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CONFIGURATION OF A FLEXIBLE AND EFFICIENT SCO2 CYCLE FOR FOSSIL POWER PLANT

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ABSTRACT

As part of the sCO2-Flex project, funded from the European Union's Horizon 2020 research and innovation program under grant agreement N° 764690, the consortium has set about developing a fossil fuel power cycle that allows both more flexibility and less emissions than currently operating power cycles. For this objective, the consortium has decided to work on a supercritical CO_2 (sCO_2) cycle in order to be able to gain in modularity in terms of size reduction, in efficiency because it is more efficient than a water-steam cycle, in flexibility because the design will be simplified and above all will take into account future constraints from the design stage.

EDF was responsible for providing the consortium with the most interesting fossil fuel cycle configurations from a flexibility and performance point of view. To this end, an iterative approach has been adopted and will be presented later in the paper.

First, 21 different cycle configurations were modelled in order to assess their impact on the performance for coal power plant application. Based on the expertise of the EDF R&D team, a selection of a few cycles has been made to be presented to different experts in order to determine: the industrial capacity to obtain equipment with the expected performance, the operability of this type of cycle according to these technical characteristics (the more complex a cycle will be to operate, the greater the risk of failure).

In a second step, all the current flexibility constraints were synthesized for the cycles in operation, as well as the influential factors to guarantee this flexibility (operating ramp of such a component, constraints related to the reliability of a component...). Then, on the basis of future energy mix scenarios and interviews with operators, we also drew insight about the future evolution of these constraints.

Finally, on the basis of the first selection of cycles and future flexibility constraints, cycle configurations were selected within the consortium, taking into account also the potential industrial difficulties and costs for the development of components, in particular for the boiler, which is a key element for future markets for this type of cycle.

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INTRODUCTION

Global electricity production has been undergoing major upheavals in recent years. The increase in production from renewable energies, most of which are fatal, and the political will to reduce greenhouse gas emissions are a difficult equation to solve. Indeed, if the reduction of gas emissions requires the closure of fossil power plants, the need to compensate for the intermittent production of renewable energies by ultra-flexible means of production argues in favor of maintaining these same plants. In addition, most of the world's electricity generation is still provided by fossil fuel power plants. It is this ambivalence that led the sCO_2-Flex project team to propose working on a completely new type of cycle adapted to a fossil power plant: a supercritical CO_2 Brayton cycle, designed to be more flexible and more efficient than current cycles.

WHY AN EFFICIENT AND FLEXIBLE CYCLE?

In recent years, global electricity production has undergone profound upheavals. Faced with the challenges of global warming, growing demand and economic challenges, electricity producers must be innovative in order to best meet society's requirements. Although renewable energies are growing rapidly, the majority of electricity in the world is produced by fossil fuel power plants, which emit high levels of greenhouse gases but contribute to the stability of the electricity grid through their flexibility. This flexibility has often improved at the cost of

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making cycles more complex because they are designed to operate in base mode and not in flexible mode, making it more difficult for operators to operate (with an increased risk of failure) and a loss of efficiency due to the requirements of environmental regulations, imposing energy-intensive pollution control equipment. Based on this observation, our idea was to start from a completely new type of cycle to integrate all the elements necessary for flexibility and environmental requirements from the design stage and thus optimize performance and facilitate the operation of this cycle.

METHODOLOGY

From the previous literature and simulations [Le Moullec, 2013; Mecheri & Le Moullec, 2016], more than 21 supercritical CO_2 cycle configurations were first modelled. On the basis of the performances obtained on different technical characteristics (overall efficiency, boiler temperatures, efficiency of the different components, flow rate...) and expert reviews on the influential parameters of the current flexibility of a thermal cycle, we made a first selection of 6 cycle configurations considered as the most interesting for both efficiency and flexibility.

In a second step, it felt necessary to better understand what the future constraints related to flexibility would be in order to integrate them into the criteria for the selection of the best cycle configurations. To do this, we had to study the current cycle limits, anticipate future cycle operating chronicles and anticipate the constraints related to increasingly rapid and significant load variations.

In the last phase of our study, we shared the results of the first two phases in order to establish a choice between 3 configurations allowing the best compromise between performance and flexibility.

FIRST SELECTION OF CYCLES CONFIGURATIONS

More than 40 sCO_2 Brayton cycle architectures can be found in the literature [Crespi et al, 2017], but not all of them are compatible with the project framework. Indeed, the chosen cycle must fit coal boiler constraints (such as low temperature of the working fluid at the boiler inlet, low pressure drops for high flow rate, good heat integration for a high boiler efficiency…), be efficient and suitable for flexible operation loads.

