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Flexible Co-Combustion of High Ratios of Sustainable Biomass with Coal in Oxy-CFB Boiler for CO_2 Capture

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Abstract

Coal-fired plants are under pressure to reduce their carbon-intensity. Available options include co-firing CO_2-neutral biomass, oxy-fuel-combustion as part of a carbon capture process or a combination of both to give a "CO_2-negative" power plant. BioCCS, the combination of CO_2 Capture and Storage (CCS) with sustainable biomass conversion, is the only large-scale technology that can achieve net negative emissions. Combining, developing and demonstrating the oxy-combustion of high ratios of sustainable biomass with coal in flexible circulating fluidized bed (CFB) boiler will bring significant advances in the reduction of greenhouse gases (GHG) emissions. Areas addressed include possibilities for: biomass characterization; handling and feeding; co-firing ratios definition; CFB oxy-co-combustion studies; combustion performance; boiler flexibility in fuel and load; main emissions analysis; slaging, fouling and agglomeration; corrosion and erosion; and implications on plant operation and associated costs. The article will detail a comprehensive understanding on sustainable biomass supply, co-firing ratios and how direct biomass co-combustion under oxy-fuel conditions can be implemented. It seeks to push biomass co-combustion in future large-scale oxy-fuel CFB power stations to high thermal shares while enhancing the power plants' operational flexibility, economic competitiveness and give operational procedures. There will be a need to consider the public acceptance of power production from coal and coal sustainability, by its combination with renewable sources of energy (biomass).

Keywords

Carbon Capture Use and Storage (CCUS), Biomass Combustion, Carbon Capture, CFB Boiler

1. Introduction

According to United Nations Framework Convention on Climate Change (UNFCCC) and the International Energy Agency (IEA), more powerful technologies are now needed to keep global warming below 2˚C and avoid irreversible climate change. There is therefore an urgent need for carbon-negative solutions such as Bio-CCS—the only large-scale technology that can remove CO_2 from the atmosphere. Bio-CCS could remove 10 Gt of CO_2 globally from the atmosphere every year by 2050, and in Europe, this amount could be of 800 million tons of CO_2 removed every year, which is equivalent to over 50% of current emissions from the EU power sector [1].

CO_2 is the most important greenhouse gas from anthropogenic sources and its concentration to the atmosphere has risen faster than ever in the last century. EU has adopted ambitious targets for reducing the emissions of greenhouse gases in the coming decades. These targets will not be achieved without significant reduction of CO_2 emissions from the energy sector, where the use of fossil fuels, primarily coal and gas, in power generation leads to approximately 40% of all CO_2 emissions in the EU.

Fossil fuel power plants provide 56% of the total electricity demand and, among them, coal power plants have a contribution of 29% in electricity generation. Energy forecasts show that fossil fuels will remain as the main primary source for electricity generation in the medium and long term. These will be a share in power generation of the order of at least 40% - 50% in 2030 [1]. For this reason the "*Energy roadmap* 2050" report highlights that carbon capture and storage (CCS), if commercialized, will have to contribute significantly to European power generation around 19% - 24% in usual scenarios.

In Europe, the European Strategic Energy Technology Plan (SET-Plan) defines the energy technologies roadmap up to 2020. One of the objectives of this Plan is to strengthen and coordinate the overall efforts in Europe on energy issues. This covers the aim to accelerate the innovation in Europe on low carbon technologies to facilitate the achievement of the 2020 targets and the 2050 vision of the Energy Policy for Europe. The targets for 2020 are:

- *To reduce greenhouse gas emissions by* 20%;
- *To ensure* 20% *of renewable energy sources in the EU energy mix;*
- *To reduce EU global primary energy use by* 20% *by* 2020.

In particular, for CO_2 emissions the EU members must enable the commercial use of technologies for CO_2 capture, transport and storage through demonstration at industrial scale, including whole system efficiency and advanced research. Therefore, the EU plans to set up a network of CCS demonstration plants by 2015 to test their viability, with the aim of commercial update of CCS technologies by around 2020.

