***

These specificities show that the sCO_2-BC is not fully compatible with current fuel-fired steam heaters (boilers) for two main reasons (among others):

1. fuel-fired furnace enclosure need to be efficiently cooled to avoid material damages,

2. low temperature heat is available in the flue gas after the combustion. This heat must be recovered by the power cycle (or recovered by increasing the temperature of the preheated air) to maximize the total recovered heat of the heater (boiler) at a fixed combustion rate.

With sub-critical steam Rankine cycles, the cooling protection of the furnace enclosure is controlled thanks to the water phase change that occurs at constant temperature (around 342°C at 150 bar). Furthermore, the water temperature is "moderate" at the heater inlet (around 200°C) which enables to recover the low temperature heat available in the economizer. That is why "steam cycle" is matching well with fuel-fired heaters.

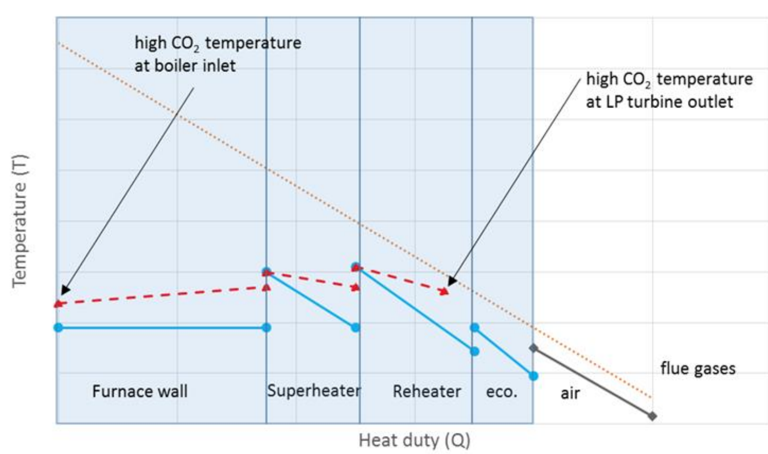


Figure 2: Coal-fired power plant qualitative T-Q diagram
(dotted orange = flue gas, blue = water, dashed red = CO_2 and gray = air)

As explained above, the sCO_2-BC is highly regenerative leading to "low enthalpy rise" requirement in the heater: only "high temperature heat" is recovered. In these conditions, the CO_2 temperature at the heater inlet is higher than for Rankine cycle (around 450°C), and since there is no phase change for the CO_2, its temperature increases in the heater. Thus, it is more difficult to control the temperature of the furnace enclosure with a sCO_2-BC. In addition, the Figure 2 shows that the combination of "low CO_2 enthalpy rise requirement" with "high CO_2 temperature at the heater inlet" leads to a theoretical high flue gas temperature (the heater economizer is useless with an optimized sCO_2-BC) which reduces the total amount of recovered heat in the heater, and thus, its efficiency **[4]**. Since the "global power plant" efficiency is the product of the power cycle efficiency times the heater efficiency, maintaining a high heater efficiency is important to ensure global power plant enhanced performances.

In these conditions, design adaptations are required to use current "water steam furnace" technology for sCO_2 applications as explained by **[4]**. These challenges can be sorted into three main parts[1]:

- Process challenges: reduction of the cycle pressure drops (including heater pressure drops), high mass flow related issues, rapid sCO_2 enthalpy increase in the heater compared to steam, overall process flow sheet optimization (cycle and power plant performances)...

- Heater layout and design constraints: enclosure furnace cooling and structural support considerations, air heater design configuration regarding the air pre-heating temperature, furnace insulation systems, global thermal integration…

- Flexibility requirements: heat load variation capacity, furnace temperature control with load variation, start-up and stop consideration…

In this context, solutions to both protect the heater furnace (moderate the CO_2 temperature at the heater inlet) and the use of "low temperature heat" that is available in flue gases are investigated.

