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SCO$_2$ CLOSED BRAYTON CYCLE FOR COAL-FIRED POWER PLANT: AN ECONOMIC ANALYSIS OF A TECHNICAL OPTIMIZATION

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ABSTRACT & NOMENCLATURE

The analysis of supercritical CO_2 Brayton cycle architectures has been performed by many scientific researchers over the years. These studied cycle architectures have advantages and drawbacks that depend on the context (application field, maximum and minimum parameter values, available heat…). In 2016, a preliminary study based on a sensitivity analysis of a supercritical CO_2 for coal-fired power plant has been performed to assess the impact of the cycle configurations on its performance. This publication was dealing with several ways to improve the sCO_2 Brayton cycle performances by using convenient cycle layout for coal power plant applications. However, the study only focused on cycle performance improvements and did not take into account the economic aspects.

This paper intends to complete this previous technical analysis by comparing the economic results with the technical optimization results. The economic analysis is done by using the combination of literature and "internally built" cost correlations.

The present work is one of the studies that can further feed the "sCO_2-Flex" European Project that involves 10 European academic and industrial partners aiming at designing a highly flexible "25 MW electrical" sCO_2 Brayton cycle for coal-fired power plant.

Abbreviation	Meaning
CAPEX	CAPital EXpenditure
COP	Compressor Outlet Pressure
L (or H) TR	Low (or High) Temperature Recuperator
LCOE	Levelized Cost of Electricity
MPa	MegaPascal
MW	MegaWatt
OPEX	OPerational EXpenditure
PFD	Process Flow Diagram
sCO_2	supercricitcal carbon dioxide
TIT	Turbine Inlet Temperature
UA	Product of U coefficient (Heat transfer coefficient) and A (exchange surface) for heat exchangers

CONTEXT

The main conclusions concerning the previous technical sensitivity analysis [1] are the following: a recompression cycle is highly recommended because the secondary compressor "partial flow" stream enables significant efficiency gains (+4.5%pt compared to basic Brayton cycle layout without recompression stage). Furthermore, "double reheat" architecture offers interesting efficiency improvement at "moderate" turbine inlet temperature (about +1.5%pt at 620°C turbine inlet temperature). In this context, the proposed power cycle architecture in [1] offers good performances with realistic maximal temperature and similar capital investment expectations than for existing "water-steam" coal power plants. This cycle architecture is illustrated in Figure 1. The operating conditions of this cycle are details in Table 1.

Table 1: Parameters of suggested sCO_2 coal-fired power cycle [1]

Variable/parameter	Value(s)	Unit
Main compressor inlet temperature	32	°C
Main compressor inlet pressure	7.9	MPa
Main compressor outlet pressure	30	MPa
Turbine inlet temperature	620	°C
Pressure drop (every component)	0.1	MPa
LTR and HTR pinch	6	K
Air-gas heat exchanger pinch	30	K
Compressors isentropic efficiency	89	%
Turbine isentropic efficiency	93	%
Alternator/Motor electrical efficiency	99.6	%
Mechanical efficiency	98.5	%
Air preheating configuration	Case C	–
Number of recompression stages	1	–
Number of reheat stages	2	–

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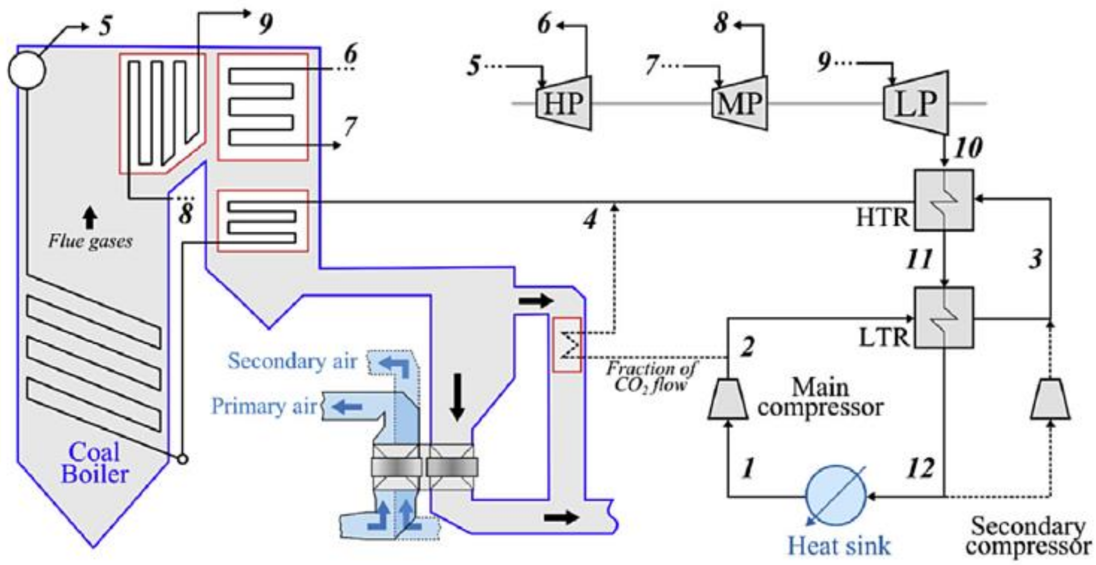

