D1.2 – Report on Flexibility constraints, Load scenarios definition

May 2018

WP 1, T 1.2

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sCO2-Flex

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Technical References

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[1] PU = Public

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

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3.2			

Summary

The European Union (EU) Energy policy has set up since 2009 a framework for the development of renewable energy in the EU. Coal plants will have to increase their flexibility to accompany the penetration of RES, to compensate for their intermittence and to provide ancillary services (frequency, voltage control, balancing).

This document aims at determining the flexibility constraints on the coal/lignite power plants (number of annual start-ups and shutdowns, load fluctuations, minimal charge load) for both the current and the future (expected) electricity network. These data enable to anticipate the conventional power plant future flexibility requirements in order to provide the convenient design of the sCO_2 cycle.

Actual power plant generation figures are given by the European Distribution Operators and enable to assess the current operating conditions of several coal power plant in Europe. Combined Cycle Gas Turbine (CCGT) power generation data are used to define the upper limit of flexibility requirements. Then, it is assumed that the future coal power plant flexibility requirements will be kept between current coal and CCGT flexibility.

The flexibility requirements and the operating conditions analysed in this deliverable will be completed and used as “inlet data” for the deliverable D1.3.

Disclaimer

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Nomenclature

Symbol	Description
sCO_2	Supercritical CO_2
WP	Work package(s)

Context

Current fossil-fuel plants have been designed to operate in base-load conditions, i.e. to provide a constant power output. Nowadays their role is changing, due to the growing share of renewables, both in and outside the European Union (EU). Fossil-fuel power plants will increasingly be expected to provide fluctuating back-up power, to foster the integration of intermittent renewable energy sources and to provide stability to the electrical grid. However, these plants are currently not fit to undergo power output fluctuations, thus it is necessary to develop innovative and cost-effective solutions that enable existing and future fossil-fuel power plants to be flexible enough to deal with these load fluctuations.

A simple definition of flexibility for a power plant can be described as its ability to adjust its net power output; such ability originates from the plant attainable bandwidth of generation and the time required to reach stable operation when starting up from a standstill.

The key operating parameters deriving from such a definition can be summarized as following:

- **Minimum load:** it represents the lowest load level at which the power plant operates under stable conditions and without fuel support (e.g. oil). A low minimum load operation reduces financial losses during "low price" hours and avoids frequent shut-downs and start-ups. In these conditions, start-up costs and associated thermal stress can be reduced. Moreover, a low minimum load operation supports the grid operator – by providing rotary inertia – if plants remain synchronized. However, minimum load operation entails significantly lower efficiencies.

- **Start-up time:** defined as the time period between the start of power plant operation and stable minimum load being reached (grid synchronization). Short start-up and shut-down times are beneficial, enabling a quick response to changing market requirements, e.g. in two shifting operation. The thermal stress connected to these procedures has the most

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severe impact on the lifetime consumption of components and equipment. Start-up times are classified as follows:

- Hot start: < 8 hours (h)
- Warm start: > 8 h and < 48 h
- Cold start: > 48 h

- **Ramp rate:** it indicates how fast a power plant can change its power output in a certain time. High ramp rates ensure a fast reaction to changed market conditions. Power plants with dynamic cycling abilities can participate in different markets (e.g. for ancillary services).

Two main challenges can be identified in designing highly flexible and fast response power plants: firstly a technical one, as thermal stress induced by load fluctuations is harmful for the equipment, reducing the lifetime, and secondly the reduced power plant performance (efficiency) due to the fact that operation outside nominal conditions is normally not optimized. Therefore the plant efficiency at part load becomes another important parameter.