Note: EDF is not a boiler (fired heater) manufacturer and all data concerning boiler/heater design and recommendation are extracted from references. Thus, this paper is not giving any new information about sCO_2 fired heater design/construction.

OBJECTIVES

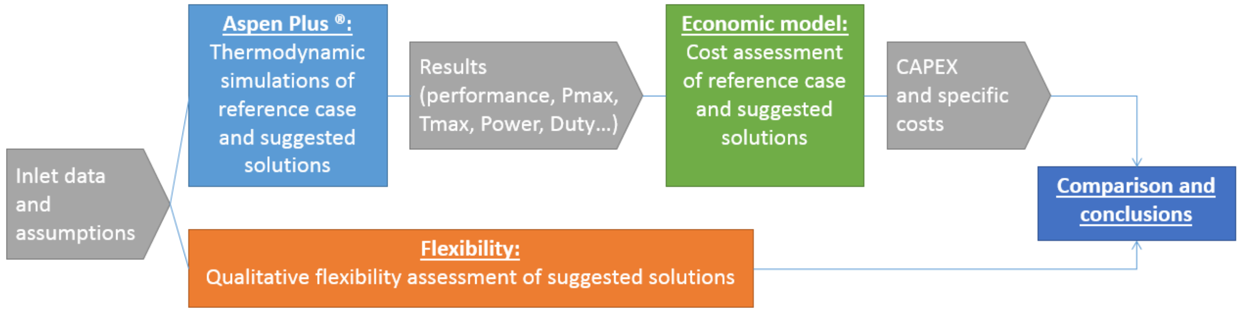
This papers intends evaluating solutions to adapt the sCO_2-BC to fuel-fired heater constraints and thermal integrity requirement. This evaluation is carried out regarding 3 criteria: **i)** technical aspects (performances, manufacturing constraints…), **ii)** economic aspects (global relative costs analysis) and **iii)** qualitative flexibility aspects (start/stop, load variations, time response). This evaluation leads to a first and simple comparison of these foreseen solutions (many hypothesis are required to ensure the calculations).

METHODOLOGY

The main objective is to analyze several solutions that attempt to avoid the fired heater problems specified above. A fixed coal-fired heater configuration is considered for the whole study (fixed combustion parameters, and thus, fixed available duty). Since there is no sCO_2-BC accurate data/values, this study relies on a relative comparison between a reference case and some interesting solutions. The applied reference sCO_2-BC is described below in the concerned section.

All the foreseen solutions to improve the "reference sCO_2-BC" are then compared to the reference case. To do so, thermodynamic simulation are done with the process modeling software Aspen Plus v8.6®. This thermodynamic process modeling enables to assess technical data (performances, design parameters…) under given constraints for each configuration. Then, these data feed a simplified economic model (heuristic model) to assess the global investment costs of each solution. Finally, a qualitative flexibility assessment based on the list of three criteria (start/stop, part-load maximal range, time-response to load variation) is done.

[1] Non-exhaustive list of related challenges. See **[4]** for more details



Thermodynamic models used for this study are the Span & Wagner equation of state (RefProp from NIST) to assess the sCO_2 thermodynamic properties, the SRK equation of state for organic fluids, hydrocarbons and water steam table for water properties.

The fixed coal-fired heater properties

The simplified coal-fired heater considered for the whole study is a "Pi" (π) shaped "boiler" with a furnace wall (FWH: the FWH duty is divided in radiative and convective parts), a superheater (SH), a low temperature reheater (LRH), a high temperature reheater (HRH), and an economizer (ECO). A simplified layout of this coal-fired heater is given on Figure 3:

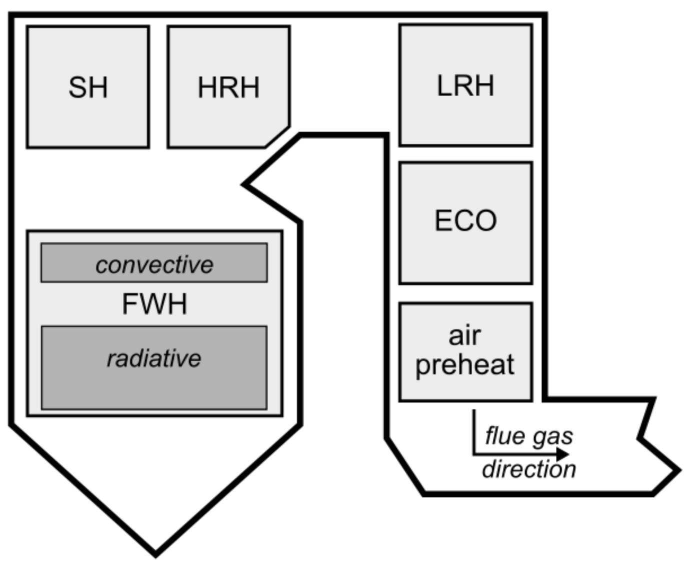


Figure 3: simplified diagram of considered coal-fired heater

The coal-fired heater is assumed to provide 448 MW_{th} of radiative thermal energy and 1543 MW_{th} of convective thermal energy from 1600°C to 320°C (assuming that the minimum temperature of the flue gas at the heater economizer outlet (ECO) is 320°C **[5-6]**). Indeed, in pulverized-coal heater technologies, the acceptable hot air temperature lays between 120°C (because exit flue gas temperature should be higher than the corrosion limit) and 400°C (due to mill internals limitations) **[7]**.

The simplified heater performances correlation is based on the amount of recuperated heat from the combustion. Thus, the heater efficiency is based on the following equation **[7]**:

$$\eta_{boiler} = \frac{Recovered\ heater\ duty\ (MW_{th})}{Combustion\ heat\ (MW_{th})}$$

The combustion heat is linked to the coal properties (Low Heating Value) and its consumption. The main data about the considered heater are the following (Table 1):

Table 1: heater main parameters

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

The reference case (cycle):

The reference case is a single recompression sCO_2-BC with single reheat as depicted in Figure 4:

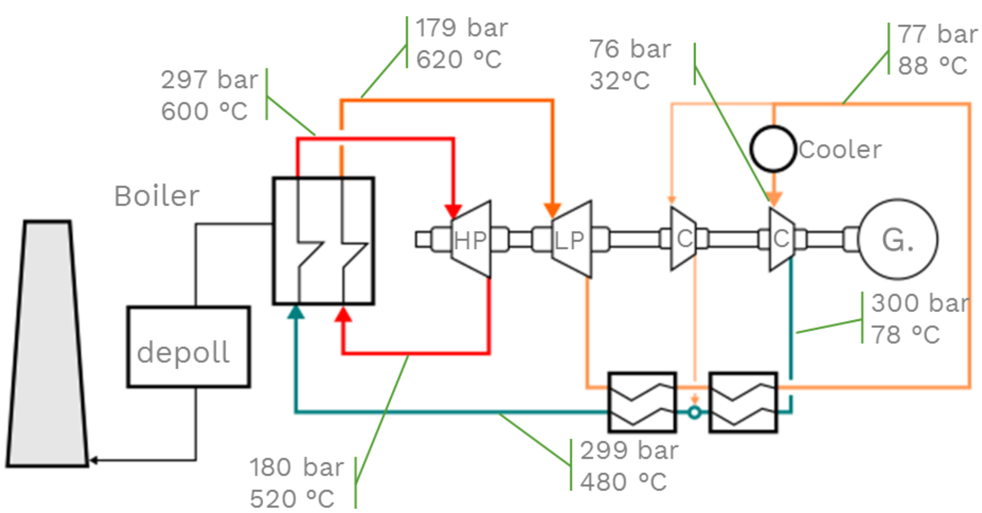


Figure 4 : Simplified process flow diagram of the supercritical Brayton cycle configuration

In any configuration, the efficiency of studied power cycle is classically defined as:

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

As a first simplification parasitic loads (fans, electrical devices…) are not taken into account.