Oxy-combustion capture is one of the leading and most cost-effective CCS technologies which have proven its potential for industrial scale power production and for retrofitting existing power stations for CCS. Oxyfuel or oxycombustion is based on the denitrification of the combustion medium. The nitrogen is removed from the air through a cryogenic air separation unit (ASU) or other method. The combustion is carried out with a mixture of pure oxygen and recirculated flue gas, the result is a flue gas containing mainly CO_2 and water. The technological progress for oxy-combustion has multiple potential paths which include the use of more sustainable fuels such as biomass.

However, there are some key research tasks that have to be solved in the coming years to deploy CCS. In particular, Oxy combustion of high ratios of biomass with coal in CFB boiler (Circulating Fluidized Bed) boilers has some technical research issues which have to be clarified: fuel characteristics, fuel availability, fuel delivery, storage and handling, combustion characteristics, slagging and fouling, corrosion and erosion, ash/bed-related issues for CFB boilers, cofiring ratios and emissions (CO_2, SO_2, NO_x, HCl, Particulate emissions).

2. Concept and Objectives

According to United Nations Framework Convention on Climate Change (UNFCCC) and the International Energy Agency (IEA), more powerful technologies are now needed to keep global warming below 2˚C and avoid irreversible climate change. There is therefore an urgent need for carbon-negative solutions such as BioCCS—the only large-scale technology that can remove CO_2 from the atmosphere. In Europe, Bio-CCS could remove 800 million tons of CO_2 from the atmosphere every year by 2050 [2].

The proposed idea focuses on the urgent need for carbon-negative solutions. These are systems which can remove CO_2 from the atmosphere, for example BioCCS, where biomass also draws CO_2 down from the atmosphere whilst it is growing. BioCCS, the combination of CO_2 Capture and Storage (CCS) with sustainable biomass conversion, is the only large-scale technology that can achieve net negative emissions. This has already been recognized at an international level: IPCC's Special Report on Renewable Energy Sources and Climate Change Mitigation and in the Technology Roadmap Carbon Capture and Storage in Industrial Applications jointly published by the IEA and the United Nations Industrial Development Organization (UNIDO) [3].

The proposed implementation idea will contribute to obtain a comprehensive understanding on sustainable biomass supply, co-firing ratios and how direct biomass co-combustion under oxy-fuel conditions can be implemented. It seeks to push biomass co-combustion in future large scale oxy-fuel CFB power stations to high thermal shares while enhancing the power plants' operational flexibility, economic competitiveness and give operational procedures.

3. State of the Art

3.1. Sustainable Biomass Availability, Characterization, Handling for Co-Combustion in Large CFB Power Stations

Currently, fossil fuels such as oil, coal and natural gas represent the prime energy sources in the world. However, it is anticipated that these sources of energy will deplete within the next 40 - 50 years [4]. Biomass, given its renewable characteristic, is one of the earliest sources of energy with very specific properties that can overcome this and other problems.

The availability of biomass is especially important when considering cofiring of biomass and coal at high ratios of biomass. It is essential that the biomass is cultivated sustainably to not affect food production or tropical rain forests. Some types of waste streams containing biomass are also suitable for cofiring. For these streams, continuity and consistency of supply are of paramount concern. Doran [5] has assessed the availability of biomass in the EU while Hansson and others [6] [7] have specifically focused on cofiring biomass with coal for electricity generation and assessed the near-term technical potential for biomass cofiring with coal in EU.

Preventing the possible negative effects of growing biomass supply will, in the longer term, require a process-oriented development of refined criteria and indicators involving relevant stakeholders. International work is already taking place to ensure that communities, biodiversity and land are protected and a number of certification schemes and sustainability initiatives are already in place, e.g. for biofuels. As it is difficult to trace such effects, this is a widely discussed subject. The European Commission has organised consultations on how to address indirect land-use change (ILUC) within existing sustainability criteria for biofuels on the EU market and it is already being addressed.