Based on the knowledge given by previous simulation experiences [Le Moullec, 2013; Mecheri & Le Moullec, 2016] and literature review [Angelino, 1968; Crespi, 2017], we pre-selected 21 cycle configurations among the more than 40 possible ones. These configurations can be divided in 6 families of cycles (6 base form) with additional options. The list of these 21 cycles and the simplified process flow diagram of studied architectures' families are given in the following Table 1 and Figures 1 to 6.

Table 1: List of the 21 pre-selected configurations

FAMILY	ADDITIONAL OPTION	CYCLE NUMBER
1 - Recompression cycle	-	11
	One reheat	12
	Double reheat	13
	One intercooling	14
	Intercooling + reheat	15
	HTR bypass	16
2 - Partial cooling cycle	-	21
	One reheat	22
	Double reheat	23
	HTR bypass	24
3 - Pre-compression cycle	-	31
	One reheat	32
	Double reheat	33
	HTR bypass	34
4 - Turbine split-flow cycle	-	41
	One reheat	42
	LTR bypass	43
5 - Preheating cycle	-	51
	One reheat	52
	Double reheat	53
6 - Split-expansion cycle	-	61

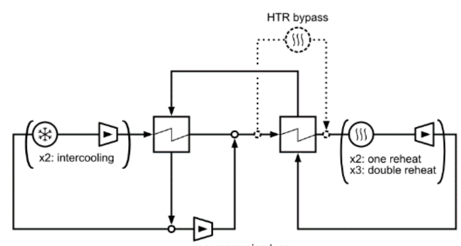

Figure 1: Recompression cycles Family

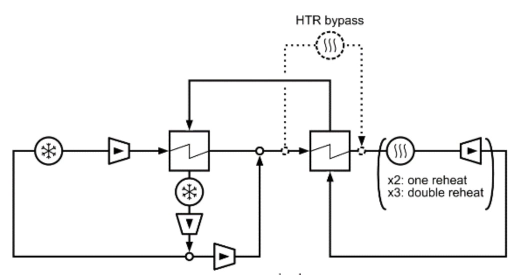

Figure 2: Partial cooling cycles Family

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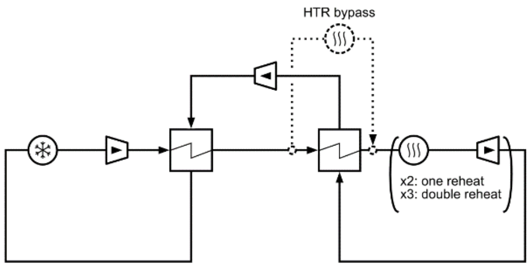

Figure 3: Pre-compression cycles Family

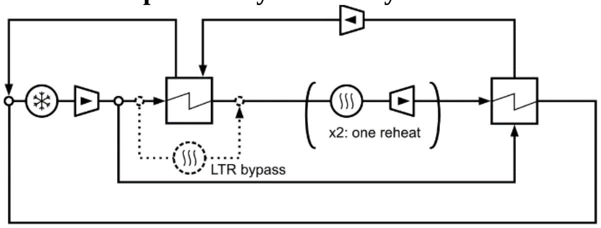

Figure 4: Turbine split flow cycles Family

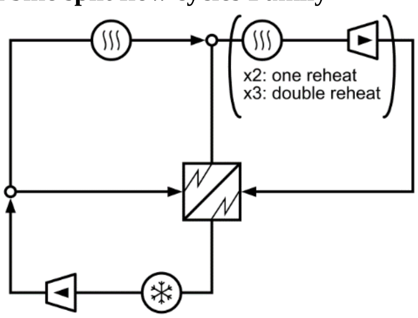

Figure 5: Preheating cycles Family

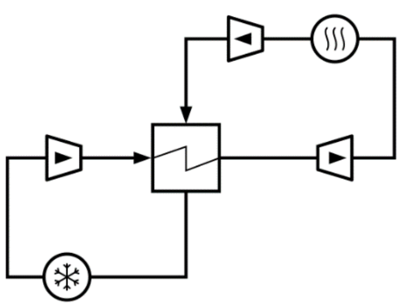

Figure 6: Split expansion cycle Family

To help us in the choice of several configurations, we decided to implement a sensitivity analysis on our selection of 21 cycle configurations. The sCO_2 Brayton cycle is very sensitive to many parameters [Dostal, 2004; Mecheri & Le Moullec, 2016]. In our study, the pressure drops, the maximum temperature/pressure and the cooling temperature impacts on the cycle performance (cycle net efficiency) were assessed regarding the setting displayed in the Table 2. These parameters and the new values were chosen after a first interview of experts.