Figure 1: Process Flow Diagram (PFD) of suggested coal-fired power plant configuration in [1]

The pressure ratio of this cycle has been optimized to maximize the net cycle efficiency with a fixed maximum pressure of 30 MPa. Then, in this case, the cycle optimal minimum pressure is 7.9 MPa [1].

Improving the cycle performances logically leads to the maximization of the cycle temperature and pressure ratios. At fixed low temperature and pressure, it means that the cycle performance rise is related to the maximization of the cycle maximal temperature and pressure. However, increasing the cycle maximal temperature and pressure requires the use of specific high-grade and expensive materials to withstand corrosion and thermal stresses. Also, high performance cycles require very efficient recuperators in order to maximize the cycle heat integration. However, efficient recuperators have larger footprint and thus, are more expensive. In this context, the search for high performances is expected to have a large economic impact. The question is "how much does it cost to achieve higher efficiency"?

OBJECTIVES

This paper intends to complete the technical analysis done in 2016 [1] by achieving an economic evaluation of the proposed sCO_2 Brayton cycle architecture in order to observe if the technical conclusion matches with the economic conclusion. The economic analysis is done by using "equipment cost" correlations found in literature or internally built (see details in the methodology section below).

The present work is one of the studies that can further feed the future European Project "sCO_2 Flex". 10 European academic and industrial partners are involved is this project that aims at designing a highly flexible "25 MW net electrical" sCO_2 Brayton cycle for coal-fired power plants.

METHODOLOGY

The aim of this paper is to challenge the technical optimization results obtained in the study [1] by assessing the cost of the suggested sCO_2 Brayton cycle configurations in [1].

The work is divided in 4 parts:

1. Assessing the economic impact of the cycle configuration (number of reheat from 0 to 2).
2. Assessing the economic impact of the turbine inlet temperature (TIT) [600°C – 700°C – 800°C].
3. Assessing the economic impact of the recuperators' "pinch temperature" value (3K – 6K – 10K).
   (these first steps enable to find the best cycle configuration from the economic point of view).
4. Economic sensitivity analysis: observing the impact of a main component cost increment (+30%) and discount (-30%) on the total specific costs (see "Economic sensitivity analysis" description below).

Economic model

The cost analysis of this study does not intend to give accurate and absolute costs. The aim of the economic analysis is to compare the cost of different technical configurations. The economic evaluation method is based on the cost calculation of the main cycle components (boiler, turbomachineries, recuperators, coolers). As a first economic assessment, this study only focuses on the Capital Expenditure (CAPEX).

The 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) [2; 3]. These direct and indirect costs can be expressed as a function of the "total component cost".

DOI: 10.17185/duepublico/46091

In this context, the CAPEX can be defined as in equations 1

$$\begin{aligned} CAPEX(\$) &= direct + indirect\ costs \quad and \quad indirect\ cost = x_1 \times direct\ costs \\ &= (1+x_1) \times direct\ costs \quad and \quad direct\ costs = (1+x_2) \times \sum component\ cost \\ &= (1+x_1) \times (1+x_2) \times \sum component\ cost \end{aligned} \tag{1}$$

where x_1 and x_2 are coefficients respectively fixed at 8% and 26% [2; 3], which means that the CAPEX can be expressed as a function of the total component cost as shown in equation 2.