In this context, the innovative sCO_2 cycle (which is the subject of the current project) will be specifically designed in order to provide a better answer than current coal fired power plants, especially concerning flexibility parameters, thus better fitting future load scenarios based on high RES penetration; the sCO_2 cycle flexibility goals can be seen in the following table:

Table 1: flexibility performances for different power plant types

	Power plant type					
	sCO_2-Flex	Coal (State of the art)	Coal (current average)	Lignite (State of the art)	Lignite (Current Average)	Natural Gas Combined Cycle
Flexibility criteria						
Minimum load	20%	25%	40%	50%	60%	40%
Ramp-Rate % nom load/min	>6	4	1.5	2.5	1	5-6
Hot start in h. (after <8 hours off)	<2	2.5	3	4	6	1
Cold start in h. (> 72 hours off)	<4	5	10	8	10	3
Efficiency criteria						
Efficiency at nominal load	>48 %	46%	33%	43.5	36%	55-60%
Consumption (T/Hour)						
Fuel (500MW)	<152.2	158.8	221.4	297.3	355.1	-[4]
Fuel (100MW)	<30.4	31.8	44.3	59.5	71	-

Objectives

This study aims at assessing the flexibility constraints on the operation of coal/lignite plants, based on the above mentioned parameters (minimal load, start-up time, load variation speed, performances at partial load, etc.); current technologies are taken into account, which will provide a benchmark to compare sCO_2 based plants' performances in terms of flexibility.

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Another objective of the study is to analyse current coal-based power plants' operation in order to define a typical yearly load profile, in terms of number of start-ups and shut-downs, load variations and part-load operation time. Such profile, relevant to today situation and generated from experimental data, will be used to define future scenarios based on higher RES penetration, where more flexibility is required to fossil fuelled plants.

The results of this deliverable will act as "inlet data" for the simulations to be performed both on the sCO_2 cycle capability to withstand grid needs, and on the consequences that such flexible operation have on the components performance and expected lifetime.

Methodology

The study is based on real data relevant to current coal plants operation within the EU on one hand, and on the outcomes of prospective studies related to an EU electrical system integrating a high share of renewables on the other hand. Current coal plant performances are used as a reference to benchmark sCO_2 plants which are supposed to better perform in terms of fast start-ups and load variations.

Due to the great variety of coal plants in Europe, ranging from very old power stations from the '60s to recent new-builts, a distinction is made in this study between state of the art plants, featuring the best available technologies, and what can be defined as "most commonly used" plants, which are older but still constitute the bulk of EU coal fleet.

Furthermore, some figures from actual CCGT operational data are taken into account to show what it can be considered as the technical upper limit in terms of flexibility, thanks to their intrinsic ability to cope with fast ramps, short start-up time and part load high efficiency. The idea behind is that it can be plausible, for future flexible coal fired plants, to try to design a system whose performances are somewhere in between those of today coal units and today CCGT.

1.1 Most commonly used coal plants: flexibility performances

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:

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Table 2: 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% P_{Net})
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 2 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).

1.2 Most commonly used coal plants: start-up and shut down constraints

In France, different procedures must be adopted when shutting down a coal plant, depending on the foreseen down-time:

- Down-time **shorter than one week**: the boiler and loops are kept in the same conditions as when the plant has been shut down;
- Down-time **longer than a week but shorter than a month**: the loops and boiler are emptied when warm and then left in these conditions;
- Down-time **longer than a month**: all loops and the boiler are emptied when warm and swept with dry air;
- Down-time **duration unknown**: at the time of shut-down, the system is kept as it is; after one week, the plant is restarted and depending on the situation it is either reconnected to the grid for generation or shut-down again allowing the boiler and loops to be emptied

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when warm; then, depending on the foreseen down-time, it can be kept as it is or swept with dry air.

1.3 Most commonly used coal plants: start-up analysis

As already mentioned in the first paragraph, depending on the down time duration before a start-up, the latter is defined Hot, Warm or Cold; in general a Hot start-up follows a down time no longer than 8h, while a Warm one happens after more than 8 and less than 48h from the shut down and a Cold start-up definition covers all situations where the plant has been shut down for more than two days, up to the extreme case when the boiler has been emptied (so after at least one week down time, according to paragraph 1.2).

Table 3: Q600 start-up time; hot restart in orange, warm restart in yellow and cold ones in light blue.

Total down-time before restart:	8h	<48h	72h	5 days	Emptied boiler
Forewarning	1h	1h	1h	1h	-
Start-up preparation	0h30	3h30	5h	5h30	8h15
Start-up → Coupling	1h	2h	3h	3h30	3h45
Loading up to Pc_{min}	1h	1h30	2h	2h	3h
Loading Pc_{min} → Pc_{MAX}	1h	1h	1h	1h	1h
Total time to reach Pc_{MAX}	4h30	9h	12h	13h	16h

As it can be seen in Table 3, the step with the greatest impact on overall start-up time, especially for Cold ones, is the one relevant to the plant preparation, which accounts for 50% of the total time in cases where the boiler has been previously emptied (down time > one week).

The following steps leading to grid coupling and reaching minimum load respectively show again important time differences passing from Hot to Warm and mostly Cold start-up, while the last step to get to maximum power is the same independently from the plant starting conditions, meaning that by that time all differences have already been overcome.

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In order to better understand the various actions which have to be taken in each start-up phase, and the physical reason resulting in time constraints, a detailed analysis of a cold start is described here below.

Table 4: Q600 cold start-up description

Action	Constraints	Time needed
Cooling loop conditioning		30 min (venting)
Feed-water tank fill-up if needed (depending on initial conditions)		
Vacuum made in the **condenser**		
Feed-water tank de-aeration and heat-up to 130°C	Rate < 60°C/h	~ 2 h (due to de-aeration)
Boiler fill-up with water from the feed-water tank	Rate < 80°C/h (on HP reheater)	~ 2 h
Boiler conditioning and rinsing		~ 20-30 min
Boiler air preheating system start-up		~ 30 min
Boiler sweeping (air side)		~ 10 min
Boiler firing (fuel oil first, then progressively pulverized coal) and heat-up	Rate < 120°C/h	
De-nitrification system start-up	(when boiler temp >150°C)	
Feed pump: switch from electric to turbo. Need to accelerate up to 3000 rpm following a precise speed-up profile)		
Steam turbine start-up. Need to accelerate up to 3000 rpm following a specific speed-up profile	Metal temp > saturated steam temp + 50°C	~ 1h 30 min
Steam turbine coupling (+40MW)		
Steam turbine load augmentation (start-up of depollution system)		

The start-up description in Table 4 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.

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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 (ex. Another tranche already in operation).

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 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 sCO_2 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:

- **sCO_2 boiler**: most of the current coal-boiler constraints are expected to be still with new sCO_2 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);
- **sCO_2 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.

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1.4 State-of-the-art coal plants performances

This section shows flexibility performances of three state of the art European coal plants, all based on USC (ultra-supercritical) technology, which can be considered as the direct competitors of a sCO_2 based system:

- Belchatow II Unit 1 (Poland): completed in 2011, this 858MW lignite-fired unit is part of the largest European power station (total capacity exceeding 4GW) and it features the following steam live parameters: 554°/582°/266 bar (SH and RH temperatures, max pressure);
- Walsum Unit 10 (Germany): completed in 2013, it is a hard coal-fired unit with an installed capacity of 725MW (600°/620°/274 bar) ;
- Boxberg Unit R (Germany): completed in 2012, it is a USC 675MW lignite-fired power plant (600°/610°/286 bar).

The flexibility performances of the three units can be summarized as in Table 5:

Table 5: comparison of three state of the art coal-fired units in Europe

	Belchatow	Walsum	Boxberg
Fuel type	lignite	hard coal	Lignite
Minimum load (% P_{Nom})	45%	35%	35%
Average ramp rate (% P_{Nom}/min)	2-6%	3.5-6%	4.6-6%
Hot start-up	140 min	66 min	80 min
Cold start-up	360 min	290 min	310 min

As a further reference which could be mentioned is the new USC (ultra- supercritical) unit which was supposed to be built at the Polish Rybnik power plant; the construction is now on hold, due to difficulties in terms of permissions and market situation, but the design was completed and lead to a 110 minutes hot start-up time and 190 minutes for a cold one (after 50h shutdown).

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1.5 Yearly operation figures for coal plants

As already pointed out in the introduction, the future role of fossil fuel power plants will be to support the grid for those periods where renewable sources alone cannot match the electrical demand; their operation has already changed though, and today these plants undergo frequent load fluctuations, starts and stops.

Such operations can be harmful for the plant in terms of expected lifetime, as they stress the components and can result in fatigue issues; especially cold start-ups and fast load changes when starting from the minimum load.

To provide some figures relevant to today's situation, a few coal units currently operating in Europe have been taken into account over one operational year (2017).

Generation data of a few CCGTs are included in the analysis, with the idea that they represent the upper limit in terms of flexibility, given that they are today used as mid-merit or even peak plants (depending on market specificities).

A first-glance to the yearly (2017) production profile of such power plants already shows the different situation of similar units depending on the market they operate in.

Two of the state-of-the-art plants previously described, Boxberg (GER) and Belchatow (PL), run in baseload mode showing little load variations during the year and a few start/stop cycles (apart for a long stop, presumably for maintenance reasons, in summer/fall), as it can be seen in Figure 1 and Figure 2.

Figure 1: Boxberg R (GER) power plant production in 2017

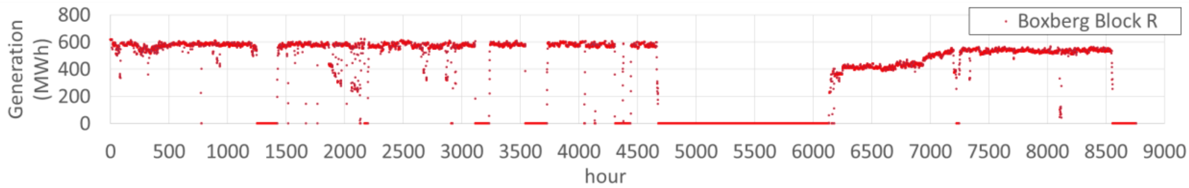
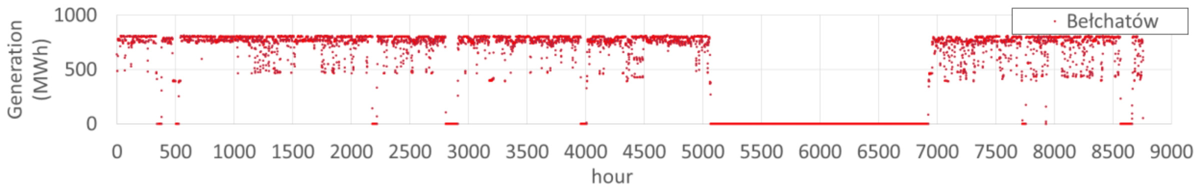


Figure 2: Belchatow II (PL) power plant production in 2017



The third state-of-the-art described power plant, Walsum (GER), shows a much more fluctuating load profile, with frequent, and sometimes prolonged, stops (Figure 3)

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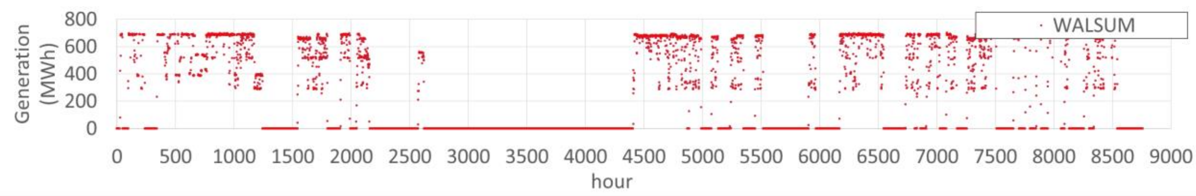
Figure 3: Walsum (GER) power plant production in 2017



Other good examples of flexible use of coal power plants in today's market can be seen in Figure 4, Figure 5 and Figure 6, respectively showing the Italian newest coal plant of Torvaldaliga Nord, Unit 4 (USC technology, 600°/600°/250 bar), the English Draxx-5 Unit (sub critical technology, in operation since the 80's) and the high efficiency Danish Nordjyllaend-3 (double reheat, 582°/580°/580°/290 bar); it can be noticed the heavy use of the plants in their entire power range, as well as the higher flexibility of the newest Italian and Danish plants, capable of decreasing the power output down to one third, whereas the older UK one cannot go below 50% of the nominal power.

Figure 4: Torvaldaliga Nord unit 4 (ITA) power plant production in 2017

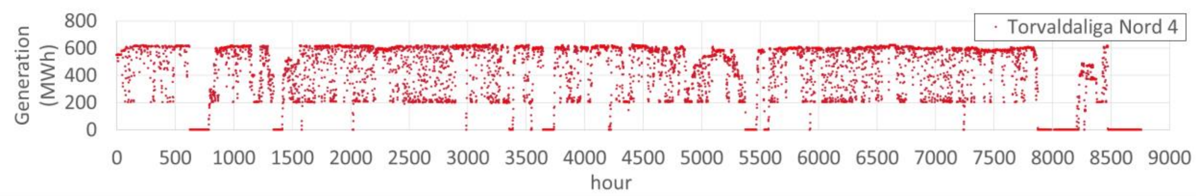


Figure 5: Draxx-5 (UK) power plant production in 2017

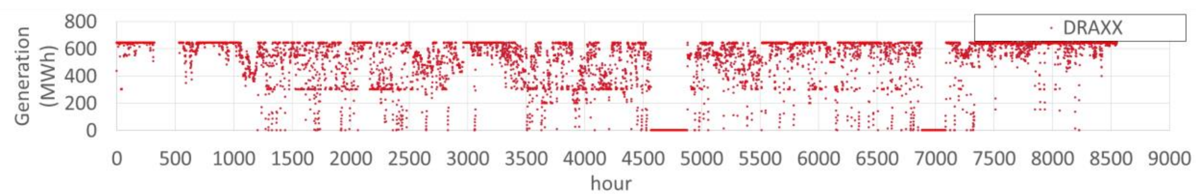
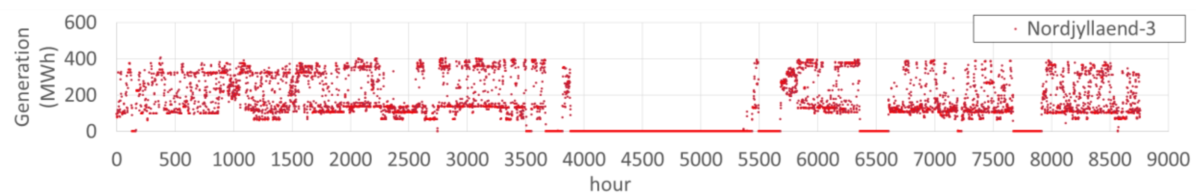


Figure 6: Nordjyllaend-3 (DK) power plant production in 2017



To complete the panorama, Figure 7 and Figure 8 display the load profile of two French Q600, the technology which is still largely used in Europe today.

As seen from other graphs, the long summer down-time is probably due to maintenance reasons, while more frequent start/stop cycles are visible with respect to the previous Italian and English examples.

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Generally speaking it's difficult to be sure about the causes of load fluctuation and cycling: it can both be due to the presence of high RES shares and to the presence of cheaper not RES alternatives (nuclear, for instance).

Figure 7: Cordemais 4 (FR) power plant production in 2017

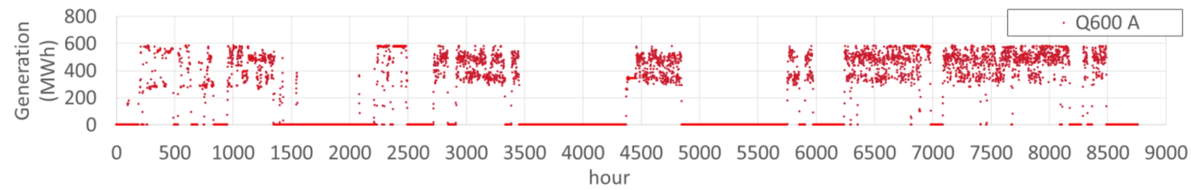
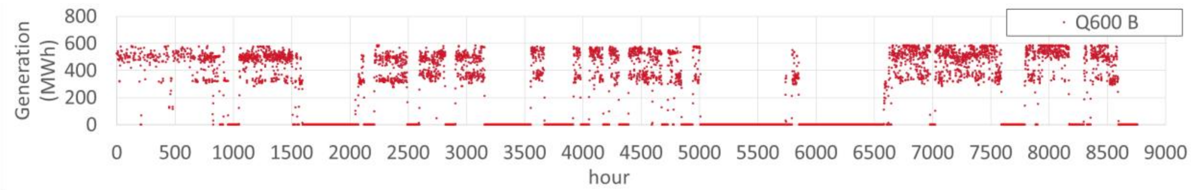


Figure 8: Cordemais 5 (FR) power plant production in 2017



As a comparison, Figure 9 and Figure 10 show the load profile of two Italian CCGTs; depending on the geographical position, therefore on the local market congestions and RES share, very different situation are possible: Altomonte CCGT's profile is not so different from that of a coal plant, while Piacenza is used more as a peak unit than a mid-merit one.

To a certain extent it can be considered that this is the future for coal fired units, in a scenario with high RES shares.

Figure 9: Altomonte (IT) CCGT production in 2017

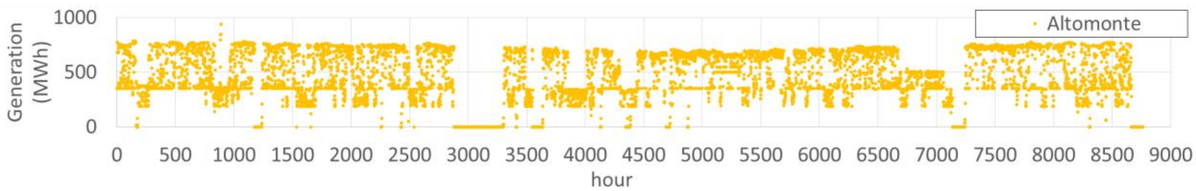
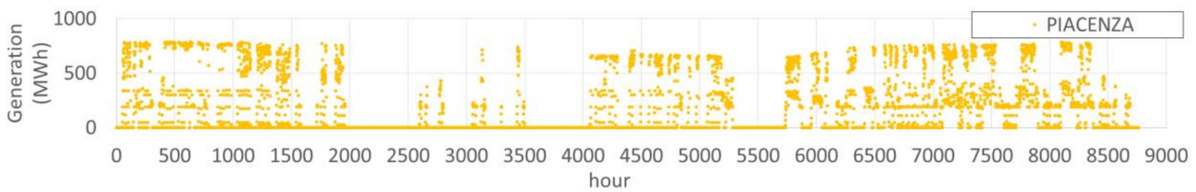


Figure 10: Piacenza (IT) CCGT production in 2017



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1.5.1 Startup/stop cycles analysis

As it can be seen from the yearly load profile of different coal and gas fired power plants shown above, one of the key features of mid-merit and peak operation is the number of startup/stop cycles which such power plants undergo.

As already pointed out, cycling is quite demanding for a coal unit and it can affect its residual lifetime; therefore the number of startup/stops per year of operation is a crucial parameter to design a new flexible thermodynamic cycle; thus, a dedicated analysis of today's behavior of different plants' technologies in different European markets has been performed to provide some figures to start from.

Two big electricity markets, such as France and Italy, have been taken into account, with some differences of approach between them: the study, in fact, focused on several years of operation (2012 to 2017) for a few power plants in France, while a larger pool of power plants (both coal fired and CCGT) has been considered over a single year (2017) in Italy.

The outcomes have been synthetized in Figure 11 and Figure 12.

Figure 11: yearly start-ups for coal fired power plants and CCGT – average figures for French (2012-2017) and Italian (2017) market;

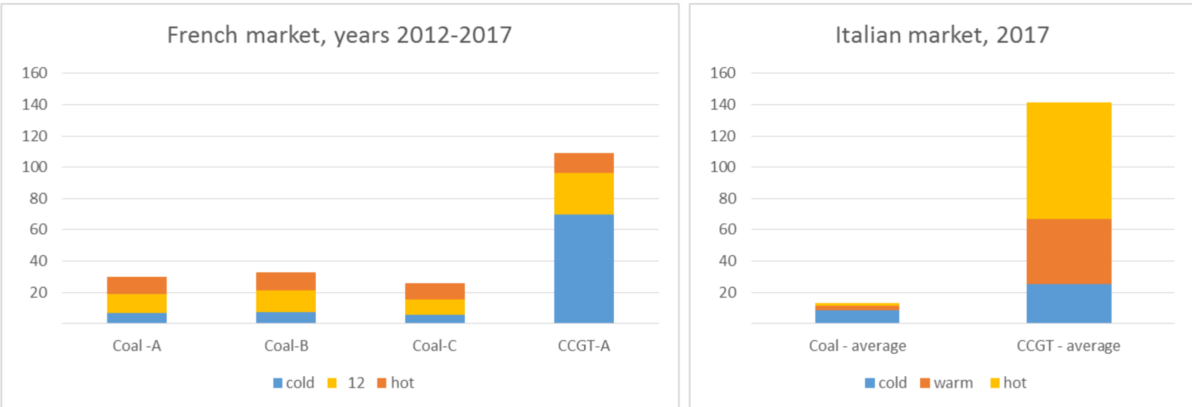
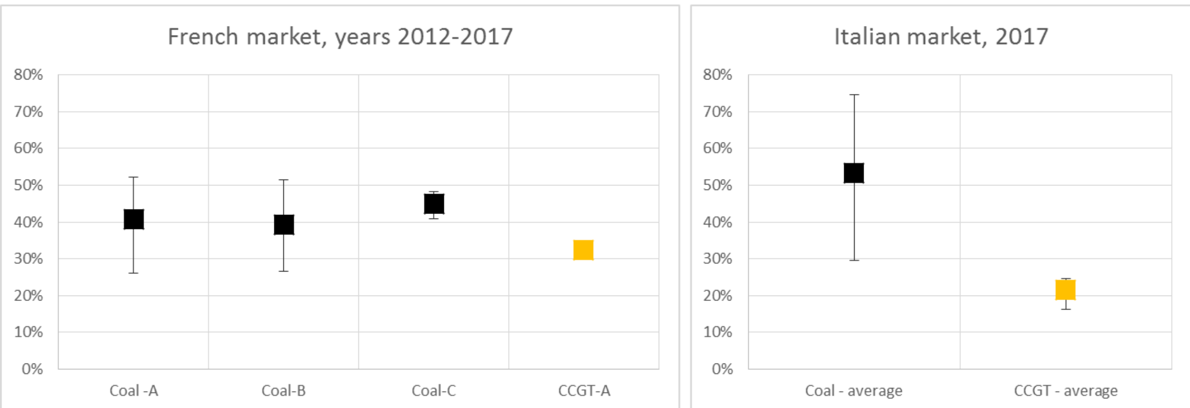


Figure 12: load factor for coal fired power plants and CCGT – average figures for French (20121-2017) and Italian (2017) market;



In terms of start-ups, the great difference between today's coal fired plant and CCGT is clearly visible, the latter having to undergo more than a hundred cycles per year while coal units are

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below 20-30; a different strategy of operation is also evident through the graphs, with much more hot re-starts for the Italian CCGTs compared to the French ones.

Considering load factor figures, it's more difficult to try to extract useful information as they don't represent a well-defined event such as a start-up/shut down; nevertheless a general trend is clear: coal plants have higher numbers of equivalent operational hours, reflecting their role of baseload generation units. They also show higher variability in load factor, both in terms of year of operation (French case) and in terms of unit (Italian case).

1.6 Future coal plant operation scenarios

As part of the effort to reduce carbon emissions from the energy sector, the European energy strategy envisages a wide scale deployment of low-carbon electricity generation from renewable energy sources (RES). According to the current EU Climate and Energy package the share of RES should increase from 20% in 2010 to 35-40% in 2020 with a target of 55% by 2050.

Today hydro generation is by far the larger European RES, but it is already well exploited and limited opportunities for further development are foreseen; therefore, the European RES strategy will be strongly based on the deployment of wind and PV generation.

Starting from an energy share of 10% in 2014, the share of variable RES such as wind and PV in the EU mix is expected to reach 20% in 2020 and 30% in 2030; a factor of three is therefore the key figure to develop a scenario at the horizon 2030, considering that it's exactly variable RES as wind and PV which are supposed to have an impact on the operation of future fossil fuelled plants, such as coal plants which are the subject of this study.

Some information can be found in literature, like a 2014 analysis by IEA on the impact of the RES share increase on future coal and gas fired power plants; the study is relevant to the German market at the horizon 2020-2025.

Figure 13: Annual full load hours (left) and part-load operation time (right) for benchmark power plants under increasing RES shares (source: IEA analysis, 2014)

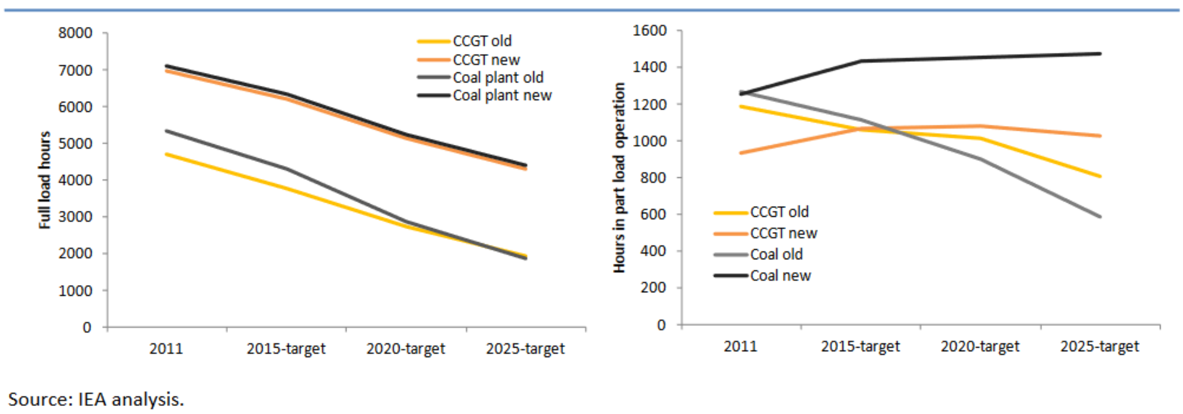

Figure 13 clearly shows that the main impact will be that both old and new fossil plants will reduce their full load operation in the future; in terms of part load, while old plants will again reduce their operation as they will not be able to compete due to low efficiencies, new ones

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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, as shown in Table 6.

Table 6: Number of power plant start-ups per year (source: IEA analysis, 2014)

	2011	2015-target	2020-target	2025-target
Old Coal plant	44	46	44	32
New Coal plant	20	39	49	54
Old CCGT	113	99	105	92
New CCGT	73	98	132	140

Figures of the year 2011 in Table 6 are well in line with the actual data from the Italian and French markets, therefore the two scenarios at the horizon 2020 and 2025 can be considered as a good reference for the purpose of this document.

Conclusions

This study allowed to gather information about existing coal fired plants by assessing their flexible abilities as well as to gather some important figures relevant to CCGTs (considered as the reference in terms of flexible operation due to the increase of RES shares in the future electric market).

Given the high variability of current coal power plant technologies, varying from old power plants dating from the 60's and the 70's (which still represent the bulk of coal based generation) to the state-of-the-art (assumed to be the Ultra Supercritical technology), specific figures for each technology are provided and examined separately.

A detailed analysis of a conventional 600MW class coal plant has been performed, to get some insights about the technical reasons which determine the actual start-up time ("critical" path); the goal is mainly to be able to distinguish the time constraints related to the presence of a "water-steam cycle" and those that are expected to be linked to the presence of a "boiler furnace". The time constraints related the "water-steam" cycle should be different (or even disappear) compared with a power plant using a "sCO_2" cycle, while the boiler current time constraints are expected to be quite similar since the firing technology will stay the same.

Finally, the latest section of this report describes some interesting scenarios that use actual current figures and future expected (targeted) operating conditions. It shows that the number of annual start-ups of conventional power plant (gas or coal) are expected to be stable for old technologies and to increase for new technologies.

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References

[Marian Piwowarski, 2009] Piwowarski M. Optimization of steam cycles with respect to supercritical parameters. POLISH MARITIME RESEARCH, Special issue 2009/S1; pp. 45-51. https://www.degruyter.com/downloadpdf/j/pomr.2009.16.issue--1/v10012-008-0043-3/v10012-008-0043-3.xml

[Johannes Trüby, 2014] Trüby J. Thermal Power Plant Economics and Variable Renewable Energies, IEA Insights Series 2014, December 2014 https://www.iea.org/publications/insights/insightpublications/TRUEBY_PowerPlantEconomicsFINAL.PDF

[Vera Silva, 2015] Silva V., Burtin A., Technical and Economic Analysis of the European Electricity System With 60% RES. EDF R&D, June 2015 https://www.edf.fr/sites/default/files/Lot%203/CHERCHEURS/Portrait%20de%20chercheurs/summarystudyres.pdf

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