D1.3 – Report on the selected cycle architecture

August 2018

WP 1, T 1.3

Authors: Mounir MECHERI and Stefano BEDOGNI

sCO2-Flex

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Technical References

Project Acronym	sCO_2-Flex
Project Title	Supercritical CO_2 Cycle for Flexible and Sustainable Support to the Electricity System
Project Coordination	Albannie Cagnac sCO_2-flex Project Coordinator Email: albannie.cagnac-1@edf.fr Tel: +33 (0)1 30 87 86 64
Project Duration	January 2018 – December 2020 (36 months)

Deliverable No.	1.3
Dissemination level [1]	PU
Work Package	1
Task	1.3
Lead beneficiary	EDF
Contributing beneficiary(ies)	POLIMI, CV REZ, UJV, GE, UDE, USTUTT, FIVES Cryo
Due date of deliverable	31/08/2018
Actual submission date	

[1] PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Document history

V	Date	Beneficiary	Author
1	2018/--/--	EDF	Mounir MECHERI & Stefano BEDOGNI
2	2018/08/28	EDF	Albannie CAGNAC (Review)
3.1			
3.2			

Summary

This deliverable summarizes the results of the task 1.3 entitled “Report on the selected cycle architecture”. The deliverable D1.1 gives thermodynamic performance analysis of 21 cycle architectures. It is not possible to provide entire cycle design for all of them.

The aim of this document is then to select 3 cycle architectures among the 21 analysed configurations regarding 3 main criteria such as i) cycle performance, ii) boiler integration/integrity and iii) cycle simplicity/feasibility (manufacturing constraints, flexibility, control and regulation). This selection enables the partners to focus on the design of a specific and reduced number of cycle architectures. Finally, this report provides the heat and mass balance tables for these selected cycles.

Furthermore, additional information given regarding the forecasted and expected coal power plant operating conditions in 2030 to complete the deliverable D1.2. These data are required for component design and dynamic simulations (part load, cycling, start and stop).

The results of this deliverable will be used as “inlet data” for the next steps of the project.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 764690.

Disclaimer

Any dissemination of results must indicate that it reflects only the author's view and that the Agency and the European Commission are not responsible for any use that may be made of the information it contains.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

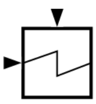
Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Nomenclature

Symbol	Description	Unit
sCO_2	Supercritical CO_2	-
WP	Work package(s)	-
T	Temperature	°C
P	Pressure	MPa
D	Heat duty	MWth
E	Electrical power	MWe
M	CO_2 Mass flow	kg/s
EFF	Efficiency	%
HTR	High temperature recuperator	-
LTR	Low temperature recuperator	-
H. Ex	Heat Exchanger(s)	-
XX	Double digit number	-

Acronym	Partner
POLIMI	Politecnico di Milano
BHGE	Baker Hughes General Electric
EDF	Electricité de France

Symbol	Type	Labelling
	Heat sinks	MSCUSXX
	Heat sources (heaters)	MSHSOXX
	Compressor	MSCOMXX
	Turbine	MSTURXX
 or 	Recuperator	MSRCUXX

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Context

The global objective of the sCO_2-Flex European project is to design a 25 MWe Brayton cycle working with supercritical CO_2 (sCO_2). Many configurations of the sCO_2 cycle can be considered for coal application and the cycle architecture is not fixed at the beginning of the project.

Because it is not possible to design the cycle components for all these configurations (time-consuming), the project must focus on a reduced number of cycle architectures among the several available configurations, avoiding the risk of precluding the most convenient cycle layout for the project.

Thus, preliminarily to this selection, a global screening and performance assessment of the most interesting cycle architectures regarding the project framework has been completed on 21 cycle architectures in the deliverable D1.1. Such number needs to be reduced to 3 cycle architectures for the next steps of the project.

This document is explaining how these 3 cycle architectures are selected.

The results of this deliverable will be used as “inlet data” for the next steps of the project.

Objectives

The main objective of this study is to select 3 cycle architectures among the 21 studied in the D1.1.

Also, additional data regarding the forecasted and expected coal power plant operating conditions in 2030 to complete the deliverable D1.2.

Summary of D1.1.

The cycle “numbering” of analysed architectures is specific to this study: it contains two digits (#XX), the first one indicating the “base form” or the “family” of the analysed architecture and the second digit corresponding to “additional cycle modifications” applied to the “base form”.

For examples, cycle #11 belongs to the recompression cycle “base form” (or family) without any additional modification, while cycle #12 also belongs to the recompression cycle “family” but with one reheat, etc. (see Table 1).

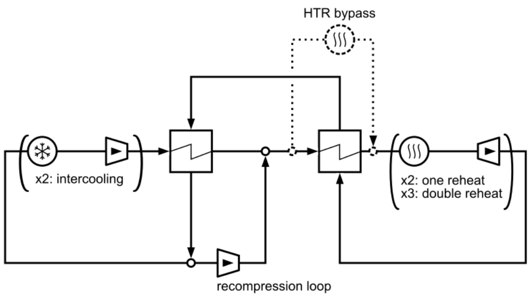
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 764690.

Table 1: List of analyzed cycle architectures in the deliverable D1.1.

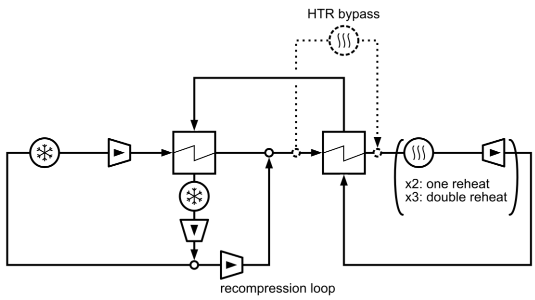
Base form (family)	Additional modification	Cycle Number	Cycle net efficiency (%)
1 - Recompression cycle	-	11	42.28
	One reheat	12	43.81
	Double reheat	13	44.95
	One intercooling	14	42.69
	Intercooling + reheat	15	43.05
	HTR bypass	16	42.34
2 - Partial cooling cycle	-	21	40.08
	One reheat	22	42.12
	Double reheat	23	44.41
	HTR bypass	24	40.29
3 - Pre-compression cycle	-	31	38.81
	One reheat	32	40.89
	Double reheat	33	41.69
	HTR bypass	34	38.89
4 - Turbine split-flow cycle	-	41	35.45
	One reheat	42	28.69
	LTR bypass	43	35.48
5 - Preheating cycle	-	51	37.29
	One reheat	52	38.45
	Double reheat	53	40.18
6 - Split-expansion cycle	-	61	33.17

Figure 1: simplified process flow diagrams of architectures' "base form"

1- Recompression cycles



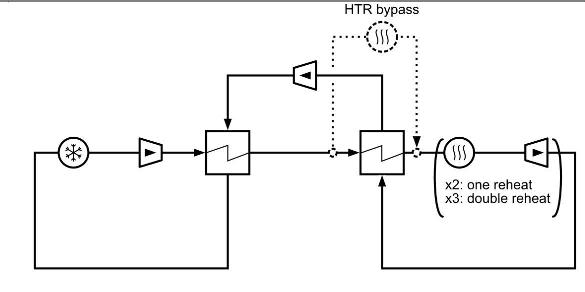
2- Partial cooling cycles

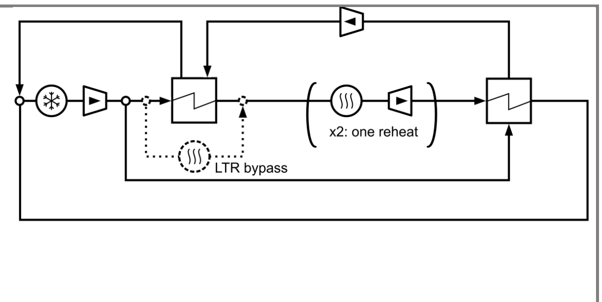


3- Pre-compression cycles

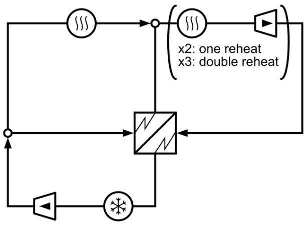
4- Turbine split-flow cycles

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

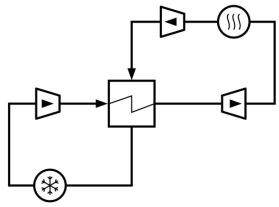




5- Preheating cycles



6- Split-expansion cycles



Methodology

This section describes the methodology used to select 3 cycles architectures among the 21 cycles proposed in the D1.1. (see Table 1 above).

Based on deliverables D1.1, D1.2 and partners' experiences, the selection of 3 cycle architectures is done regarding 3 criteria: 1) cycle performance, 2) boiler integration and integrity, 3) cycle flexibility (simplicity, regulation and control). Indeed, each of these criteria create constraints that need to be considered: for example, each cycle architecture has an impact on the design of the main components (some architectures require components that are more difficult to manufacture or to control and regulate than in other cases). In cases where an entire cycle family proves to be fit for a specific criteria, the choice of a single cycle within the family is indeed made based on a trade-off of its behavior concerning all the other defined constraints (see for example paragraphs 1.2, 2.1 and 2.2).

This section describes the main constraints imposed by the boiler and the turbomachines, and how cycle architecture can respect these constraints while keeping our objective of having a flexible and efficient thermodynamic cycle.

Cycle selection

They are two kind of constraints to select the cycle configuration: i) constraints concerning sCO_2-Flex project objectives and ii) constraints related to cycle component limitations.

1. Constraints related to the project sCO_2-Flex objectives

The main objective of the sCO_2-Flex project is to design an efficient and flexible Brayton thermodynamic cycle that is working with supercritical CO_2.

1.1. 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 (close to 45%, while the alternatives in family 1 all have lower than 44% cycle efficiency). 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 (see below, paragraph 2.1).

1.2. Flexibility and the control of the cycle

sCO_2-Flex project aims at designing a flexible power plant. 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.

Cycle architectures offering the simplest layout are families 3, 5 and 6 (respectively Pre-compression cycles, Preheating cycles and Split-expansion cycles). Due to very low performance, cycle family number 6 is not considered.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

2. Constraints related to the main components

2.1. Boiler related constraints

Coal boiler integrity depends on the cooling capacity of the working fluid (CO_2 in this case) to protect the boiler tubes and wall surfaces. When water is used as working fluid, the material protection is guaranteed by the evaporation of water which is done at constant temperature for a given pressure value. However, when CO_2 is used as working fluid in the Brayton cycle, there is no phase change and CO_2 temperature rises in the boiler, which is impacting the boiler integrity if CO_2 exceeds the material temperature upper limit. That is why CO_2 temperature in the boiler must be securely and accurately controlled to ensure material protection.

Furthermore, boiler efficiency is linked to the amount of recovered heat from the combustion at any temperature level. If CO_2 enters the boiler at high temperature (i.e. above 400°C), the available “low temperature” heat from the combustion cannot be recovered, reducing boiler efficiency, and eventually, global power plant efficiency. In this context, the recommended maximal CO_2 temperature at the boiler inlet is 470°C.

However, as seen in the previous section, efficient cycles have high regenerative rate, and thus, high CO_2 temperature at the boiler inlet. A compromise must then be found between cycle and boiler efficiency improvement.

They are two ways to reduce CO_2 temperature at the boiler inlet: i) by reducing the “compression heating effect” by using intercooled compression, ii) by bypassing the High Temperature Recuperator (HTR) which is heating CO_2 to high temperature just before the boiler.

In this context, partial cooling cycles (family 2) offer lower CO_2 temperature at the boiler inlet. For example, partial cooling cycle with two reheats (cycle #23) has a boiler CO_2 inlet temperature of about 482°C while recompression cycle with two reheats (cycle #13) CO_2 temperature at the boiler inlet is about 540°C.

Also, all cycles that bypass, or do not have, HTR enable to reduce CO_2 temperature at the boiler inlet. For example, families 4, 5 and 6 (respectively Turbine split-flow cycles, Preheating cycles and Split-expansion cycles) as well as “HTR bypass” configurations have lower boiler inlet CO_2 temperature than the reference cycle #11.

From the boiler integrity point of view, families 2, 4, 5 and 6 as well as “HTR” bypass configurations of families 1 and 3 can be favorable. However, families 4 and 6 are eliminated from selection because of very low cycle efficiency. Finally, cycles #23 and #33 are considered.

2.2. Turbomachines related constraints

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.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 764690.

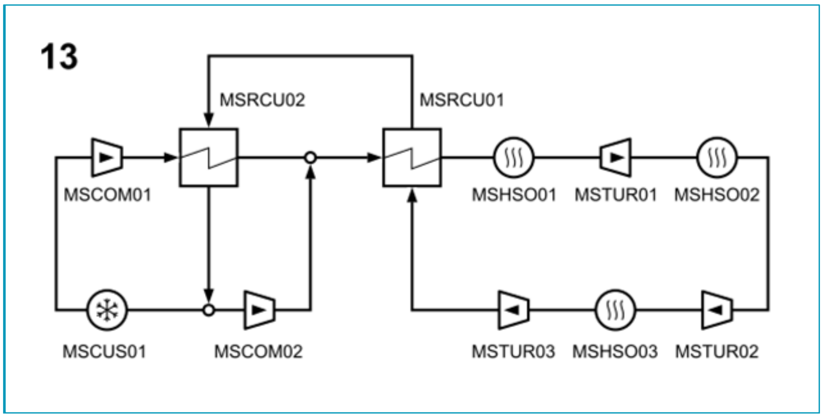
From the mechanical and manufacturing point of view, the most suitable group of cycle configuration is the "family" n°3, followed by the number n°2 and finally, the n°1 which represent complex turbomachines due to CO_2 temperature, pressure and flow rate conditions. It can be observed that this ranking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

Cycle families 3 and 2 are considered from the turbomachines point of view

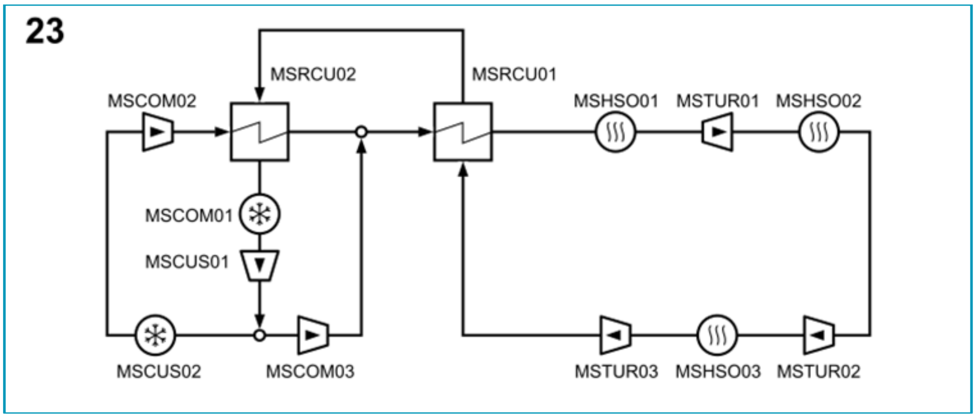
3. Conclusion about cycle selection

Finally, regarding all specified criteria, the 3 selected cycles for the next step of sCO2-Flex project are the following:

- Cycle #13 for cycle performance

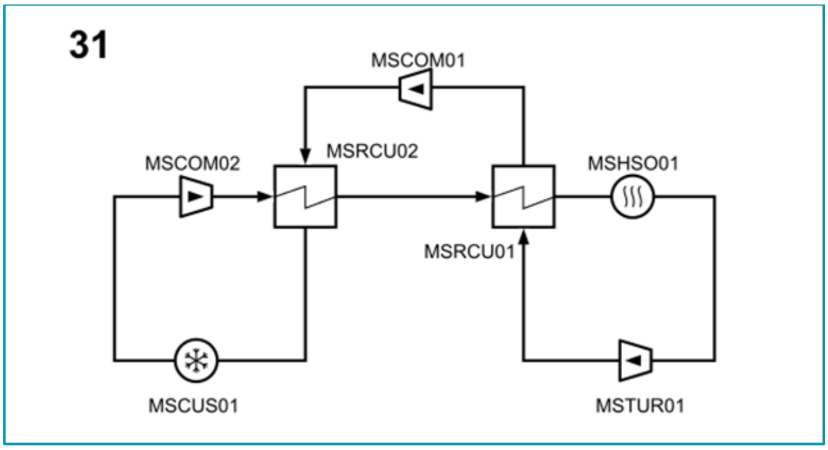


- Cycle #23 for both boiler integrity and turbomachines (good turbomachine performances).



- Cycle 31 for simplicity, turbomachines and boiler integrity.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.



Detailed "heat and mass balance" tables and process flow diagrams (PFD) of these selected cycles are given in appendixes.

Next table is summarizing the advantages and drawbacks of each selected cycle regarding cycle performance, the turbomachinery and boiler integrity, the expected flexibility, the size of recuperators and the CO_2 mass flow rate.

Table 2: Estimation of impact of selected cycles on several parameters

Cycle number →	#13	#23	#31
Performance	++	+	-
Turbomachinery	-	+	++
Boiler	-	+	++
Flexibility	+	-	++
Recuperators	-	+	-
CO_2 flow rate	-	+	-

The recompression cycle with two reheats (#13) has the best cycle performance but is expected to bring difficulties for the turbomachines design and manufacturing. Also, due to high temperature at the low pressure turbine outlet, the High Temperature recuperator (HTR) operates at high CO_2 temperature (which requires high grade materials) and leads to high CO_2 temperature at the boiler inlet (~540°C) which is unfavourable for the boiler. Furthermore, the relatively high CO_2 mass flow value (~243 kg/s) can also be seen as a negative aspect for the cycle. The high cycle efficiency (good cycle heat recovery) implies the use of large recuperators.

The partial cooling cycle with two reheats (#23) is mitigating the negative aspects of the cycle #13 while insuring rather good cycle performance. Indeed, it has lower CO_2 temperature at the boiler inlet (~482°C) and requires a lower CO_2 mass flow (~190 kg/s), resulting in better boiler integrity and smaller recuperators. Also, the turbomachines have slightly better

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

performances. However, this cycle has 3 compressors and 3 turbines which can be difficult to regulate and optimize.

Compared to other selected cycles, the pre-compression cycle (#31) is simpler (no recompression loop and only one compressor and one turbine), convenient for turbomachinery (performance and design/manufacture) and has a lower CO_2 temperature at the boiler inlet (~459°C). Furthermore, there is less pressure stresses in the Low Temperature Recuperator (LTR) since the main compressor is located before the LTR hot stream inlet (which is not the case for cycles #13 and #23). However, this cycle suffers from lower performances (absence of recompression loop) and requires a high CO_2 mass flow (~318 kg/s) which is unfavourable for the recuperators.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Load scenarios for 2030 and regulation services

This section provides additional information regarding the deliverable D1.2. In this context, more data about future expected flexibility requirements and regulation rules are given below.

1. 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” [1].

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 3: EU coal fleet figures based on 2030 scenario

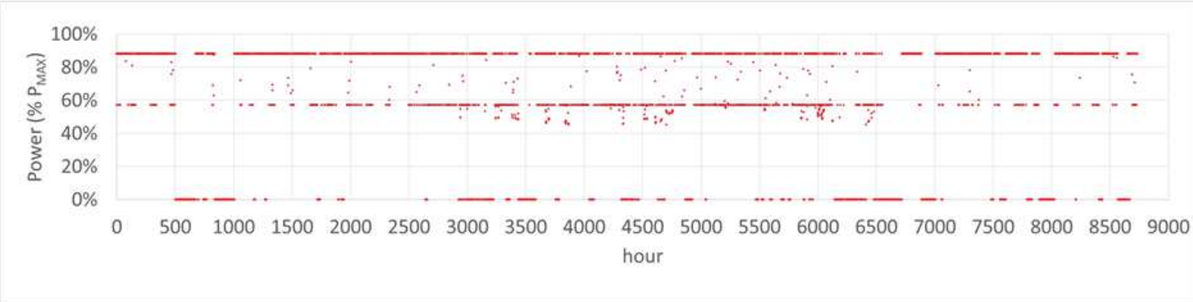
Country	Number of unit (coal)	Number of start-ups per unit per year (average)
Germany	20	25
Czech Rep.	18	19
Poland	13	27
Italy	6	26
Netherland	4	36
Finland	3	36
Austria	2	32
Spain	2	56
Ireland	2	57
Hungary	1	67
Slovakia	1	82

[1] EU Reference Scenario 2016 https://ec.europa.eu/energy/en/data-analysis/energy-modelling [accessed online August 2018]

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 764690.

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 2):

Figure 2: 2030 Reference Plant operation



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.

2. Regulation rules and grid requirements

This section summarizes the grid requirements for those power plants playing a role in network regulation. The network code relevant to grid connection of generators is country specific, but it is somewhat harmonized around Europe as it shall comply with the Commission Regulation. For the sCO_2-Flex project needs, a summary of such requirements relevant to Italy and France is provided, to have an idea of the little differences in figures which are imposed by each national TSO, while remaining in the range defined by the EU Commission.

2.1. Primary Regulation

For eligible plants (Maximum power >10MW, except for RES plants), Primary Regulation (PR) is mandatory and automatic. Operational requirements for participating to PR:

1. Speed measurement accuracy > 0.02% in every operating condition;
2. **Frequency Response Deadband**[2] not greater than ± 10 mHz;
3. Capability to operate the plant continuously with any **droop**[3] grade between 2% and 8% (*6% for France*), for any frequency between 47.5 and 51.5 Hz;

[2] Frequency Response Deadband is an interval used intentionally to make the frequency control unresponsive.

[3] Droop (σ_P) = it is the ratio of a steady-state change of frequency to the resulting steady-state change in active power output, expressed in percentage terms. The change in

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

A 1.5% (*2.5% in France*) of plant nominal power must be dedicated to PR when running at maximum or minimum power (i.e. the actual plant operating bandwidth is reduced at the top and bottom ends by 3% (*5% in France*) nominal power overall).

When running at a power level ranging inside the operating bandwidth, primary regulation requirements change based on actual grid frequency: a distinction is made between Normal Conditions (i.e. frequency included in a ± 100 mHz range around the nominal 50 Hz) and Emergency Conditions (i.e. frequency ranging between 47.5 and 51.5 Hz).

In Normal Conditions, the plant shall provide a Primary Reserve Bandwidth (ΔP_e) proportional to the frequency variation (Δf) and the droop (σ_P) imposed by the Transmission System Operator (TSO), as it follows:

$$\Delta P_e = -\frac{\Delta f}{50} \times \frac{P_{eff}}{\sigma_P} \times 100$$

Where P_{eff} is the nominal power.

Terna, the Italian TSO, requires that, for a power plant speed regulator:

- Droop grade be set to 5%;
- Frequency Response Deadband be smaller than ± 10 mHz (± 20 mHz for CCGTs).

So defined ΔP_e shall be provided in 30 seconds overall, with at least half of it provided in 15 seconds.

In Emergency Conditions, with higher frequency deviation, the same relation between Δf and ΔP_e as in normal conditions apply, until reaching plant operational limits in terms of maximum or minimum power; such power variation shall be provided with the maximum tolerable gradient, a figure which is certified by the plant owner to the TSO by means of type tests.

Both in Normal and Emergency Conditions, once the required power output is achieved the Unit shall maintain such output for at least 15 consecutive minutes.

In France, ΔP_e shall be integrally released for a frequency variation of ± 200 mHz; as for Italy, such power variation must be provided in 30 seconds overall, with at least half of it in 15 seconds, and continuously maintained for at least 15 minutes.

---

frequency is expressed as a ratio to nominal frequency and the change in active power expressed as a ratio to maximum capacity or actual active power at the moment the relevant threshold is reached. $\sigma_P = -\frac{\Delta f}{50} \times \frac{P_{eff}}{\Delta P_e} \times 100$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

2.2. Secondary Regulation

The Secondary Regulation (SR) is managed by the speed regulator of a power plant on the basis of the acquisition and elaboration of an input signal by the TSO. The power plant control system shall be able to translate such a signal into a load variation going from 0 to 100% of the available Secondary Reserve (50% = no power variation, 100% = full positive half bandwidth, 0% = full negative half bandwidth).

The Secondary Reserve bandwidth is calculated as the maximum variation of the power plant output in 200 seconds (some examples of ramp speed, from actual power plants: CCGTs are at around 50 MW/min, while coal plants can provide at least 20-30 MW/min), and such power block defines the power level that can be offered to the regulation market.

Secondary Reserve shall be provided continuously for at least 2 hours' time.

In France, 4.5% of PR bandwidth shall be dedicated to SR; it shall be possible to ramp from one end of the bandwidth to the other in 800 seconds (normal ramp) or 133 (max ramp); such figures are being revised and may be soon modified for European harmonization.

2.3. Profile management of the power plant production

The final production schedule is the result of the different markets' outcomes (Day Ahead, Intraday and Ancillary Services Markets), where the plant owner offers the plant production and services, and the TSO adjustments on single plant production programs based on the grid needs; in terms of program granularity and grid constraints, it goes as it follows:

- The plant owner offers on the day-ahead market on hourly based blocks; the resulting schedule, depending on which offers have been accepted, is made of step variations;
- At the end of all market sessions (except for real-time adjustments), the TSO splits the production program into quarter hours and smooths the steps according to the power plant's typical ramps, as declared by the plant owner on the relevant register for generation units. Also in case of schedule modifications required by the TSO due to any possible grid stability need, such deviations are made once again taking into account the plant flexibility figures. As a specific example, Italian's TSO Terna manages a single minute granularity dispatching programs, but the final energy balance for the plant owner is made on a quarter hour basis, thus providing some flexibility to the plant regulation system.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Conclusions

The main objective of this report is to select 3 cycle architectures (among the 21 proposed in deliverable D1.1). These selected architectures are:

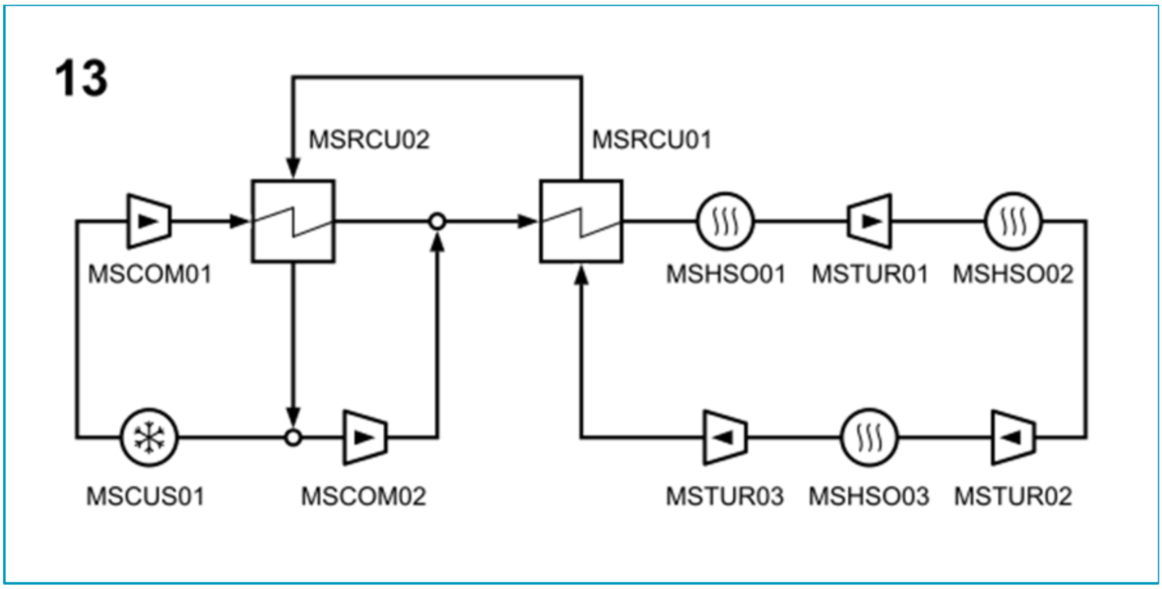
- Cycle #13 for cycle performance
- Cycle #23 for both boiler integrity and turbomachines (good turbomachine performances).
- Cycle 31 for simplicity, turbomachines and boiler integrity.

Their impacts on important parameters for the sCO_2-Flex project have been assessed and are summarized in the next table:

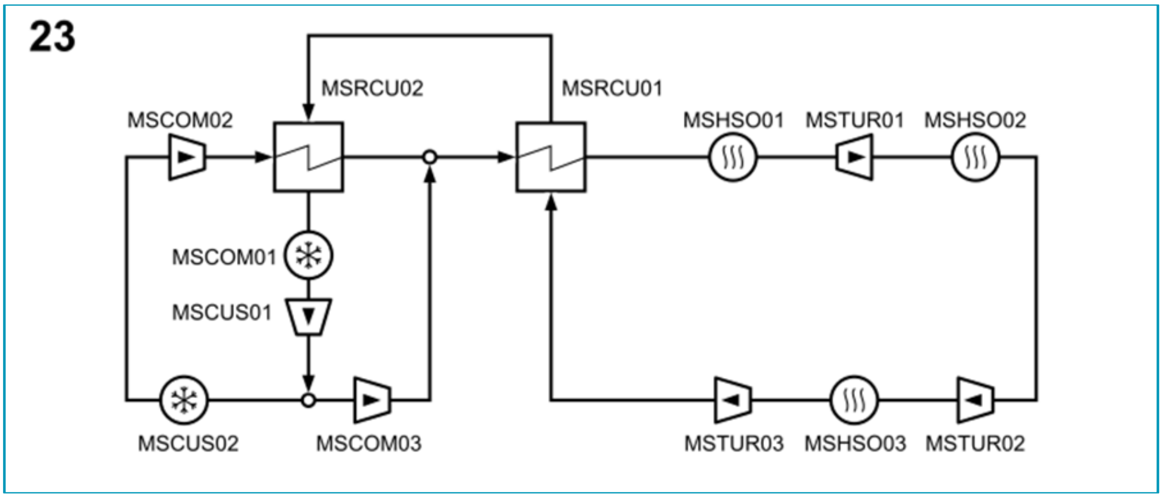
Cycle number →	#13	#23	#31
Performance	++	+	-
Turbomachinery	-	+	++
Boiler	-	+	++
Flexibility	+	-	++
Recuperators	-	+	-
CO_2 flow rate	-	+	-

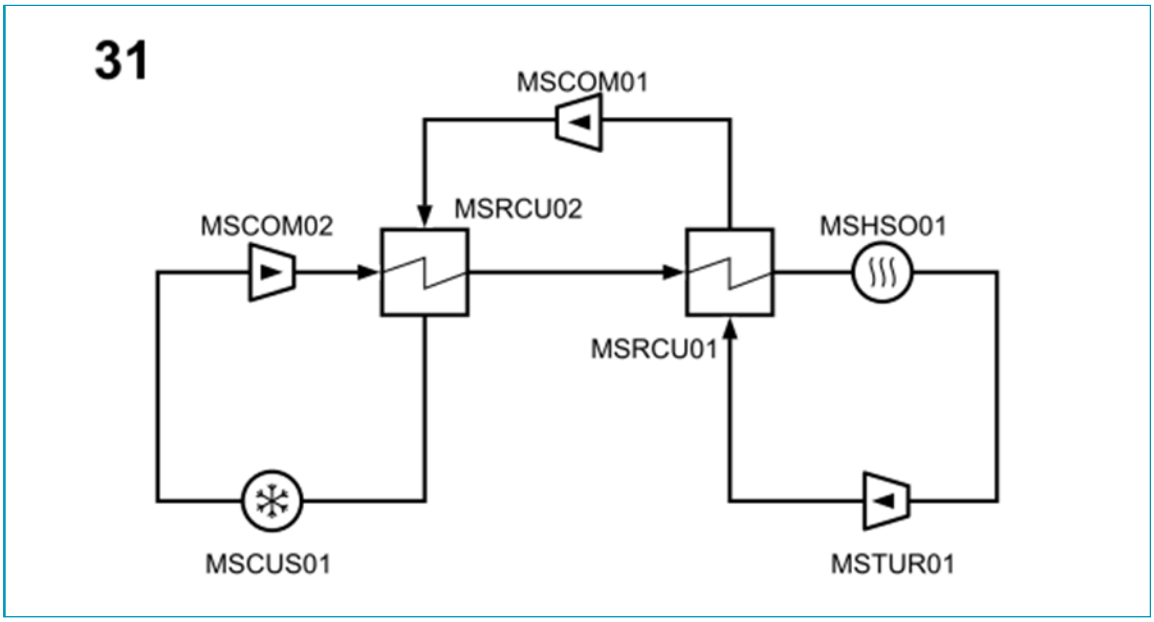
Appendix

A. Process flow diagrams



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.





This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

B. Heat and mass balance

Component	Parameter	Unit	13	23	31
MSCUS01 (cooler)	T1	°C	79.6	78.1	61.0
	P1	MPa	8.016	5.742	11.841
	T2	°C	33.0	33.0	33.0
	P2	MPa	7.979	5.713	11.781
	D	MWth	28.84	12.56	37.26
	M1	kg/s	156.1	189.3	317.6
MSCUS02 (cooler)	T1	°C	-	62.0	-
	P1	MPa	-	8.10	-
	T2	°C	-	33.0	-
	P2	MPa	-	8.06	-
	D	MWe	-	16.85	-
	M1	kg/s	-	107.3	-
MSCOM01 (compressor)	T1	°C	33.0	33.0	200.8
	P1	MPa	7.979	5.713	9.055
	T2	°C	69.6	62.0	233.5
	P2	MPa	25	8.10	11.9
	E	MWe	4.86	3.31	9.57
	M1	kg/s	156.1	189.3	317.6
MSCOM02 (compressor)	T1	°C	79.6	33.0	33.0
	P1	MPa	8.016	8.06	11.781
	T2	°C	192.2	68.1	51.0
	P2	MPa	24.875	25.0	25.0
	E	MWe	7.29	3.28	6.93
	M1	kg/s	87.1	107.3	317.6
MSCOM03 (compressor)	T1	°C	-	62.0	-
	P1	MPa	-	8.10	-
	T2	°C	-	169.4	-
	P2	MPa	-	24.875	-
	E	MWe	-	6.45	-
	M1	kg/s	-	82.0	-
MSRCU01 (HTR)	T1	°C	587.9	541.4	500.9
	P1	MPa	8.10	5.80	9.10
	T2	°C	202.2	179.5	300.8
	P2	MPa	8.060	5.771	9.055
	T3	°C	192.2	169.5	190.7
	P3	MPa	24.875	24.875	24.875
	T4	°C	540.5	482.4	458.4
	P4	MPa	24.750	24.750	24.750

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Component	Parameter	Unit	13	23	31
	D	MWth	109.1	75.02	110.52
	M1	kg/s	243.2	189.3	317.6
	M3	kg/s	243.2	189.3	317.6
MSRCU02 (LTR)	T1	°C	202.2	179.5	233.5
	P1	MPa	8.06	5.771	11.9
	T2	°C	79.6	78.1	61.0
	P2	MPa	8.016	5.742	11.841
	T3	°C	69.6	68.1	51.0
	P3	MPa	25	25.0	25.0
	T4	°C	192.2	169.5	190.7
	P4	MPa	24.875	24.875	24.875
	D	MWth	36.74	22.54	86.92
	M1	kg/s	217.6	189.3	317.6
	M3	kg/s	156.1	107.3	317.6
MSHSO01 (heater)	T1	°C	540.5	482.4	458.4
	P1	MPa	24.750	24.750	24.750
	T2	°C	620.0	620.0	620.0
	P2	MPa	24.55	24.55	24.50
	D	MWth	24.33	32.68	64.36
	M1	kg/s	243.2	189.3	317.6
MSHSO02 (heater)	T1	°C	568.4	566.1	-
	P1	MPa	16.0	15.0	-
	T2	°C	620.0	620.0	-
	P2	MPa	15.9	14.9	-
	D	MWth	15.57	12.65	-
	M1	kg/s	243.2	189.3	-
MSHSO03 (heater)	T1	°C	567.1	572.9	-
	P1	MPa	10.5	11.0	-
	T2	°C	620.0	620.0	-
	P2	MPa	10.4	10.9	-
	D	MWth	15.75	10.93	-
	M1	kg/s	243.2	189.3	-
MSHSO04 (heater)	T1	°C			-
	P1	MPa			-
	T2	°C			-
	P2	MPa			-
	D	MWth			-
	M1	kg/s			-
MSTUR01	T1	°C	620.0	620.0	620.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Component	Parameter	Unit	13	23	31
(turbine)	P1	MPa	24.55	24.550	24.50
	T2	°C	568.4	566.1	500.9
	P2	MPa	16.0	16.0	9.1
	E	MWe	13.95	11.37	41.48
	M1	kg/s	243.2	189.3	317.6
MSTUR02 (turbine)	T1	°C	620.0	620.0	-
	P1	MPa	15.9	15.9	-
	T2	°C	567.1	572.9	-
	P2	MPa	10.5	11.0	-
	E	MWe	14.40	9.98	-
	M1	kg/s	243.2	189.3	-
MSTUR03 (turbine)	T1	°C	620.0	620.0	-
	P1	MPa	10.4	10.9	-
	T2	°C	587.9	571.8	-
	P2	MPa	8.10	5.80	-
	E	MWe	8.82	16.68	-
	M1	kg/s	243.2	189.3	-
Total cooling duty MSCUSXX	D	MWth	28.84	29.41	37.26
Total heating duty MSHSOXX	D	MWth	55.65	56.26	64.36
Total compression work MSCOMXX	E	MWe	-12.15	-13.04	-16.50
Total expansion work MSTURXX	E	MWe	37.17	38.03	41.48
Net cycle efficiency	**EFF**	**%**	**44.951**	**44.408**	**38.817**
Lowest boiler inlet temp.	T	°C	540.5	482.4	458.4

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.