$$CAPEX\ (\$) = 1.3608 \times \sum component\ cost\ (\$) \tag{2}$$

In this study, the component cost functions are assumed to be "power function" [4] with the global expression shown in equation 3

$$component\ cost(\$) = a \times (Parameter)^b \times f_p \times f_t \tag{3}$$

(where: "a" and "b" are empirical coefficients that depend on each considered components (turbomachinery, heat exchangers, boiler), "Parameter" represents characteristic variables i.e.: the heat duty for the boiler, the UA factor for heat exchangers (recuperators and coolers) and the electrical power for turbomachineries, f_p and f_t are pressure and temperature factors that simulate the rise of material cost with temperature and pressure.).

The f_p and f_t factors are defined as shown in equations 4

$$f_p = \begin{cases} 1\ if\ P_{max} < 100\ bar \\ \alpha \times P_{max}\ (\text{in bar}) + \beta \end{cases} and$$
$$f_T = \begin{cases} 1\ if\ T_{max} < 400\ °C \\ \gamma \times T_{max}^2 (\text{in °C}) + \delta \times T_{max}\ (\text{in°C}) + \varepsilon \end{cases} \tag{4}$$

where α, β, γ, δ and ε are empirical parameters.

Also, the specific cost defined as the ratio of the "CAPEX" over the "net power electrical power output" is used as the criterion to find the best economic solution (equation 5).

$$specific\ cost\ (\$/kW_e) = CAPEX\ (\$)/Net\ electrical\ power\ output\ (kW_e) \tag{5}$$

This economic simplified model is used to complete the sensitivity analysis done within the study [1].

Assumptions

As for the study [1], the boiler design is assumed to be fixed for all analyzed cycle configurations in this paper. Also, CO_2 purity is assumed to be 100%. As a first simplification, the electricity consumption of auxiliaries is not considered.

CO_2 is assumed to be cooled by air (air inlet temperature of 20 °C) with a flow rate of about 13 000 m3/s. As said above, the auxiliary consumption is not taken into account in this study, as in [1].

Economic sensitivity analysis

An economic sensitivity analysis is done on one chosen sCO_2 Brayton cycle configuration. This analysis consists in modifying the cost of an equipment (first upward +30% and then downward -30%) to assess its impact on the total cycle specific costs (all other costs being fixed).

In this study, this cost increment (and reduction) is applied on the boiler, the turbomachinery and the recuperators' costs.

RESULTS

Impact of the cycle configuration (number of reheat from 0 to 2):

In the study [1], the sCO_2 Brayton cycle performance has been assessed regarding the number of reheat (from 0 to 2) for three different TIT (600/700/800°C) while the main compressor outlet pressure (COP) varies. In this paper, the economic model is applied on these cases, applying the same conditions/assumptions (see [1] for details).

Figure 2 illustrates both the net cycle efficiency (solid lines, left axis) and its corresponding specific cost (dashed lines, right axis) as a function of the main COP for 0, 1 and 2 reheats (for TIT of 600°C).

From the performance point of view, the logical conclusion is that, first, the efficiency rises with the number of reheat, and secondly, there is an optimal pressure ratio (for a given TIT) that depends on the number of reheat.

From the economic point of view, we can see that the best option depends on the COP and, contrarily to the technical results, is not linked to the highest number of reheat. This observation makes sense because 1) reheats involve higher averaged temperature in the turbines, 2) the maximum temperature in the High Temperature Recuperator (HTR) is also higher, 3) and the number of pipes that go from the boiler to the power block increase).

For low pressure ratio (COP from 20 to ~26 MPa), the "0 reheat" configuration has the lowest specific cost. Above a COP of 26 MPa, the "1 reheat" configuration offers the lowest specific cost.