The issues regarding the delivery, storage and preparation of biomass are different from those of coal. These issues will be particularly apparent when cofiring high biomass ratios. It may also be necessary to add extra flexibility in fuel storage and handling facilities to utilise multiple sources of biomass. The handling and flow properties of biomass are usually more problematical than coal due to the fuel size variation and high fibre and oversized particle content. Several aspects should be evaluated, such as: the design of receiving pits and pre-screens, the transport capacity of conveyors and reclaimers, the sizes of the intermediate stores need, moisture content, temperature, gas composition and dust control in the long-term storage. The lack of experience on the behaviour of those fuels in the complete combustion process cycle at high thermal shares hinders their application in industrial power production.

In addition to that, the biomass could be an important economic vector for rural areas development apart from achieving the 2050 objectives for CO_2 emissions reduction. Coal mining is another important economical vector, and by using coal as base fuel, coal mining can benefit from sustainable energy production and increase its feasibility.

3.2. Oxyfuel Technology

Over the past 20 years of oxy-fuel combustion research, most of the work done focused on an investigation of oxy-fuel combustion of coal. Many uncertainties of the technology have been clarified. For example, comprehensive information on oxy-coal flue gas emissions (e.g.: NO_x, SO_x) has been established. Recently completed and ongoing oxy-fuel proposed ideas (e.g. OXYBURNER, RELCOM, OXYCORR, FLEXIBURN, MACPLUS) are at this point aiming to overcome identified barriers for commercial deployment of the technology (e.g. slagging, fouling and corrosion issues, burner scale-up, flame stability, etc.). Very recently, issues related with the downstream processing of CO_2 in oxy-fuel CCS chain (e.g.: Hg induced Al-corrosion) have gained more attention.

Although significant amount of research proposed ideas have been carried out on oxy-fuel combustion of coal, there are still knowledge gaps to be resolved in order to ensure the successful deployment of the technology. Investigations for biomass co-combustion under oxy-fuel conditions, only very limited information (derived from laboratory scale tests) are available.

3.3. Biomass Co-Firing under Air and Oxy-Fuel Conditions

Direct biomass co-combustion in large scale power plants has been applied commercially in numerous power stations all over the world, most of them operating with pulverized fuel. Co-combustion thermal shares up to 30% have been commercially realized, while the majority of power stations with biomass co-combustion are operating in the range of 5% - 15%, with an increasing tendency in respect to shares within the last decade. According to the IEA, more than 150 power plants worldwide have experience of cofiring biomass or waste fuels, at least on a trial basis. Though many coal-fired power plant have cofired low percentages of biomass, only about a dozen have cofired high percentages (>15% by weight) over extended periods.

Biomass co-firing ratios strongly depend on the characteristics of the biomass used and the layout of the power plant. Achieving elevated co-firing ratios has proved difficult as untreated biomass is typically fibrous and inhomogeneous in nature. It has a lower energy density and different inorganic composition to hard coal; it is also vulnerable to biodegradation and hydrophilic in nature.

Sloss [8] has reviewed the emissions from cofiring coal, biomass and sewage sludge. In general terms, the majority of studies reviewed in the report demonstrated that, assuming combustion conditions are optimised, the cofiring of biomass with coal resulted in a reduction of major pollutants such as SO_2 and NO_x [9] [10].

It has been found that utilizing biomass in boilers offers many economical, social and environmental benefits such as financial net saving, conservation of fossil fuel resources, job opportunities creation and CO_2 and NO_x emissions reduction [4]. However, care should be taken to other environmental impacts of biomass such as land and water resources, soil erosion, loss of biodiversity and deforestation. Fouling, marketing, low heating value, storage and collections and handling are all associated problems when burning biomass in boilers.

The availability of a secondary high-volatile fuel feed in a coal power plant with biomass co-combustion can enable operators to realize quicker load changes. In such highly flexible operating modes, temporally increased co-combustion shares up to 50% are a likely scenario. The impact of co-combustion on emissions in highly flexible operating modes has not been comprehensively studied.