Table 2 : Modified parameters for sensitivity analysis

MODIFIED PARAMETER	NEW VALUES
Heat exchanger and boiler pressure drops	HEx pressure drops = 0.1% of inlet pressure Boiler pressure drops = 0.1 MPa
Heat exchanger and boiler pressure drops	HEx pressure drops = 1% of inlet pressure Boiler pressure drops = 0.5 MPa
Boiler outlet maximal temperature	550°C (with compressor outlet pressure = 20 MPa)
Boiler outlet maximal temperature	700°C (with compressor outlet pressure = 30 MPa)
CO_2 minimal temperature (cooling temperature)	30°C
CO_2 minimal temperature (cooling temperature)	34°C

Once our 21 cycle configurations were known and the parameters of the sensitivity analysis determined with the help of the experts, we were able to carry out the modelling work for each of the configurations and their respective sensitivity analyses. We used the process modelling software AspenPlus® with RefProp (NIST) thermodynamic database to obtain the design point of each cycle architecture is based on a sensitivity analysis. This screening method enables to assess the best cycle performances (given the fixed constraints) but also to obtain the global heat and mass balance table which is important for the components' pre-design and design steps. The process simulation of cycle architectures is done regarding several assumptions and fixed parameters as defined below.

Table 3: Assumptions on fixed parameters

PARAMETER	UNIT	VALUE
Net cycle production	MWe	25
CO_2 temperature at the heat sink outlet (MSCUSXXT2)	°C	33
Maximum CO_2 temperature at the heater outlet (MSHSOXXT2)	°C	620
Maximum CO_2 pressure at the main compressor outlet (MSCOMXXP2)	MPa	25.0
Compressors isentropic efficiency	%	80
Turbine isentropic efficiency	%	90
Pressure drops in the heater (MSHSOXX)	MPa	No reheat: 0.25
		One reheat: 0.2 + 0.1
		Two reheats: 0.2+0.1+0.1

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		HTR/LTR bypass : 0.1+0.2
Pressure drops in the recuperators (MSRCUXX)	% of inlet pressure	0.5
Pressure drops in the heat sink heat exchanger (MSCUSXX)	% of inlet pressure	0.5
Maximum number of intercooling	1	
Auxiliary consumption	MWe	-
Boiler maximal efficiency	%	94
CO_2 purity	%	100

RESULTS OF MODELLING AND SENSITIVITY ANALYSES

After modelling each of the 21 cycle configurations and performing the associated sensitivity analyses, we observed the impact of each of the parameters studied and established a list of 6 cycles configurations as offering the best compromise between performance and flexibility at the end of the first stage of our study. The conclusions associated with the effects of the parameters, as well as the 6 selected cycles, are presented below.

The first general conclusions concerning all studied architectures are:

- Effect of reheating: the reheating process consists in dividing the expansion step of the process and to send back the sCO_2 in the boiler to heat it again before finishing the expansion step. As a general statement, the CO_2 mass flow is reduced when the cycle efficiency increases at fixed electricity power production. In our study constraints, the electricity power production is fixed to be 25 MW_e: thus, the CO_2 mass flow decreases with the application of reheating process.
- Effect of intercooling: The intercooling consists in dividing the compression stage in two (or several) parts between which the CO_2 is cooled before finishing the compression stage. Intercooling enables to slightly increase the cycle efficiency (and thus the CO_2 mass flow rate at fixed electricity production) while ensuring at slightly lower CO_2 temperature at the boiler inlet.
- Effect of bypassing the recuperator: The high (or low) temperature recuperator bypass consists in extracting a fraction of the main CO_2 mass flow at the H (or L) TR inlet. This modification has a minor impact on the cycle performance and enables to reduce the minimal CO_2 temperature at the boiler inlet.

The main sensitivity analysis results are:

- As expected, the cycle pressure drops, and the boiler outlet temperature have high impact on the cycle efficiency. Cooling temperature and main compressor outlet pressure have lower impact of the cycle performance.
- As the electrical power production is fixed ($25MW_e$), better efficiency implies a lower CO_2 mass flow. Indeed, the efficiency improvement is mainly due to the amount of "recovered heat" in the recuperators, especially in the HTR. The cycle temperature balance is also impact by the pressure drops. Also, the "minimal boiler inlet temperature" is indeed impacted by the boiler outlet temperature: for a given cycle, higher boiler outlet temperature leads to higher turbine outlet temperature, thus, a higher "heat recovery" in the HTR and finally, a higher boiler inlet temperature.
- Cooling temperature variation study shows that the cycle performance will be affected by variability on the cooling temperature (flexibility).

Figure 7 illustrates the net cycle efficiency (in %) sensitivity with variation of the main compressor outlet pressure (MSCOM01P2 in MPa) for 3 different boiler outlet temperatures (MSHSOT2 in °C) for the cycle 11. It can be observed that, as predicted in [Dostal, 2004], the maximum cycle temperature has a stronger impact on the cycle next efficiency that the main compressor outlet pressure, which means that efforts to improve the net cycle efficiency must be concentrated to solve "high CO_2 temperature related issues" more than "high pressure related issues". Of course, this conclusion is drawn regarding only the net cycle efficiency and should be balanced by considering other aspects (economic, flexibility…).

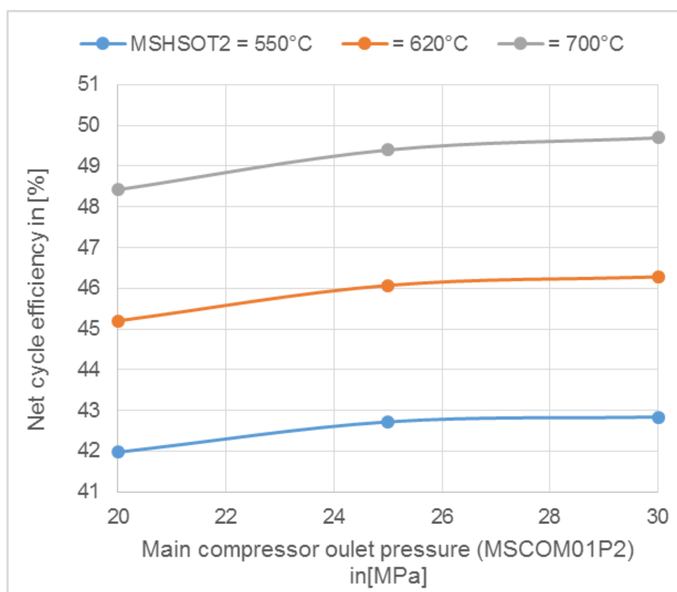

Figure 7: Cycle 11 (figure 1) net cycle efficiency (in %) as a function of the main compressor outlet pressure

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(MSCOM01P2 in MPa) for 3 different boiler outlet temperatures (MSHSOT2 in °C).

FIRST SELECTED CONFIGURATIONS

Three families of configurations have performances that are too low compared to our initial requirements (efficiency around 40%, which is equivalent to the average efficiency of current power plants). These families are as follows:

- Preheating cycles,
- Turbine split-flow cycles,
- Split-expansion cycle.

Despite their unattractive performance, we presented these cycle configurations to various experts, who confirmed our choice to eliminate them for the rest of the process, noting also the possible difficulty of managing supercritical CO_2 during cycle operation, due to the different splits or by-passes of these configurations.

We have therefore selected from the three families of remaining configurations, the best cycles in terms of efficiency and technical constraints on the various components (for example, the boiler, an essential element for flexibility, cannot withstand a low temperature that is too high because the cycle could not withstand too many cold restarts).

The following table summarizes the 6 selected cycle configurations and the main associated technical characteristics.

	Recompression cycles			Partial cooling cycles	Precompression cycles		
Cycle number	**11**	**12**	**13**	**23**	**31**	**32**	**33**
Cycle net eff. (%)	46.08	48.38	48.97	42.77	42.99	45.22	45.72
Rejected Heat at the cooler (MWth)	28.54	26.37	26.02	33.50	32.38	29.94	29.54
Min boiler inlet temp. (°C)	439.3	514.6	541.2	467.7	453.9	528.0	555.4
Boiler eff. (%)	88,5	84,3	82,9	86,9	87,7	83,6	82,1
Total CO_2 mass flow (kg/s)	239.5	221.6	217.6	200.1	279.4	264.4	260.6

ANALYSIS OF CURRENT AND FUTURE FLEXIBILITY CONSTRAINTS

After identifying 6 relevant cycles for the rest of our study, we focused on understanding current and future needs in terms of flexibility from the perspective of the fossil power plant operator. To this end, we have conducted interviews with experts, bibliographies of future regulations and simulations of future operating reports based on scenarios involving more renewable energies and therefore more restrictive for thermal power plant operators in terms of load variations and number of start/stop times.

Load scenario for 2030 (50% of renewable energy):

The EU Reference Scenario is one of the European Commission's key analysis tools in the areas of energy, transport and climate action It allows policy-makers to analyse the long-term economic, energy, climate and transport outlook based on the current policy framework. It is not designed as a forecast of what is likely to happen in the future, but it provides a benchmark against which new policy proposals can be assessed. National experts from all EU countries actively participate in its preparation.

The reference scenario is in phase with the European energy and environmental targets:

- 50% of renewable energy in the electricity mix (of which 27% is wind power),
- + 27% of energy performance.

Based on the EU 2016 reference scenario – energy trend for 2030 (EU REF 2016 - 2030), the European electricity mix has been estimated for 20 European countries in 2030. According to this estimation, 11 countries will still have coal-power plant production in 2030: Austria, Czech Republic, Finland, Germany, Hungary, Ireland, Italy, Netherland, Poland, Slovakia and Spain.

Next table summarizes the main figures about coal-power plant production estimation.

Table 4: EU coal fleet figures based on 2030 scenario

COUNTRY	NUMBER OF UNIT (COAL)	NUMBER OF START-UPS PER UNIT PER YEAR (AVERAGE)
Germany	20	25
Czech Rep.	18	19
Poland	13	27
Italy	6	26
Netherland	4	36
Finland	3	36
Austria	2	32
Spain	2	56
Ireland	2	57
Hungary	1	67
Slovakia	1	82

To identify the partial load operating share, we used public scenarios as well as prospective scenarios from network operators.

The following figure shows the evolution of the number of starts and part-load operation.

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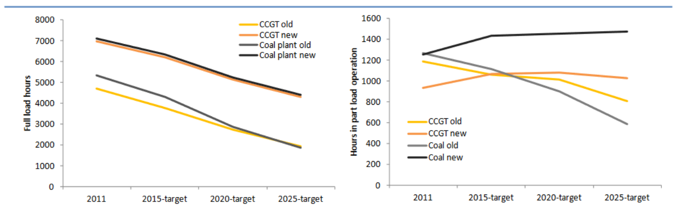

Source: IEA analysis.

Figure 8: Annual full load hours (left) and part-load operation time (right) for benchmark power plants under increasing RES shares (source: IEA analysis, 2014) (cf Annex)

The figure clearly shows that the main impact will be that both old and new fossil plants will reduce their full load operation in the future; in terms of part load, while old plants will again reduce their operation as they will not be able to compete due to low efficiencies, new ones with better flexibility performances will still be able to participate to the market increasing their part load operation, the price to pay being an increased number of startup/stops.

For sCO$_2$-Flex purposes, a single unit yearly operation profile is chosen, to be used as a reference for the simulations aiming at assessing the cycle's capability to cope with future grid needs as well as the relevant efficiency figures (see Figure 8):

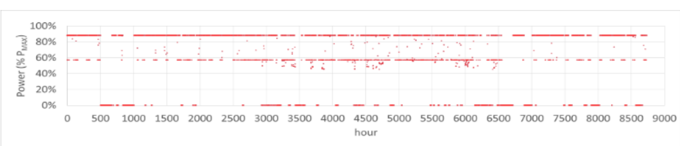

Figure 9: 2030 Reference Plant operation (cf Annex)

The chart is normalized on maximum power (P_{MAX}); the plant is supposed to participate to grid regulation, therefore a 12% power bandwidth is dedicated to such operation on both top and bottom ends of the operational power range: therefore the actual power never exceeds 88% P_{MAX} and seldom drops below 57% (minimum power being set at 45% P_{MAX}).

Such Reference Plant undergoes around 70 start-stop cycles, mostly hot and warm ones, meaning that the stops mainly last less than 48 hours.

Flexibility constraints

For this part of our study, the French Q600 power stations have been used as the reference for what has been defined as "most commonly used coal plants"; this may not be totally fair in terms of representativeness (average figures would probably be a better choice), nevertheless it allows to describe a real plant and to provide real and more coherent figures, resulting in more meaningful information.

The Q600 main parameters describing their capabilities in terms of flexibility (as it has been defined in the previous paragraphs) are listed in the table below:

Table 4: Q600 flexibility performances

PARAMETER	VALUE
Net continuous power output:	580 MW
Minimum continuous load:	280 MW
Load variation ramp:	+5 / -7 MW/min (+8% / -12% PNet)
Start-up time:	Cold start-up: 13h Warm start-up: 9h Hot start-up: 4.5h
Minimum up time after start-up:	8h
Primary Reserve power:	+ 40 MW @max power + 20 / -12 MW @min power
Secondary Reserve power:	± 60 MW @max power ± 20 MW @min power

In addition to the already mentioned minimum load, load ramp and start-up time, a few further parameters in Table 4 allow to have a better picture relevant to Q600 operational constraints:

- The minimum required time between two consecutive events of connection and disconnection from the grid (which results from the need to assure a proper sweeping of the combustion chamber and of the air preheaters);
- The allowances for primary and secondary regulation, which must be kept available for grid balancing (and which are paid for accordingly by the TSO).

For our question, load variation ramps and stop/start times are the important points that will allow us to determine if a supercritical CO2 cycle can be more flexible than a conventional cycle. We have therefore tried to understand which elements of the cycle (component, operation,...) have an influence on these points.

In a conventional cycle, the start-up description is relevant to cold conditions; depending on the down time, some elements like the feed-water tank and the boiler have to be re-filled or not. All the heat exchangers (preheaters, superheaters and reheaters) are isolated and the turbine is under vacuum.

The first step is to restart the plant cooling loop, then to be sure of the water level inside the feed-water tank, needed to compensate for the water losses linked to the activation of the extraction pumps. The condenser is then put under vacuum and water circulates in the loop in order to be properly de-aerated, before starting to heat up. The boiler as well is filled with water, and some constraints must be taken into account during the heating process, in order to limit thermal stresses on the materials and components. In this phase the heat source is the auxiliary steam which comes either from an auxiliary boiler or from other sources available on site.

Before firing the boiler, some time is needed to rinse the inside of the tubes and sweep the outside (air side), in order to get rid of any particle which could have been left from the previous shut down; after that the burners are put in operation

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and the boiler is fired; at first with auxiliary oil burners, then progressively by means of pulverized coal. The system is heated up again with some temperature rate constraints, while the turbine is being bypassed; the electric feed pumps are replaced by turbo pumps and the de-nitrification systems is activated.

When the proper steam grade is reached, the turbine inlet valve is opened and the turbine is progressively accelerated and heated.

The acceleration process consists in a sequence of speed increase at specific rates followed by short periods at constant speed in order to evenly heat up all the turbine elements and to eliminate all possible eccentricity issues. Furthermore, specific constraints on the temperature difference between steam and turbine organs are there, in order to avoid uneven thermal expansions, resulting in material stresses (or even in contacts between the rotor and the stator) as well as steam condensation on metal surfaces, generating water droplets which can be a cause of mechanical stress on the blades.

Once the turbine speed is stable at 3000 rpm and all the relevant parameters are ok, the alternator can be coupled with the grid, applying from the beginning some tenths of megawatts (normally 40) to avoid that any power flashback causes a grid disconnection.

In conclusion, both boiler and turbine of current coal power plants require time-consuming procedures during start-up in order to limit stress on these components (which could impact their residual lifetime). Considering the new sCO2 cycle, which is the purpose of this project, some hypotheses can be made at general level, which will be further analysed in the future deliverables once the cycle architecture and the equipment are designed:

- sCO2 boiler: most of the current coal-boiler constraints are expected to be still with new sCO2 Boiler technologies, the only difference being the working fluid (the combustion should still be the same and the global geometry is not expected to be completely different from current technologies);
- sCO2 turbine: it is expected to be much more compact than current steam turbines, therefore, problems related to thermal expansion will be different: the reduced dimensions of the equipment are likely to limit the differential expansion, but at the same time they cause an increased impact of leakage losses on turbine efficiency, which may lead to a reduced "rotor-stator" spacing, resulting in stricter tolerances in terms of differential expansion.

FINAL SELECTION OF CYCLES

On the basis of cycle modelling and our analysis of flexibility requirements, we therefore presented the 6 cycle configurations to experts in boilers, turbomachines, heat exchangers and thermal cycle operation to ask them to identify the 2 most relevant cycles to keep for the rest of the work of the sCO_2-Flex project. Their conclusions are as follows:

Constraints related to the project sCO_2-Flex objectives

- Performance

Regarding the performance constraint, the selection turns towards the most efficient cycles (family 1: recompression cycles). Cycle efficiency highly depends on its regenerative rate: highly regenerative cycles allow for high amount of recovered heat in the recuperators, thus requiring less heat input in the boiler for the same power output, leading to a cycle efficiency increase. A direct consequence is that high efficiency cycles have high CO_2 temperature at the boiler inlet (all other parameters being fixed).

Cycle 13 offers the best expected cycle performances. However, a double reheat cycle is more complex and challenging for the turbomachines; furthermore, CO_2 temperature at the boiler inlet is about 540°C, which is higher than 470°C and not recommended for boiler integrity.