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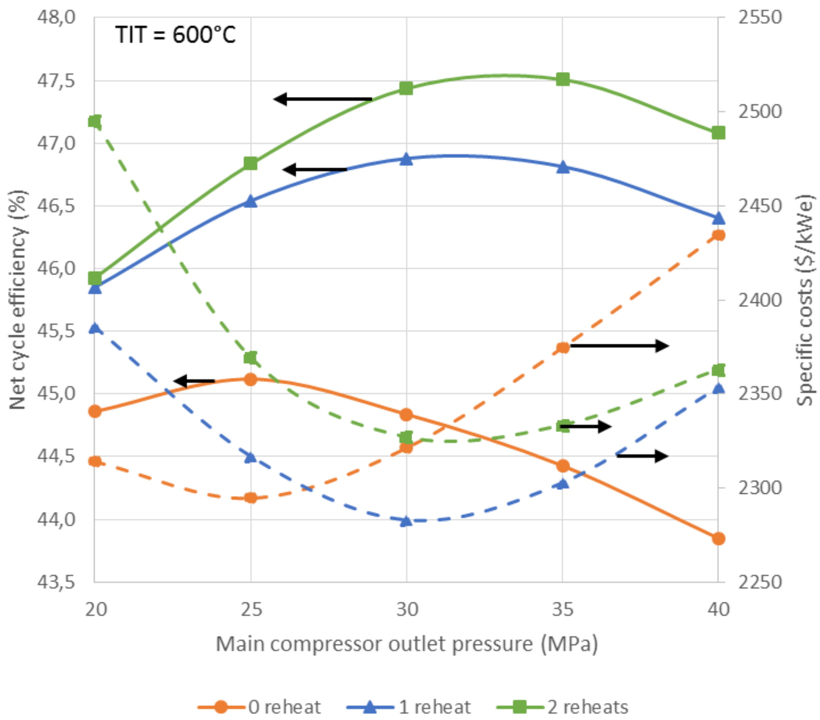

Figure 2: Net cycle efficiency (solid lines, left axis) and specific costs (dashed lines, right axis) as a function of the main compressor outlet pressure for TIT = 600°C for 0, 1 and 2 reheats

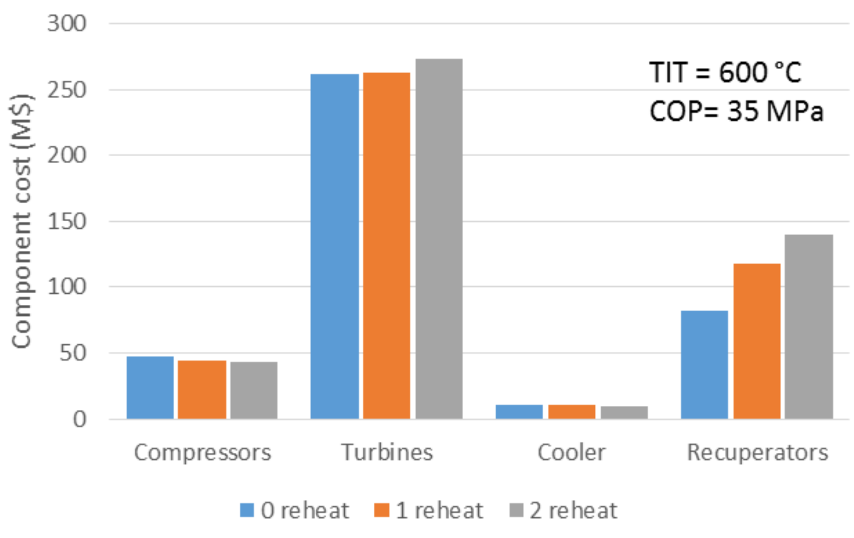

Figure 3: Component costs (except boiler) for TIT = 600°C and main compressor outlet pressure of 35 MPa for the three cycle configurations

Figure 3 shows the component cost breakdown for the 3 studied configurations (for TIT = 600°C and COP = 35 MPa). It can be observed that when the number of reheat rises:

- the cost of recuperators increases. This is due to higher temperature at the HTR hot side inlet and thus, higher exchange surfaces and more expensive materials.
- The cost of turbine rises. This is due to higher average CO2 temperature in the turbines.
- The costs of compressors and cooler decrease. Indeed, given that the boiler heat duty is fixed, the CO2 flow rate in the cycle decreases while the cycle efficiency increases (i.e. when the number of reheat rises). Lower CO2 flow rate

DOI: 10.17185/duepublico/46091

leads to lower "compressor power" consumption and lower "cooler duty".

When the TIT rises to 700°C, the specific cost increase with the number of reheat as depicted in Figure 4 below. Indeed, the COP where the specific cost of "0 reheat" and "1 reheat" configurations are crossing is above 40 MPa.