Co-combustion is considered to be a viable measure to compensate changes in gas flow rates, combustion temperatures and gas temperatures in the radiative and convective paths during biomass co-combustion and avoid their negative impact on plant operation and efficiency. However, the knowledge on oxy-fuel mono- and co-combustion of biomass is very limited. Only very few reports and peer-reviewed publications dealing with this matter are publicly available without any information on the technique's performance in technical and large scale, this leaves many significant questions unresolved.

3.4. CFB Co-Combustion, Oxy-Combustion and Oxy-Co-Combustion

CFB development started during the mid-1970s. In 1979, the first commercial CFB unit was started up in Finland. Following this successful installation, the number of installations has been increased rapidly in the past decades. CFB boilers are usually smaller than large utility boilers—ranging from 50 to 500 MW_{th}—more flexible regarding fuels and typically located in close proximity to urban areas or industrial facilities [11].

Typical benefits of CFB boilers compared to pulverized coal boiler are the fuel flexibility, the low combustion temperature contributes to low NO_x levels and cost-effective SO_2 capture with limestone. The flexibility of the fluid-bed process offers an outstanding benefit for CFB in retaining more uniform furnace temperature profiles, metal temperatures and local heat production rates in air-firing as well as oxygen-firing and under varying load conditions. Limestone addition into the furnace for sulphur capture under oxygen-firing conditions can ease subsequent separation of CO_2 from flue gas [12].

Due to availability and heterogeneity problems of biomass and CFB flexibility for burning different fuels, co-combustion in CFB is the solution.

3.5. CFB Co-Combustion

CFB boilers have been commonly utilized for co-combustion of biofuels and coal due to the high degree of fuel flexibility of this technology in relation to particle size, density, moisture and ash content of the fuel. CFB boilers designed for coal combustion can generally switch to waste/coal cofiring with a relatively small investment [13].

There are several factors related to the composition of the fuel ash which can adversely affect the operation of CFB boilers [14]. In most fluidized bed combustors, there is a tendency for fuel ash and bed material to sinter and form agglomerates. Excessive agglomeration can lead to poor air distribution and eventually to defluidisation of the bed.

The increasing requirement for CFB boilers to co-fire biomass and waste fuels has increased the stress on the boilers, necessitating more frequent replacement cycles and increased maintenance costs. Detailed investigations of corrosion have been conducted at the 80 MW_{th} CFB boiler at Grenå in Jutland, Denmark, which fired a 50/50 mixture of coal and straw [15]. The corrosion rates of the superheater tubes were found to be five to twenty-five times faster than when firing coal alone [16] [17] [18] [19] [20].

3.6. CFB Oxy-Combustion

Oxygen-fired circulating fluidized bed (CFB) steam power plant is a viable option for near-term CO_2 capture. Oxy-CFB boiler is fired with pure oxygen plus recirculated flue gas (mainly CO_2) instead of atmospheric air, resulting in a flue gas stream with a high CO_2 concentration. Consequently, CO_2 can be separated from the flue gas stream relatively easily [21]. A CFB is ideal for application of oxygen firing because the CFB process recirculates a large stream of cooled furnace solids that aids in the control of combustion temperature. Other advantages of an oxygen fired CFB include fuel flexibility, good emissions performance, boiler island cost savings as compared to PC and Stoker firing, and ease in scale up [22].