- Flexibility and the control of the cycle

Complex and multipart cycle architectures can be difficult to control and regulate. From this point of view, the most flexible solution would probably have a simple cycle architecture (small number of recirculation loops or components are easier to control and regulate). However, as explained above, the cycle efficiency highly depends on its architecture (for example: recompression loop is highly recommended to have high cycle performances but it brings additional complexity). A compromise must be found between the cycle performance and the layout simplicity for better flexibility.

Constraints related to the main components

- Boiler

Coal boiler integrity depends on the cooling capacity of the working fluid (CO_2 in our case) to protect the boiler tubes and wall surfaces. The CO_2 temperature in the boiler must be securely and accurately controlled to ensure material protection.

Due to the corrosion problems of the materials, the fact that the heat exchange surfaces may be larger than for a steam boiler, as well as the fact that the temperature management of the sCO2 will not be done in the same way as for a conventional boiler, we have decided to designate a new boiler model, in order to choose the most suitable materials to resist corrosion, put in place the necessary strategies to control the CO2 temperature and integrate as much as possible the pollution control equipment

Our objective will then be to have a new boiler design with similar (or lower) cost and footprint than a conventional boiler.

- Turbomachinery

Concerning the turbomachines, two main aspects can be considered: i) the performance of each turbomachine (isentropic efficiency) and ii) the mechanical issues related to manufacturing process and the regulation/control at part load.

Depending on the cycle architecture, the design of the turbomachines changes (size, rotation speed, number of stages…). In this context changing the cycle architecture involve turbomachine efficiency and geometry variations at fixed power output. Thus, some architecture "families" are more interesting than others from the turbomachines point of view.

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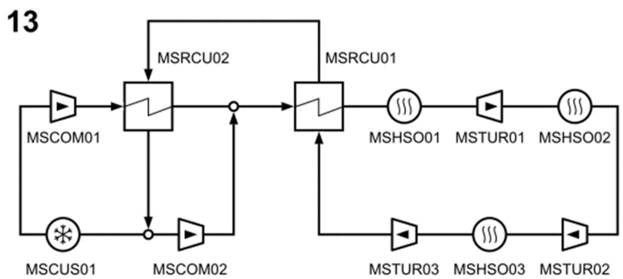
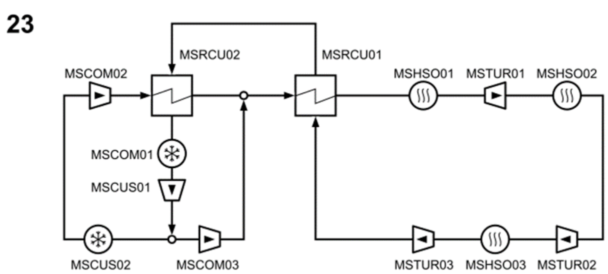
From the mechanical and manufacturing point of view, the most suitable group of cycle configuration is the "family" n°3, followed by the number n°2 and finally, the n°1 which represent complex turbomachines due to CO_2 temperature, pressure and flow rate conditions. It can be observed that this ranking is not favourable for the performance of the cycle. Here also, a compromise must be found between these two constraints

Finally, regarding all specified criteria, the 3 selected cycles for the next step of sCO_2-Flex project are the following:

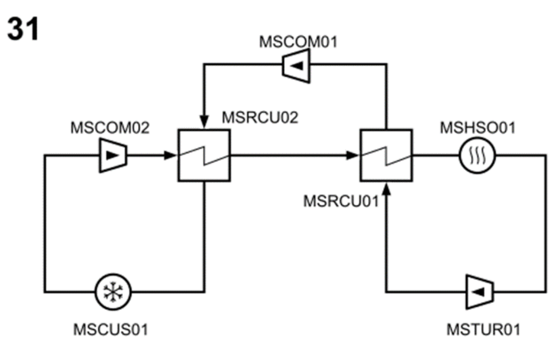
• Cycle 13 for cycle performance



• Cycle 23 for both boiler integrity and turbomachines (good turbomachine performances).



• Cycle 31 for simplicity, turbomachines and boiler integrity.



CONCLUSION

Our main objective for this study was to find several configurations of supercritical CO_2 cycles that would offer a compromise between performance and flexibility. One of our main difficulties was to succeed in breaking free from the habits associated with conventional steam and water cycles. To do this, we first identified and modelled 21 cycle configurations, based on the scientific literature and our first work on supercritical CO_2 cycles. From the results of this step, we sought to determine what would be the main constraints related to flexibility with this type of cycle (constraints different from those known for water/steam cycles). We conducted a sensitivity analysis on the main influential parameters to determine their real impact. Then, based on several scenarios anticipating a strong increase in renewable energies in the European landscape (50% of electricity production), we established new annual reports on the operation of thermal power plants in order to establish hypotheses on load variations and the number of power plant shutdowns and start-ups.