In the study [1], the sCO_2 Brayton cycle performance has been assessed regarding three TIT values (600°C – 700°C – 800°C) while the main COP varies. In this paper, the economic assessment is done in these same conditions.

From the economic point of view, it can be observed that the best option depends on the pressure ratio. But, contrarily to the "efficiency" best result, the "economic" best case is not related to the highest TIT. Indeed:

- for COP ≤ 26 MPa, it can be observed that the less expensive cycle is the "no reheat" configuration with a TIT of 600°C,
- for COP > 26 MPa, the "one reheat" configuration (TIT = 600°C) offers the best option.

The global lowest specific cost in the given conditions is observed for a "one reheat" cycle with TIT = 600°C and COP = 30 MPa.

Impact of the recuperators' pinch value:

In this section, the impact of the recuperator performance on the specific cost is analyzed. Indeed, performant heat exchangers with small pinch temperature are required to obtain efficient cycles but they have larger exchange surfaces and thus, larger volumes and material mass. In these conditions, the costs of a heat exchanger can drastically increase with its performance, especially while using high grade materials to prevent corrosion or thermal stresses.

In this section, three "pinch temperature" values are considered (respectively, 10, 6 and 3 K) for a "double reheat" cycle configuration and a 600°C TIT.

In these conditions, Figure 6 shows that the lowest specific cost can be obtained with "6K pinch" recuperators when the COP stays below ~22 MPa. For higher COP, the "10K pinch" case offers the lowest specific cost. Indeed, as explained above, performant heat exchangers are bigger and thus, they require more material to be built. As they are made of expensive materials, their cost are highly impacted by the chosen "pinch temperature" value. To conclude on the impact of the heat exchanger performance, a compromise must be found between high cycle performances and low specific costs, as for the TIT or the number of reheat.

It can also be observed on the Figure 6 that the "economic" optimal COP is different than the "technical" optimal COP for each case.

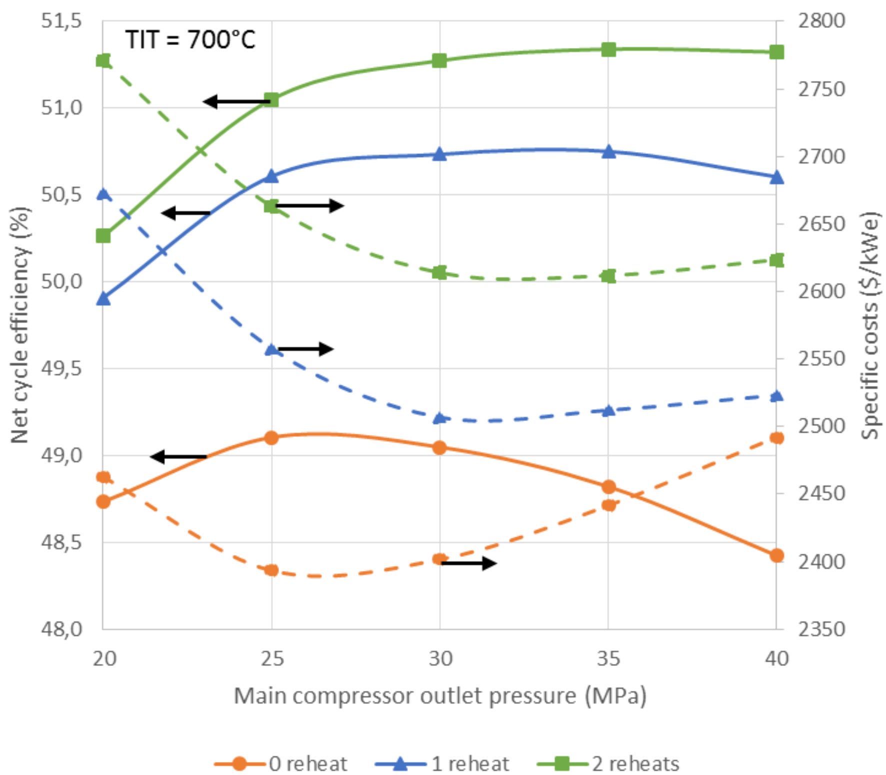

Figure 4: Net cycle efficiency (solid lines, left axis) and specific costs (dashed lines, right axis) as a function of the main compressor outlet pressure for TIT = 700°C for 0, 1 and 2 reheats