The main parameters of the references case are given in Table 2:

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

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	%

Cost correlation (CAPEX):

Since there is no large scale sCO_2-BC in operation today, very few information is available regarding sCO_2-BC cost data, especially for large scale power cycles. Furthermore, the readiness level of a sCO_2-BC is still moderate which means that the current cost data are likely to evolve with commercial development of the technology. In this context, the cost analysis of this study does not intend to give an accurate and absolute equipment costs. The aim of the economic analysis is to be able to compare the proposed solutions with the reference case and to observe global trends. Also, as the heater configuration is fixed for the whole study, it does not make sense to include the heater cost (which is constant in our case) in the relative costs analysis. Then, only the cost of main components are being estimated (CO_2 turbines and compressors, recuperators, ORC pump, coolers).

The Capital Expenditure (CAPEX) is composed of direct costs (purchased equipment, piping, electrical, civil work, transport, direct installation, auxiliary services, instrumentation and control, site preparation) and indirect costs (mainly engineering, supervision, start-up) **[8 - 9]**:

$$CAPEX\ (\$) = direct\ costs\ (\$) + indirect\ costs\ (\$)$$

The direct costs are expressed as a function of the total component costs **[9]** and are calculated as following:

$$direct\ (\$) = 1.26 \times components\ (\$)$$

Indirect costs are assumed to be 8% of the direct costs **[9]**:

$$indirect\ (\$) = 0.08 \times direct\ (\$)$$

Which means that the CAPEX can be expressed as a function of the components' cost:

$$\begin{aligned} CAPEX\ (\$) &= direct\ costs\ (\$) + indirect\ costs\ (\$) \\ &= 1.08 \times direct\ costs\ (\$) \\ &= 1.3608 \times components\ (\$) \end{aligned}$$

Equipment cost functions in this study are assumed to be "power function" **[10]** with the following global expression:

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

Where “a” and “b” are empirical parameters that depends on the considered component, f_p and f_T pressure and temperature factors. These factors depends on the maximum component pressure and temperature. The aim is to express the cost rise due to the use of high grade/quality materials when the CO_2 reaches high temperature and/or pressure. Thus, these two factors are defined as follows:

$$f_p = \begin{cases} 1\ if\ P_{max} < 100\ bar \\ \alpha \times P_{max} + \beta \end{cases} \quad and \quad f_T = \begin{cases} 1\ if\ T_{max} < 400\ °C \\ \gamma \times T_{max}^2 + \delta \times T_{max} + \varepsilon \end{cases}$$

Flexibility criteria:

Complete and accurate flexibility analysis of an industrial process is very complex and necessitates the use of specific dynamic models and accurate knowledge of each component. This paper does not intend to give accurate (quantitative) flexibility assessment but aims at giving a global (qualitative) overview of the flexibility of studied solutions.

The flexibility analysis is then done upon three criteria (start/stop procedure, part-load range, time-response to load variation). Each criteria can be divided in three parts: “positive (+)”, “neutral (=)”, “negative (-)”. Next table illustrates the meaning of the flexibility assessment for the three observed criteria:

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

List of analyzed solutions:

In this paper, the studied solutions to adapt the sCO_2-BC to coal-fired heater requirement are the following:

1. Another sCO_2 Brayton cycle (cascaded cycle) as proposed in **[4]**.
2. An Organic Rankine Cycle (ORC with butane).
3. A Very high temperature air pre-heating process.
4. A LTR bypass sCO_2-BC configuration.
5. A HTR bypass sCO_2-BC configuration.

Note: as said above, these calculations are first estimations with simplified assumptions. Further data are required to refine obtained results.

The simplified process flow diagrams of these analyzed solutions are depicted in appendix.