Once all the results and assumptions were available, we were able to choose 3 interesting configurations for our project with operating and component experts.

During the rest of our project, we will work to optimize the most interesting configuration for both flexibility and performance. The selection among the 3 configurations will be made according to the developments of the turbomachines, exchangers, boiler as well as the optimization of the control-command.

NOMENCLATURE

HEX: Heat Exchanger
HTR: High temperature recuperator
LTR: Low temperature recuperator
MSCUSXX: Heat sinks of the cycle n°XX
MSHSOXX: Heat sources (heaters) of the cycle n°XX
MSCOMXX: Compressor of the cycle n°XX
MSTURXX: Turbine of the cycle n°XX
MSRCUXX: Recuperator of the cycle n°XX
TSO: Transmission System Operator
PR: Primary Regulation
SR: Secondary Regulation

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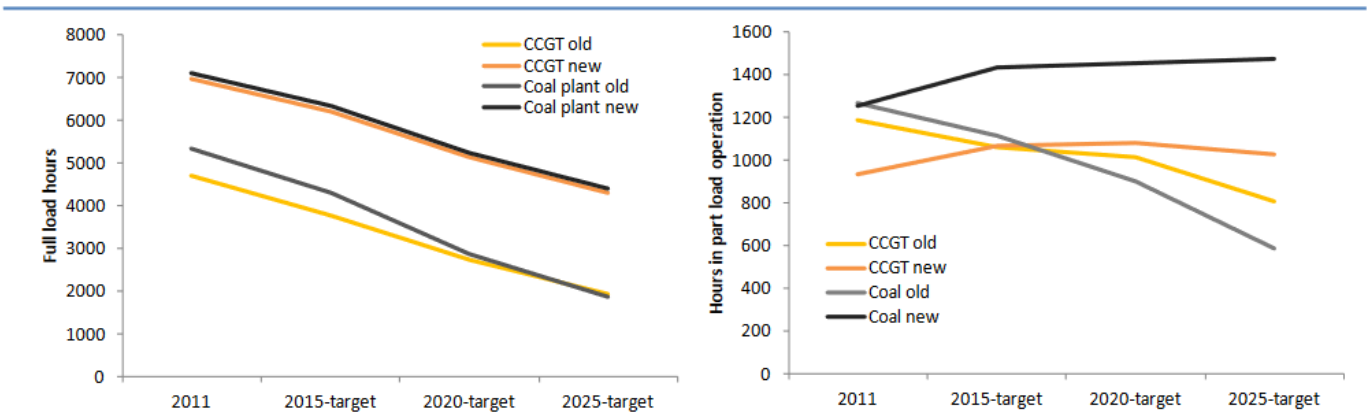
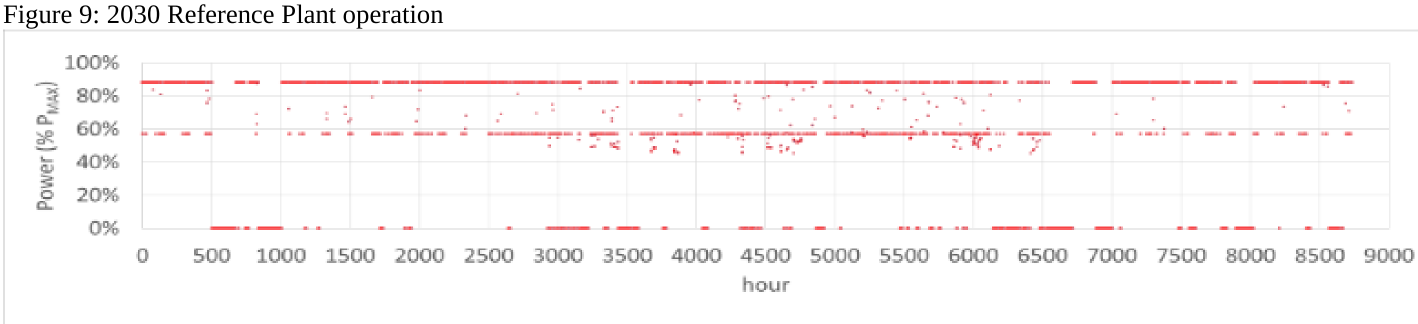
ANNEX

Figure 8: Annual full load hours (left) and part-load operation time (right) for benchmark power plants under increasing RES shares (source: IEA analysis, 2014)



Source: IEA analysis.

Figure 9: 2030 Reference Plant operation



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