DOI: 10.17185/duepublico/46091

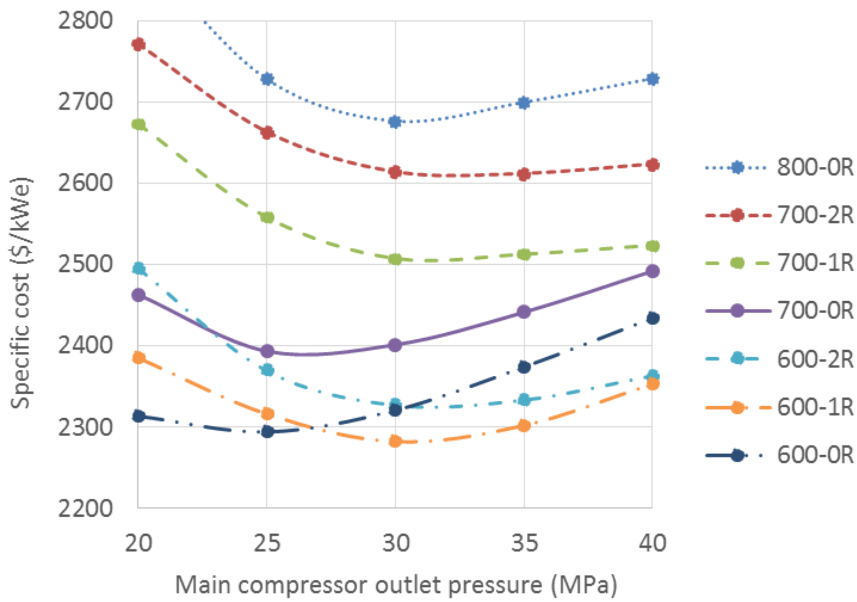

Figure 5: Specific costs (in $/kWe) as a function of the main compressor outlet pressure (in MPa) for several cycle configurations (legend: xxx-yR: "xxx" being the temperature in °C and "y" the number of reheat)

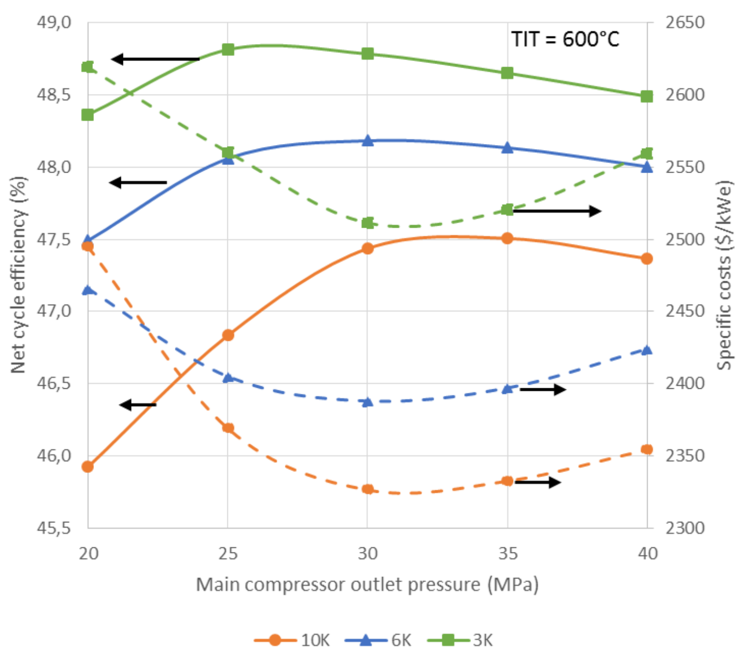

Figure 6: Net cycle efficiency (solid lines, left axis) and specific costs (dashed lines, right axis) as a function of the main compressor outlet pressure for TIT = 600°C for three "temperature pinch" values (10K, 6K and 3K)

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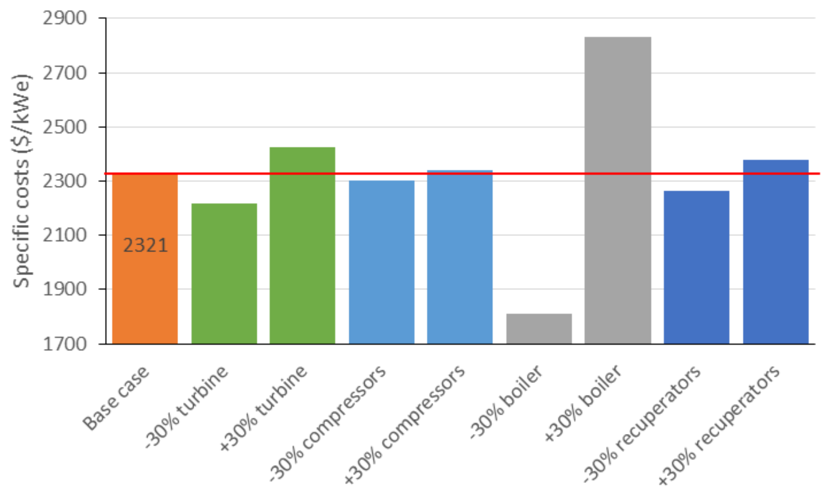

Figure 7: Specific costs variations as a function of main component cost increment (+30%) and discount (-30%) for a "no reheat cycle configuration, TIT = 600°C, COP = 30 MPa, recuperators pinch value=10K.

Economic sensitivity analysis:

The aim of this section is to assess the sensitivity of the economic model used in this study. To do so, a fixed configuration is chosen ("one reheat", TIT = 600°C, COP = 30 MPa, recuperators' pinch value = 10K) while the economic model is modified: a cost increment of +30% (and respectively a discount of -30%) is applied for each main component, one at a time.

Figure 7 shows the results of the "economic sensitivity analysis". Logically, the economic impact of the main components depends on their share in the global cost balance. Thus, these results show that the boiler cost modification has the biggest impact on the specific cost (all other parameters being fixed), followed by the turbine, the recuperators and the compressors. Then, it is more interesting to focus research and development effort to reduce costs of the boiler to maximize de cost reduction of such cycles.

CONCLUSION AND DISCUSSIONS

This paper deals with a preliminary economic analysis applied on a previous technical survey [1] that have been made to assess the sCO_2 Brayton cycle performance in a coal power plant with different cycle configurations. The cost analysis of this study does not intend to give accurate and absolute costs. This economic analysis enables to compare different technical cycle configurations. The economic evaluation method is based on the calculation of the main components' costs (boiler, turbomachineries, recuperators, coolers). As a first economic assessment, this study only focuses on the Capital Expenditure (CAPEX).

The technical results obtained in [1] led to the conclusion that the recommended cycle for such application is a "double reheat" cycle configuration with a 620°C turbine inlet temperature and using recuperators with a "6K temperature pinch" value. Indeed, looking for the best performances leads to maximize the turbine inlet temperature while reducing the heat exchanger "temperature pinch" value and pressure drops. However, these actions requires the use of expensive components.

The economic analysis shows that (within the studied framework and the given assumptions) the cycle configuration that offers the lowest specific cost (Capital expenditure over the net power production) is a "one reheat" configuration with a 600°C turbine inlet temperature. Also, the optimal cycle pressure ratio is different while considering the cycle efficiency or the specific cost. Finally, the sensitivity analysis show that the boiler is the critical component with the highest impact on the specific cost. Thus, cost reduction efforts must be focused on the boiler to have the highest impact on the global power plant specific cost.

PERSPECTIVES

As explained, this economic model only stands on the CAPEX and specific costs of the considered cycle configurations. Also, this model undergoes some limitations due to assumptions and hypotheses (this model has not been benchmarked on real cases because there are few available economic data of sCO_2 Brayton cycles or sCO_2 boilers). In this context, the economic model is still under construction and some perspectives can be expected to improve it as detailed in the following paragraph.

The simplified economic model used in this paper relies on the power plant CAPEX regarding its main components. Further work is then required to include the Operational Expenditure (OPEX) to then be able to calculate the Levelized Cost Of Electricity (LCOE) which is an appropriate criteria to compare different electricity production solutions. This perspective requires additional data concerning the boiler

DOI: 10.17185/duepublico/46091

(because OPEX includes costs such as combustible costs, salaries…) and about the power plant itself (number of hour of production at full load, availability factor…).

Secondly, further work is required to adapt the methodology for flexible power plant (part load conditions) given that performances and electricity production rate depend on the operating conditions.

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