RESULTS

The obtained results are summarized in Table 3. All solutions (except the “high temperature air preheating”) induce change in both cycle performances and specific costs. Globally, the “high temperature air preheating” solution has the same results than the reference case except the amount of the recovered heat from the heater. However, this solution leads to other problems related to high air temperature with high mass flow (material problems, large heat exchangers). These problems of “very hot air handling” exist in glass or metal industries. In terms of flexibility, the sCO2-BC are not known to be highly flexible but it is assumed they can be used in “base-load” conditions.

Table 3: comparison of the reference case and the suggested improvements regarding performances and costs, Fired-heater aspects and flexibility aspects

		Reference (R)	R + Air preheating	R + LTR bypass	R + HTR bypass	R + ORC	R + Cascaded
Performances and costs	Cycle Efficiency	**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)
Flexi bility	Start/stop		=	=	=	=	-
	Load range		=	+	+	+	+
	Time-response		=	=	=	+	+

Compared to the reference case, the “HTR bypass” solution has the biggest electricity production rate (+119.2 MW_e mainly due to higher CO_2 flow rate) and a good specific cost reduction (-42.5 €/kW_e) despite a slightly lower cycle efficiency (due to the fact that number of components does not differ from the reference case, only turbomachinery capacity and piping are modified). Similarly, the “LTR bypass” solution offers a good electricity production increase (+95.6 MW_e compared to the reference case) and the lowest specific cost (-51 €/kW_e). In terms of flexibility, both “HTR and LTR bypass” solutions are assumed to absorb fluctuations more easily than the reference cycle (given that these configurations has higher mass flow and a bypass piping) by adjusting partial CO_2 flow rate and adapt to the heater duty variations.

The “ORC” solution also proposes higher production rate (+ 86 MW_e) thanks to the heat available in the heater economizer. This solution enables to use the main sCO_2-BC at his best configuration, keeping its efficiency to the highest level. This solution requires to buy a whole additional cycle which impacts the CAPEX (+68 M€ compared to the reference case). However, the specific cost of this solution is anyway lower than the reference case (- 8 €/kW_e). In terms of flexibility, ORCs are known to be highly flexible (quick start/stop, wide operational range) which can be an advantage for real time control.

The “cascaded cycle” solution involve a reduction of the global production (-41.7 MW_e). However, the use of “moderate” temperature CO_2 cycle enables to reduce investment cost which lead to an interesting specific cost (-48.6 $/$kW_e$). Also, in terms of flexibility, having two different cycles enable modular production (possibility to switch off one cycle to reduce the electricity production). However, start and stop operation are expected to be difficult on sCO_2-BC cycle: in this context, it is expected to be also tricky for two sCO_2-BCs.

DISCUSSIONS

This papers shows that some cycle configurations can be adapted to fit the sCO_2-BC to the coal-fired heater requirements. In this paper, 5 options have been compared to the reference case in order to assess their performances, specific costs and qualitative flexibility.

As observed on the results, the "HTR bypass" solution appears to be the best from the electricity production point of view and the "LTR bypass" from the specific cost point of view. Other solutions are also interesting since they offer higher production rate (ORC solution), or low specific costs (cascaded cycles) as much as improvement of the flexibility. Few other configurations can be tested: among them, combining "post-combustion carbon capture system (CSS)" with sCO_2-BC can be an interesting solution because the carbon capture process requires heat at rather low temperature (for example, heat available at the heater/boiler "ECO" exchanger).

However, this study is only giving a first estimation (simplified cost model, qualitative flexibility assessment) and further work must be done to improve the accuracy of these results, in particular regarding the flexibility assessment that is very simplified in this study.

Furthermore, specific challenges regarding the heater design (configuration, pressure drop, layout and material…) are assumed to be succeeded in this document, which is not the case currently. Thus, specific heater/boiler studies must be carried out to have better knowledge of the feasibility of solutions such as exposed in this paper.

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APPENDIX

The simplified process flow diagrams of the analyzed cycles in this paper: