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FLEXible operation of FB plants co-Firing LOw rank coal with renewable fuels compensating vRES

FLEX FLORES

Dissemination Level: Public

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EXECUTIVE SUMMARY

The overall demand in reducing greenhouse gas emission for avoiding the global warming is pushing the power generation in using renewable sources mainly deriving from wind and photovoltaic. This action leads to significant changes in the structure of European electricity generation and distribution systems. In particular, such a kind of system requires buffer actions to ensure the stability of the electrical grid and to cope with the peaking resources needed at hours of high demand. In this contest conventional power plants have to increasingly shift their role from base-load plants to fluctuating back-up plants in order to control and stabilize the power grid. Combustion plants should be able to run both at the lowest part load possible at the highest possible efficiency which means high operation flexibility. Furthermore the request of renewable energy imply the conversion of the conventional power plants in co-combustion type able to burn different type of biomass as renewable fuels.

Within this contest the Circulating Fluidized Bed Combustors (CFBC) plants are ideal for efficient power generation because they are capable to fire broad variety of solid fuels from biomass to low rank coals under controlled conditions avoiding SO_x and NO_x pollutants emissions. The FLEX FLORES project aims at obtaining some Key Results that can be synopsized as followings:

1. Higher availability factor for the plant (achieved with steady plus reliable operational mode parameters)
2. High ramp-up rates (up to 5%MCR/min) and faster start-up procedures of the plant
3. The plant will be available under a wide range of different blends of Low Rank Coal (LRC) and biomass (increase of biomass share, operational strategies for a wide range of LRC substitution)
4. New operation strategies implementation and new devices assessment
5. Increase of the components lifetime avoiding wastes of energy plus raw resources

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1 Introduction

The EU overall policy leading towards the promotion of energy from renewable sources has the important target to fulfil at least 20% of its total energy needs with renewables within 2020. This ambitious plan includes both the power generation and transports.
Concerning the power generation, the use of renewable sources mainly deriving from wind and photovoltaic leads to significant changes in the structure of European electricity generation and distribution systems. In particular, such a kind of system requires buffer actions to ensure the stability of the electrical grid and to cope with the peaking resources needed at hours of high demand. Coal fired power generation plants can be used for this purpose. The CFBC (Circulating Fluidized Bed Combustors) plants offer, in particular, many advantages summarized as follows:

- Fuel flexibility
  The possibility of substitution of part of coal with low rank coals (like lignite) or even with other potential fuels like biomass gives the possibility of a rational use of the resources available in areas where the generation plant is located.
- Downstream flue gas cleaning is not usually needed
  The capability to capture SO_x during combustion by means of the injected sorbent together with the relatively low NO_x emissions makes the flue gases enough clean in most of the cases.
- No high capital costs or high auxiliary power are required

The activities of FLEX FLORES project are aimed at filling the current gap existing between the use of CFBC plants for power generation to their full integration in the new context described above. Aspects including the optimization of multi-fuels (mixes of fossil coal with low rank fuels including biomass) combustion and operational conditions to maximize the efficiency of the plant will be cared. Furthermore mandatory aspects strictly related with the need to go from a "baseload resource status" to a "peaking resource status" at hours of high demand will be optimized as well.
A fully integrated approach is the best way to reach the goal. This approach involves different scales starting from laboratory activities supported by modelling and passing to validation at pilot/industrial plants aimed at the optimization of both multi-fuels/process aspects and material performances in flexible conditions. The results can be used as guidelines for retrofitting of existing plants and for the construction of new ones. Environmental benefits are also expected in terms of minimization of the pollutant emissions through the study of the control system and through the optimization of in service lifetime of both refractories for boilers and metallic alloys for heat exchangers.

2 Overview of the project

The FLEX FLORES project aims at increasing flexibility of Circulating Fluidized Bed (CFB) technology in terms of fuels and operating conditions. This goal is required to supply energy when the variable Renewable Energy Sources (RES) are not enough to satisfy the market demand. The new concepts that are going to be explored within FLEX FLORES are mainly low rank fuel (i.e., lignite) co-combusting power plants under high ramp-up rates. The activities aim at improving retrofitting solutions of already existing plants but will not exclude the design of new ones.
The research activities will be supported by:

- Theoretical calculation of thermodynamic type and parametric oxidation model;
- Laboratory scale tests and pilot scale campaign;
- Numerical study of CFD and dynamic 1-D process modelling.

A combined sophisticated research on the operational flexibility enhancement of CFB boilers for retrofitting cases that are fed with Low Rank Coals and biomass/waste fuels blends, has not been conducted up to now. By improving the flexibility of CFB plants in terms of operating conditions and fuel types, the FLEX FLORES project will fill the gap in this field.
The main advantage of biomass co-firing is due to the possibility to mitigate the CO_2 emissions of coal sector at very low cost and short implementation time compared to other technologies. Over 100 successful field demonstrations are distributed in 16 countries. They use every major type of biomass (e.g., herbaceous, woody and wastes) combined with every rank of coal and combusted in every major type of boiler.
The Table 1 resumes the technical and environmental challenges of the co-combustion and its advantages.

Technical and environmental challenges	Advantages
Fuel handling	Highest electrical efficiency (among biomass conversion technologies)
Slagging/fouling/corrosion	Can produce power on demand
Emissions formation & gas cleaning equipment	Stability of electric grids
Ash utilization	Lower CO_2 at low cost
Biomass availability	

Table 1. Technical and environmental challenges and advantages of biomass co-combustion

For what concern low rank fuels, lignite is considered the lowest rank of coal due to its high moisture and low carbon content, as well as typically high ash content. It is used almost exclusively in power generation. In particular about 4% of the total electricity production worldwide is produced by burning lignite. Furthermore lignite is an important indigenous fuel source in several European countries. Just as overview of the European situation, Figure 1 shows the distribution of power generation capacity in different countries.

Figure 1. Overview of lignite production and power generation capacity in Europe (red: installed capacity > 2 GW, orange: installed capacity< 2 GW)

The principal advantage of CFB plants in respect to Pulverized Coal (PC) combustion plants is their greater ability to deal with variation in fuel type and quality, and their improved performance with poor quality coals in general. A schema of the fuel types for the two different plants is shown in Figure 2.

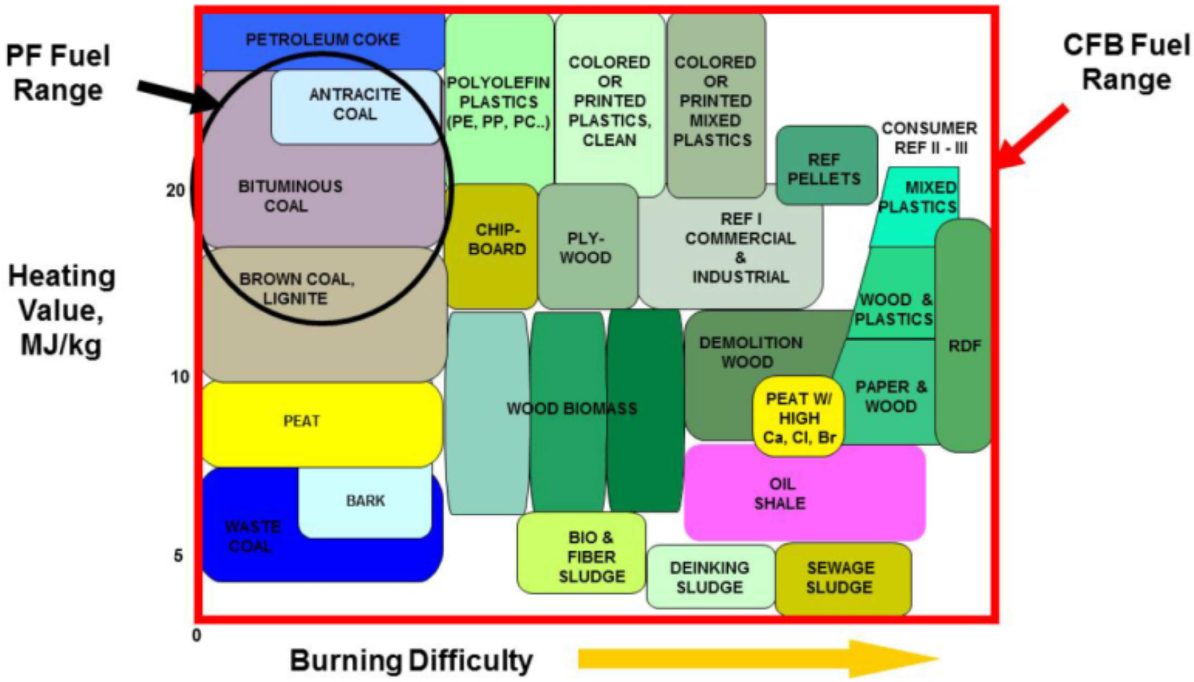

Figure 2. CFB outperforms PF technology with respect to fuel range

However, fuel flexibility is not the only key indicator for the improvement of the combustion plants for future applications. Another important key indicator is flexibility in operating conditions which is required in order to satisfy the future energy demand. In the near future due to the increase of variable RES installed capacity, which are well known for having a stochastic nature, a gap between power supply and demand will be observed more and more often (see Figure 3).

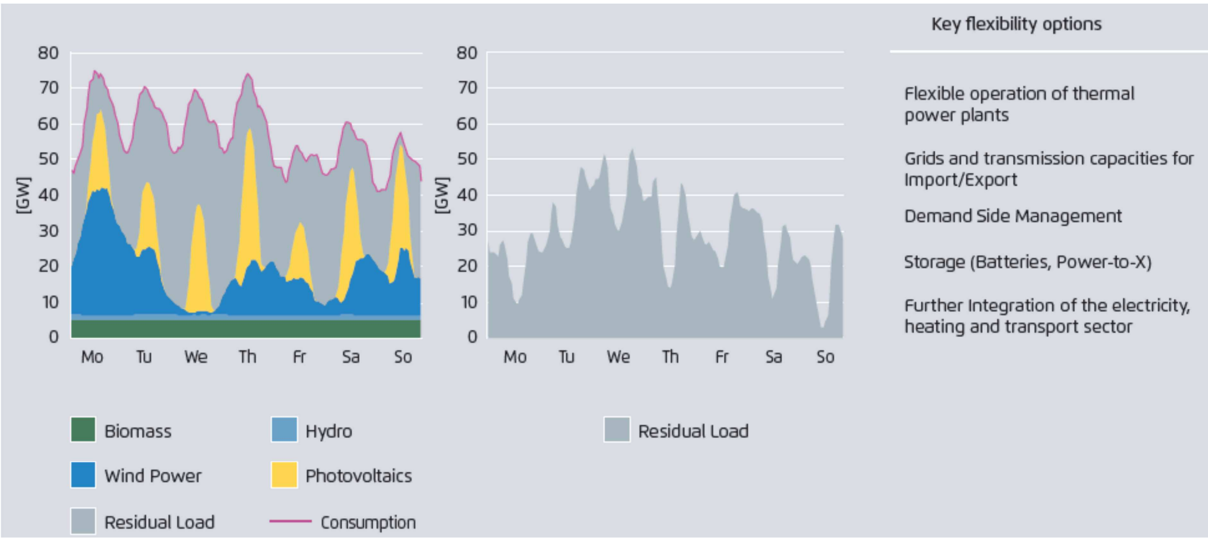

Figure 3. Expected gross electricity generation and residual load in Germany in a sample week in April 2022 with 50% renewables

To fill this gap, flexible operations of thermal plants will be required which will be able (see Figure 4):

- To increase heating and cooling rates;
- To increase the minimum and maximum load;
- To reduce start-up cost.

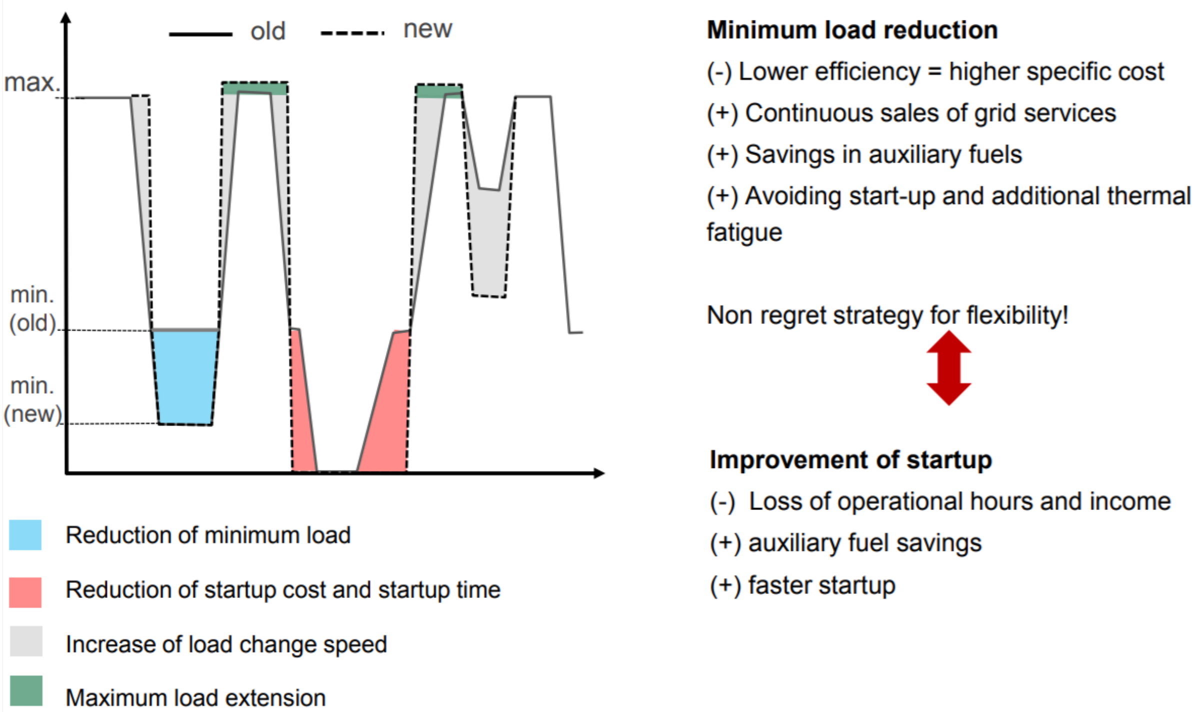

Figure 4. Requirements for the new thermal plants able to work under more flexible operating conditions in respect to old ones

In order to achieve this goal a consortium of six partners has been created which involves two industrial partners, one University, and three research centres.
In more detail the partners are:

- RINA Consulting - Centro Sviluppo Materiali S.p.A. (CSM S.p.A.) experts in materials and industrial processes based on experimental activities and theoretical evaluations by simulation/modelling activities.
- SUMITOMO SHI FW ENERGIA OY (SFW) experts in fluidized bed boiler technology and flue gas cleaning equipment's CFB boiler design, manufacturing and maintenance.
- Centre for Research and Technology Hellas (CERTH)/Chemical Process and Energy Resources Institute (CPERI) with competences in CFD and transient thermodynamic modelling mainly on combustion technologies.
- Technische Universität Darmstadt (TUDA) with competencies on solid fuel combustion processes based on simulation and experimental investigations at pilot scale.

- VTT Technical Research Centre of Finland Ltd with competences in experimental work and modelling on high temperature oxidation/corrosion, creep, creep-fatigue interaction and fa-tigue.
- Public Power Corporation of Greece (PPC) with competences on industrial plants operation since it is the major electricity utility in Greece.

A large background of the partners especially in the specific sector of combustion for energy pro-duction helps in achieving the goal of FLEX FLORES project.

Figure 5. Scale-up of CFB boiler capacity in the last twenty years with significant plants labelled [1]

During the last two decades CFB technology has increased its installed capacity to 600MWe (see Figure 5) and design is ready for 800MWe. While the construction of new fossil power plants in Europe does not seem promising. Therefore there is a high necessity to develop flexible operation concepts for existing CFBC plants and take advantage of FB fuel flexibility. Such concepts coupled with energy storage solutions can be extended to new built plans.

Figure 6 shows a sketch summarizing the logic of FLEX FLORES approach. The plant flexibility will involve both the plant operations (e.g., higher ramp up rates) and the fuel utilization (e.g., wider range of different blends LRC/Biomass). Obviously, other important aspects concerning the compo-nent lifetime in relation with the new operating conditions will be cared as well.

The operating strategy of the work is then summarized by Figure 7. The multi-level, multi-disciplinary approach involving theoretical aspects and simulations, practical verifications at differ-ent scale from laboratory to pilot plant and then full scale industrial plant will give the possibility to reach the adequate level of optimization requested so to fulfil the targets.

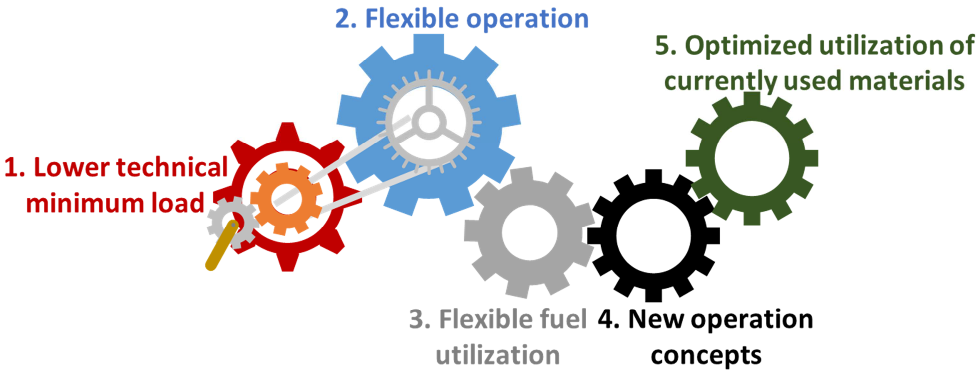

Figure 6. The expected key results from the FLEX FLORES project

The Key Results can be synopsized as:

1. Higher availability factor for the plant (achieved with steady plus reliable operational mode parameters)
2. High ramp-up rates (up to 5%MCR/min) and faster start-up procedures of the plant
3. The plant will be available under a wide range of different blends of LRC and biomass (increase of biomass share, operational strategies for a wide range of LRC substitution)
4. New operation strategies implementation and new devices assessment
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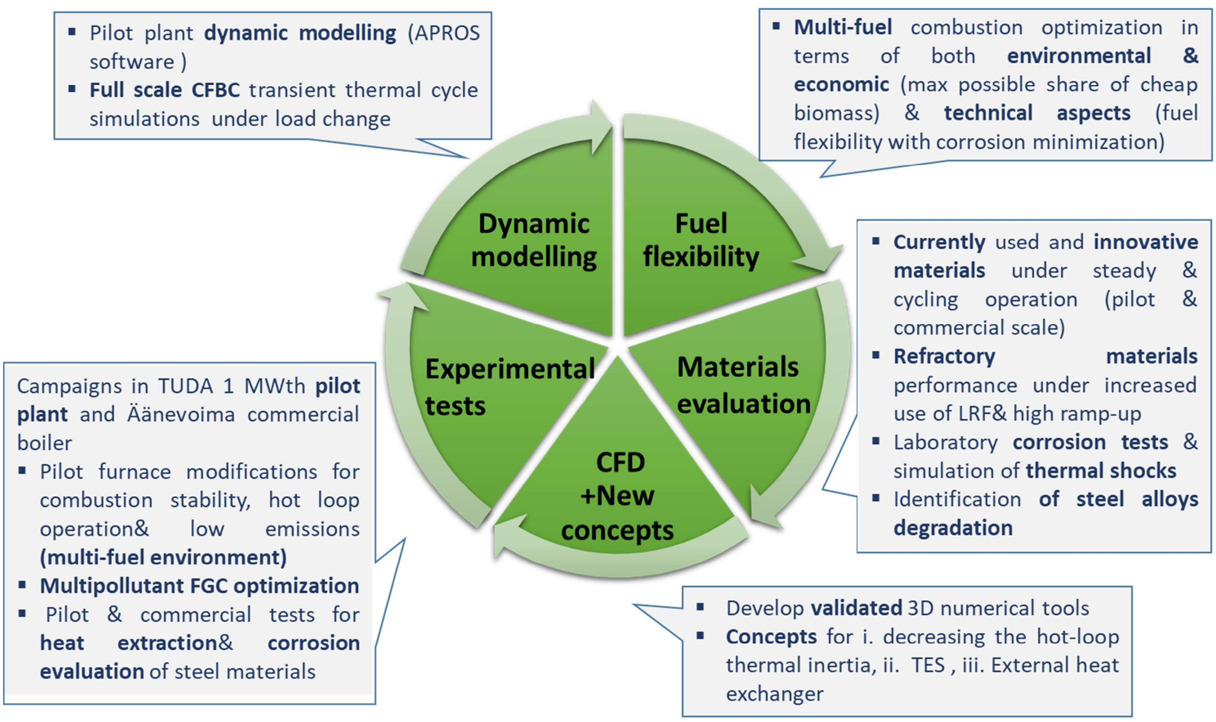

Figure 7. FLEX FLORES Strategy and Actions

Concerning the fuel flexibility, the selection of the most promising biogenic fuels will be done so to identify at least the two more promising-ones to be experimentally tested for their co-combustion with Low Rank Fuels (see Figure 8). The S2Biom integrated tool will be used as a support platform for theoretical evaluation/analysis concerning the biomass sources at regional level (see Figure 9). In such a way the user is able to make selections of biomass types and amounts available per year and potential type combinations.

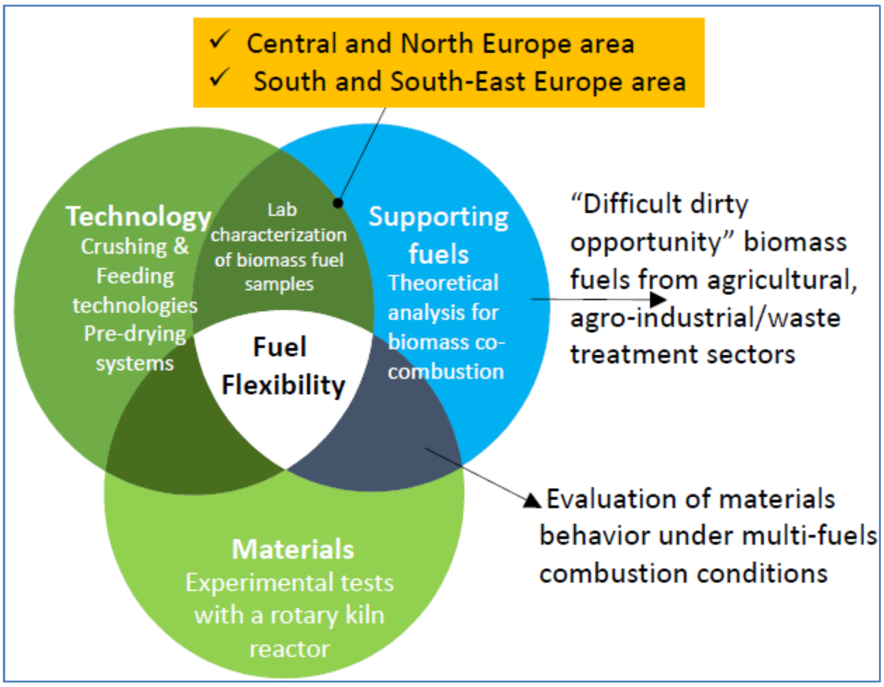

Figure 8. Fuel flexibility in CFBs plant through FLEX FLORES

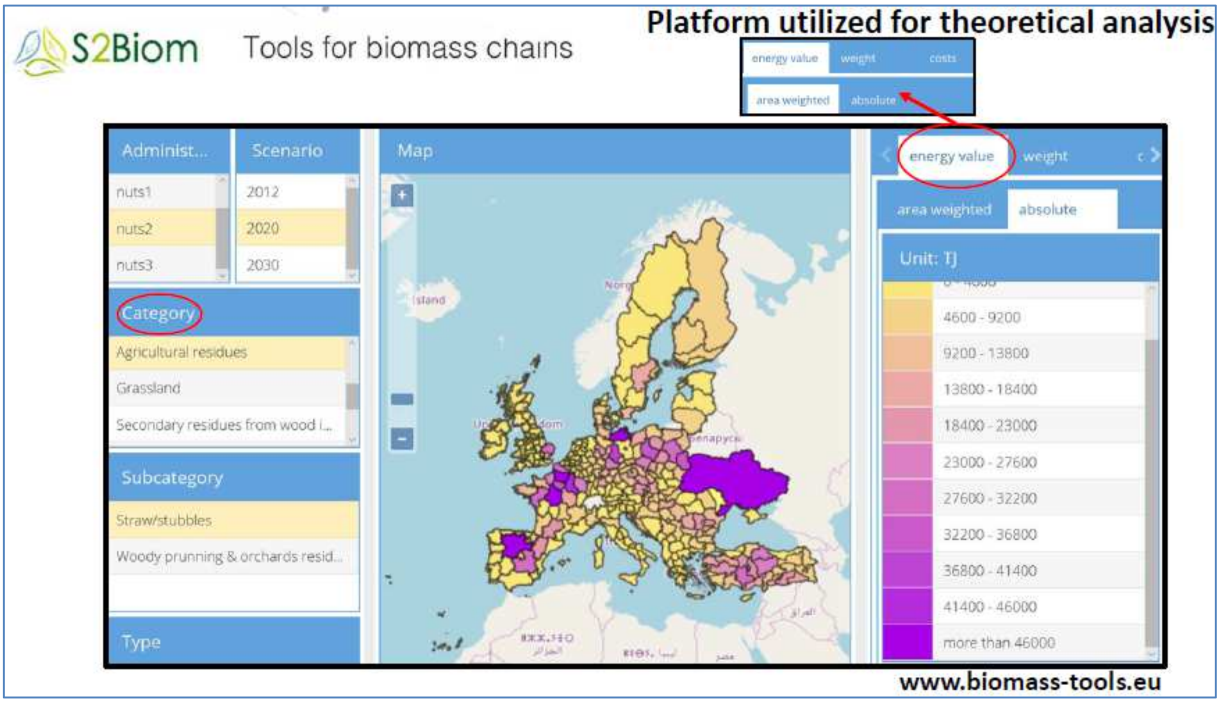

Figure 9. Example of S2Biom tools for biomass selection

The project has started by verifying on the basis of literature surveys and market analyses the most promising materials in terms of alloys for the heat exchangers and refractories for lining the combustion chamber.
Contemporarily a market analyses in comparing dryer systems for lignite and biomass has been performed which allow to optimize the efficiency of energy production.
The selection of the type of fuels to be tested in pilot scale and lab scale is already on going. German and Greek lignite will be tested.

3 State of the Art

In the last few years, there has been noticed an increased interest for operational flexibility in large scale coal-fired power plants. This is mainly attributed to the rapid development and introduction of renewable energy resources to the energy mix, such as wind and solar power that subsequently bring the challenge of larger power fluctuations in the electrical grid. In the past, the main cause of such fluctuations was the varying consumption during the day, workdays and weekends, and seasonal variations. Today, feed-in intermittency due to renewables is a new, additional source of grid fluctuations that are at least the same magnitude as those from changes in consumption. This poses extended operation modes in coal-fired plants to keep the grid stability, which include, fastload following capability and minimization of achievable load levels. Added to this fuel flexibility is an additional challenge as it provides a high level of boiler tolerance to a wide range of conventional fuels and the combustion of biomass and other opportunity fuels. In order to meet these targets, innovative boiler designs have been developed from different companies in a global level.
The dominant technology representing over 90 % of global capacity in coal-fired power generation is pulverized coal combustion (PCC), whilst a significant minority of plants is based on circulating fluidized bed combustion (CFBC). The latter, even though is a more recent boiler technology, is emerging as a real competitor to PCC system due to its higher tolerance to fuel quality and size, often firing unconventional, difficult to burn fuels such as waste, coal, biomass or even mixtures of coal with other fuels, both on a pilot and industrial scale.

3.1 Fuel flexibility of PP

A very recent review article [2] on co-gasification and waste to energy conversion confirms the suitability of Fluidized Bed Combustor for a co-fuel like biomass and waste, permitting a broader particle size range and resulting in higher efficiencies among the possible reactors. In fact, as far as particles size is concerned, size reduction leads to a more effective mass and heat transfer, which increases reaction rates hence enhancing thermal conversion. The recent paper [3] on incineration of sludge in a Fluidized Bed Combustor confirms that this technology as the most suitable choice in terms of flexibility of fuels. The experimentation performed in a pilot-scale fluidized bed plant looks promising for disposing sludge produced by the treatment of wastewater from factories in compliance of the Taiwan laws and regulations.
Several projects at different countries in the world prove the fuel flexibility capabilities of the CFBCs. The Lagisza 460 MWe CFB Power plant in Poland, is the longest operating (since 2009) supercritical CFB power plant in the world, which has paved the way for high net plant efficiencies (of

43.3 per cent (LHV) on bituminous coal with a wide range of as-received heating values ranging from 4300-5500 kcal/kg)[4]. CLECO's660 MWe Brame Energy Center, including two twin CFB boilers, located in Louisiana, US is able to burn a wide-range of market fuels, including 100% petroleum coke, 100% Illinois No. 6, 100% sub-bituminous Powder River Basin coal, and can co-fire up to 92% lignite or co-fire up to 5% paper sludge or wood waste [5]. The 205 MWe DGF Suez Energia Polska Polaniec Plant is the world's largest biomass CFB power plant that can burn a wide range of wood biomass and agricultural crops and by products, with a high net plant efficiency of 36.5 % (LHV) [6, 7]. A plant with a 42.4 % net efficiency (LHV) is the utility-scale 2200 MW Samcheok Green Power Plant in Samcheok, South Korea, which has went into operation in 2016 [8].The Samcheok plant has four 550 MW once-through ultra-supercritical (OTUSC) CFB boilers (257 barg, 603C/603C) and a built in flue gas desulphurisation (FGD) system. The plant is designed to burn a wide range of import coals, including low quality sub-bituminous high-moisture coals (20-42%) of a heating value of around 4250 kcal/kg and co-fire indigenous bituminous coal with up to 5% biomass. Finally, another supercritical 330 MWe CFB unit capable of combusting a wide selection of fuels including anthracite, bituminous coal and coal slurry has been also commissioned in Russia [9].

3.2 Operation flexibility of PP

However, fuel flexibility is not the only key indicator for an optimum boiler performance. Operation flexibility, which includes high ramp-up rates and low technical minimums, is also important. In terms of the energy performance, according to De Gisi, S. et al. [10], the fluidized bed technology applied to the SRF seems to be able to guarantee an adequate production of electricity (satisfying the market demands), showing a relative flexibility with respect to the inlet waste. However, concerning achievable ramp-up rates in CFB boilers, the literature has been scarce. According to IEA load following capabilities can be similar, but a little bit limited, compared to those of PCC units: part loads down to 25% of Maximum Continuum Rating (MCR) and load change rates of up to 7%/min are reported as feasible. Start-up times for some units can be longer than for similarly sized PCC plants [11]. CFBC is less well suited to on/off cycling, as the bed temperature needs as far as possible to remain within normal operating range, and there can be a high risk for refractory damage [12]. Some reported ramp-up rate values include these of Polish CFBC units at Lagisza, Turow, and Polaniec, which have successfully met grid requirements of 4%/min and the CFB Boiler located in Swiecie, Poland, in which there has been achieved a load change equal to 7 %/min [4]. Contrary to the CFBC boilers, there is a wide range of reported values in the literature for the maximum load following rates of coal-fired PCC units. In general PCCs, although they are designed for a narrow fuel range compared to CFBC boilers, they present quick response to load changes [11]. The twin Neurath 1.1 GW lignite-fired once-through USC units, located in Germany, can each change by 500 MW in 15 minutes (3%/min based on MCR) [13]. Higher values, of equal to 5% of maximum load/min has been reported for a 220 MW unit in the USA after control system modifications [14]. Mitsubishi Hitachi Power Systems give a rate of 7%/min from 40% to 100% output for the steam generators of new hard coal or lignite-fired plants [15], while they suggest that even 10%/min is possible. Babcock Power have reported 7%/min as a typical design value for a once-through boiler in the load range 50–90%, with demonstrated operating experience at this value with the 550 MW bituminous coal-fired unit at Rostock, Germany [16]. Finally, GE report that their pulverized coal boilers currently allow for ramp rate as fast as 6% per minute and down to 20% for hard coal and 35% for lignite based on BMCR [17].

A summary of current, best available techniques and targets for power plants in terms of operation flexibility is shown in the Table 2.

Parameters / characteristics	Currently operating PP fleet (PPs erected in the 20. century) 1)	Current BAT (PPs erected in the 21 century) 1)	Targets
Minimum load for continuous operation [%]	**15-20** for hard coal **>50** for lignite 4)	**15-20** for hard coal 2) **35-40** for lignite 3) 4)	**~15** (considering alternative & low carbon solid support fuels and their blends)
Ramping rate [%/min]	**2-3**	**5**	**~10**
Frequent start-up and shut down ability (cold/warm/hot)	Specific nr. of start-ups /shut downs foreseen per year (limited to few cold start-ups)	Possible daily start-up for hard coal PP (usually hot/warm daily, cold over the weekend)	Possible daily variations between 15-100% to avoid daily start ups
Emissions and plant efficiency MUST BE KEPT DURING PART-LOAD	Optimum design for high efficiency and lowest emissions at full load	Optimum design for high efficiency and lowest emissions at full load and some low loads	Optimum design for high efficiency and lowest emissions (IED) for load following operation

1) Best possible known, and documented
2) Usual min load operation for recent new built plants still is only around 30-40% due to lowest marginal cost of all hard coal units — Source: MHPSE
3) Oil/gas may be required as supporting fuel for lignite
4) Plants are existing in Germany or are being retrofitted with dry lignite firing to operate in the range of 20%-30% load

Table 2. Flexibility features of power plants [18].

3.3 Materials performances for flexible operating PPs

The pressure to maintain fuel flexibility, in terms of economical, low quality fuels with high efficiency, has resulted in a severe fouling and corrosion challenge for fireside surfaces of materials in boilers. In addition, the tendency toward new changing process conditions also has effects on the refractory materials lining the combustion chamber and the metallic alloys for the heat exchanger. In particular, the micro structural stability of metallic alloy can be damaged during long-term performance at high service temperatures. The refractory integrity can be damaged due to fast thermal cycling.

3.3.1 Metallic alloy for heat exchanger

In terms of metallic alloys for assure the flexible operation of CFB plants, information from the "DP700-PHASE 1" contemporary EU financed RFCS project [19] turns out to be helpful for the FLEX

FLORES. In fact the main targets of this project are to compile the most updated databases useful for selecting alloys as building materials of heat exchangers for a set of state of the art boilers. These databases are compiled on the following topics:

- material properties;
- material corrosion damage from fireside due to service conditions for a range of prospective fuels/boiler environment;
- material corrosion damage at steam side oxidation due to service conditions;
- overall material degradation due mechanical mechanism e.g. creep and fatigue.

However certification from material suppliers or simplified laboratory testing is not sufficient proof to qualify a material whose unexpected failure may cause major material losses or personal accidents. Long-term testing in commercially operating units constitutes the backbone of materials qualification. The simplest way to carry out long-term testing is to use either small test coupons or clamps anchored on the area of interest. Also longer test tubes or separate test loops are utilised in material testing. Test loop enables testing of different steam data, also covering future plants, without interfering with the steam production of the hosting commercial unit. The results give information on long-term material behaviour in both the fireside and steam side of the tubes, and the loop allows material testing in several temperatures at same time due to temperature gradient along the loop. During Finnish DIMECC project Productive boiler [20] a test loop (see Figure 10) with independent controls were designed, manufactured, and installed in an existing Äänekoski FB boiler (see Figure 11).

Figure 10 Welding test sections and setting up control valves of the steam loop

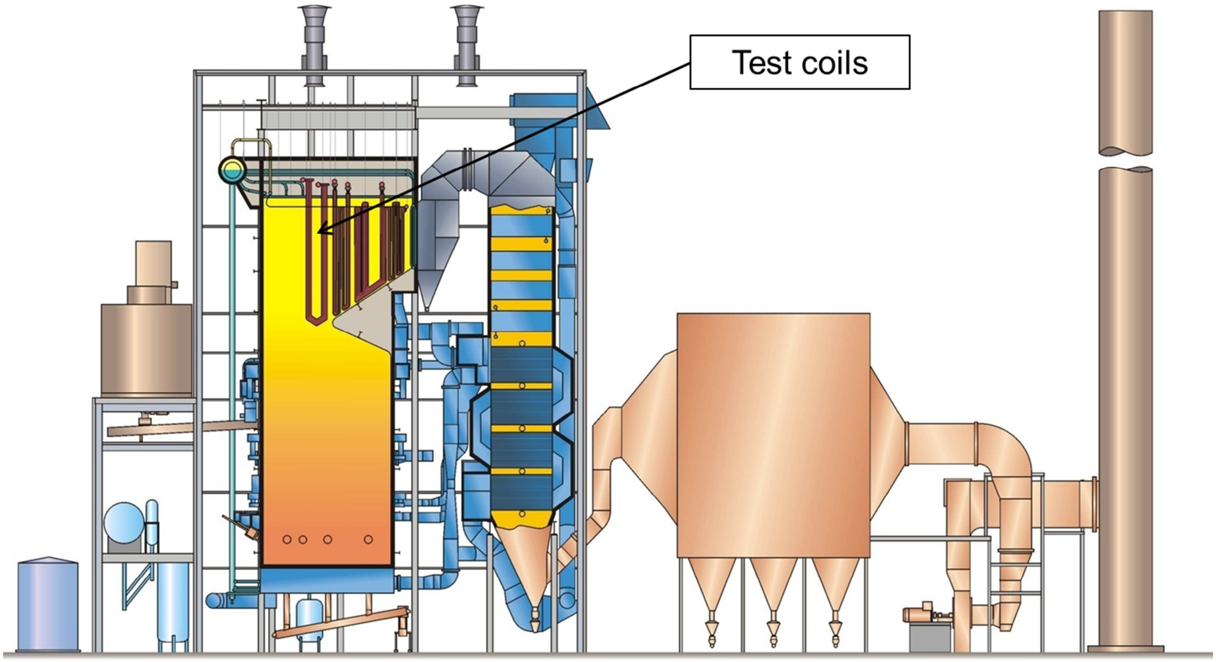

Figure 11. Test loop location in FB boiler

Tests in Äänekoski FB started in summer 2015, the plan was that test materials are collected during annual boiler maintenance shutdowns for detailed analysis in following three consecutive years. First samples were removed in May 2016 and another set of samples during May 2017 (see Figure 12). Collected samples were from exposure temperature regions of approximately 540°C and 570°C, and 620°C (2017).

Figure 12. Section of samples removed from Äänevoima FB steam test loop during May 2017 annual shutdown

Based on collected 2016 samples higher chromium content alloys have better oxidation resistance. Additionally, surface cold work (shot peening) seems to help steels to form protective oxide layer - all shot peened samples had very thin oxide layer (see Figure 12). Last samples will be removed during 2018 summer outage. After all the samples have been analysed, final conclusions can be made on fire-side corrosion as well as steam side oxidation performance, e.g. in respect of cold work effect time; oxidation kinetics (Figure 13) and oxide scale exfoliation tendency, of materials.

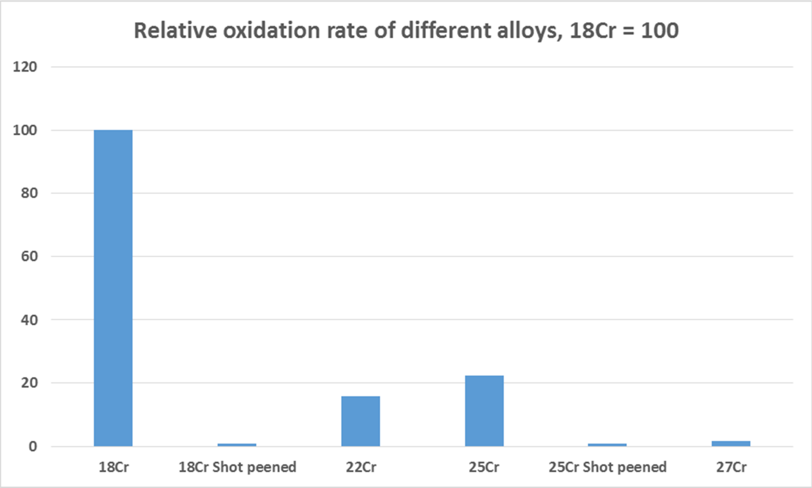

Figure 13. Oxidation rates of different materials exposed in Äänevoima FB test steam loop 2015-2016, values normalized and compared to 18Cr steel [19]

3.3.2 Refractory materials for lining the combustion chamber

For what concern the refractory materials lining the combustion chamber, in order to withstand the PP flexibility in terms of fuels they have to belong to the alkali resistance class of materials. This is due to the fact that all biomass and low rank fuel like lignite contain alkali which is now well known to be the corrosive agent for refractory materials. From the point of view of PP flexible operation the refractories are well known to manifest thermal shock due to fast heat up/down rates.

In order to withstand both conditions, an innovative class of refractories has been recently developed and patented [21] based on gradient in their chemical composition. The fireside of the new developed Compositionally Graded Refractory will be made of alkali resistant layer, the back side will be made of thermal shock resistant material in order to merge the two different properties in one single material. The overall refractory composition has to be purposely tailored as a function of the required thermal insulation of the lining in the PP.

The results from a previous EU financed project [22] will be the starting point that will be further integrated with the optimized method to analyse refractory alkali corrosion which has been published in a recent work [23].

4 Problems and related approach to solving

The problems already identified during the first discussions are the followings.

1. Refractory materials suffer thermal cycling. For this reason in order to select the best performing refractory materials it is important to know which could be the fastest heating rate that could be achieved under flexible operating conditions in industrial plants. This information will be an output of the FLEX FLORES project and therefore it is not available in time for the selection of the refractories.
2. Alloys for heat exchanger suffer corrosion due to different species volatilized by burning different fuels. For this reason in order to select the best performing alloy for heat exchanger, it is important to know the type of fuels that will be burned during the tests.

3. Low rank coal and biomass have to be identified as soon as possible in order to select the most performing metal alloy for heat exchanger.

As possible solutions for the above mentioned problems, the following approach has been identified as a good way to proceed:

A. **Problem 1**: the refractories will be selected on the basis of their best thermal shock resistance. Of course also the corrosion resistance will be an important parameter that will be also considered for the refractories selection. The planned laboratory tests (Task 2.2) and the tests with the rotary kiln (Task 1.4) will be tuned in order to test resistance against corrosion and thermal shock, respectively. In particular the rotary kiln will be heated faster than all industrial plants because of its small size and therefore low thermal inertia. Hence, the testing conditions for the materials can be considered as severer than those expected in the operating conditions of full scale plant.
B. **Problems 2 and 3**: the discussion regarding the types of fuel to be tested in pilot plant (WP4) is already started. The choice of the biomass types will be agreed within the next months. For what concern lignite, the country of origin will be Greece and Germany. However it is already known that the most corrosive biofuel is olive cake that was already tested under co-combustion conditions in a previous project. The information from previous or contemporary EU financed projects [19, 22] together with other national financed project [20] was considered for the selection of the best promising alloy materials for heat exchanger under corrosive conditions. Furthermore aggressive corrosion conditions will be purposely set up in the rotary kiln for testing the selected best promising alloy materials.

5 Outcome

The outcomes from the testing phase within the rotary kiln (task 1.4) will rank the selected materials. In fact, two types of rotary kiln tests are planned: a thermal cycling test for the refractory materials and a test under aggressive corrosion conditions for the metallic alloys. According to this operating conditions:

1. The thermal cycling tests will be able to rank the thermal shock resistance of the selected refractory materials and identify the fastest heating rate that the most performing refractories can withstand in industrial plants.
2. The best promising alloys for heat exchanger will be ranked according to the results of the corrosion resistance tests.

It is important to underline that the FLEX FLORES project has been already disseminated in the International Energy Agency – Fluidized Bed Conversion workshop hold in Skive Denmark 23-25 October 2017. The presentation was entitled "Assessing Circulating Fluidized Bed Combustors flexibility with respect to load changes and fuel type" [18].

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