Some studies have already been undertaken to investigate the process of oxygen-firing, but mostly for pulverized fuel combustion. Experimental oxygen-firing CFB studies have been done by Alstom (USA) CANMET (Canada), Czestochowa University of Technology (Poland) and VTT Technical Research Centre (Finland) and CIUDEN (Spain). These investigations, mainly focused on the basic fundamentals related to good combustion performance were achieved with high combustion efficiency and, generally, all emissions were lower or at the same level compared to air-firing. In order to fully utilize the potential provided by oxygen-firing CFB, deeper understanding of combustion parameters should be gained by experimental work on the pilot-scale combined with model development and validation [23]. The impact of several combustion parameters, such as fuel properties, oxidant staging, combustion temperature, etc., needs to be investigated and that knowledge should be implemented in the models and further utilized in the design of oxygen-firing CFB boiler. Only few concept development proposed ideas and publications on oxygen-firing-CFB power plants can be found, and most of them are based on fictional cases and are more or less overall studies of the costs and competitiveness of oxygen-firing technology. None of them ongoing or proposed oxygen-firing demonstration proposed ideas are based on CFB technology except CIUDEN's pilot-scale plant.

The most relevant international research European projects on BioCCS combustion are shown in **Table 1**. Also, **Table 2** shows relevant pilot and demonstrative coal oxy-fuel initiatives worldwide.

4. Research Approach

The research program has been structured in four stages.

Table 1. Relevant past and ongoing European Commission projects.

N°	Reference	Title	End date
1	FP7-ENERGY-2008.6.1.1-239188	FLEXIBURN CFB—Development of High Efficiency CFB Technology to Provide Flexible Air/Oxy Operation for Power Plant with CCS.	31/08/2012
2	RFCR-CT-2013-00010	BiOxySorb—Economic low carbon power production and emissions control for future and flexible biomass co-fired power stations.	30/06/2016
3	ENER/SUB/323/EEPR 2010/SI2.559733	OXYCFB300—COMPOSTILLA PROPOSED IDEA-CCS integral Commercial Demonstration Proposed idea. 323 MWe gross Circulating Fluidized Bed (CFB) supercritical oxycombustion plant, with CO_2 storage in a saline aquifer.	31/10/2013
4	RFCR-CT-2006-00010	BOFCom—Application of the biomass, oxyfuel and flameless combustion for the utilization of pulverized coals for electricity generation.	31/12/2009
5	FP6-SUSTDEV-reference: 503806	COPOWER—Synergy Effects of Co-processing of Biomass with Coal and Non-toxic Wastes for Heat and Power Generation.	30-04-2007
6	FP5-EESD-ref: ENK5-CT-1999-00004	BIO FLAM—Combustion behavior of clean fuels in power generation	28-02-2003
7	RFCR-CT-2005-00009	CFB800—Utility scale CFB for competitive coal power.	31/08/2008
8	RFCR-CT-2003-00001	CLEFCO—Advanced CFB for clean and efficient coal power.	31/12/2006
9	RFCR-CT-2006-00009	OxyBurner—Development of advanced large scale low NOx oxy-fuel burner for PF combustion.	30/06/2009
10	RFCR-CT-2009-00005	OXYCORR—Boiler corrosion under oxy-fuel conditions.	31/08/2012
11	FP5-EESD-reference: 13578	POWERFLAM2—Studies Of Fuel Blend Properties In Boilers And Simulation Rigs To Increase Biomass And Bio-waste Materials Used For Co-firing in Pulverized Coal Fired Boilers.	31-12-2006
12	RFCR-CT-2005-00006	OXYMOD—Development and experimental validation of a mathematical modeling methodology for oxy-fuel combustion for CO_2 capture in large power plants.	31/10/2008
13	FP7-ENERGY-2007-218968	DEBCO—Demonstration of Large Scale Biomass Co-Firing and Supply Chain Integration.	31-12-2012
14	FP7-SME-2011-286978	BIOCAT—Clean Air Technology for Biomass Combustion Systems.	2013-10-31
15	FP7-ENERGY-2010-268191	RELCOM—Reliable and Efficient Combustion of Oxygen/Coal/Recycled Flue Gas Mixtures.	30-11-2015
16	RFCR-CT-2008-00009	SMARTBURN—Intelligent control and optimization of power station boilers firing pulverized coal and coal/biomass blends.	30/06/2011
17	FP7-INFRASTRUCTURES-2011-284498	BRISK—The European Research Infrastructure for Thermochemical Biomass Conversion.	2015-09-30
18	RFCP-CT-2006-00011	CERCOT—CO_2 emission reduction through combustion optimisation technologies at coal-fired power plants.	30/06/2009
19	SES6-CT—2004-502666	ENCAP—Enhanced Capture of CO_2.	15-04-2009
20	FP7-PEOPLE-2012-318927	ENV-BIO—Technical and environmental analysis of advanced strategies for the energy valorization of biomass.	2016-12-31
21	RFCR-CT-2006-00007	FriendlyCoal—Cost effective and environmental friendly oxyfuel combustion of hard coals	30/06/2009
22	FP7-INFRASTRUCTURES-2011-284498	BRISK—The European Research Infrastructure for Thermochemical Biomass Conversion.	2015-09-30
23	FP7-PEOPLE-2012-IRSES-312261	ICOMFLUID—International Collaboration on Computational Modeling of Fluidized Bed Systems for Clean Energy Technologies.	2016-09-30

Continued

24	RFCR-CT-2003-00004	MINORTOP—Minimization of impact of nitrogen oxide reduction technologies on operation and performance.	31/08/2007
25	FP7-ENERGY-2011-295645	OCTAVIUS—Optimization of CO_2 Capture Technology Allowing Verification and Implementation at Utility Scale.	2017-02-28
26	FP7-ENERGY-2008-239530	RECOMBIO—Recovered Fuels combined with Biomass.	31-12-2012

Table 2. Relevant pilot and demo coal oxy-fuel projects worldwide.

N˚	Country	Name	Power
1	Germany	SchwarzePumpe oxy-fuel pilot plant in Spremberg	30 MWth
2	Australia	Callide Oxyfuel Proposed idea in Callide, oxy-fuel demo plant, retrofit	30 MWel
3	UK	White Rose oxy-fuel proposed idea, oxy-fuel demo plant in Selby	426 MWel
4	China	Shanxi oxy-fuel proposed idea, oxy-fuel demo plant in Taiyuan	350 MWel
5	China	Daqing oxy-fuel proposed idea, oxy-fuel demo plant in Heilongjiang	350 MWel
6	USA	Futuregen 2.0, oxy-fuel demo plant in Meredosia	200 MWel
7	Spain	Compostilla proposed idea, OXYCFB300, in El Bierzo	323 MWel

Stage 1—Sustainable biomass availability, characterization, handling, selection, co-firing ratios definition and oxy-co-combustion parameters study. This will study the availability of sustainable biomass as source of energy taking into account area, land uses, year and season, and other drawbacks such as handling limitations. It will be used for performing a biomass screening as select fuels (coal and biomasses). Furthermore, a comparison of CFB combustion, co-combustion, oxy-combustion and expected CFB oxy-co-combustion parameters will be defined.

Stage 2—Large scale oxy-CFB boiler demonstration of biomass and coal oxy-co-combustion. Pre-commercial scale demonstration tests of co-combustion and oxy-combustion will be needed. Based on comprehensive assessment on parameter studies air and oxy-fuel experiments will be planned and performed with selected biomasses, co-firing shares and operational changes (in load and fuel blend) Test campaigns will evaluate the performance of biomass co-combustion in air and oxy-fuel combustion mode and to investigate the performance of the system. Stage 2 will receive input from stage 1 for the planning of the test runs and it will deliver fundamental data for the parameter analysis and operational procedures definition in stage 3, and for the technical and economical evaluation in stage 4.

Stage 3—Parameters analysis, conclusions, recommendations and operational procedures. This stage will analyse data and samples from stage 2. It will focus on performance, emissions and other relevant aspects such as relevant slagging, fouling and corrosion from oxy-co-CFB-combustion. Finally guideline for best operational procedures will be by settled.

Stage 4—Risk assessment and techno-economical conclusions and recommendations. A risk assessment will be performed and techno-economical conclusions and recommendations will be drawn. The objective is to assess the impact of the results of the work carried out in earlier stages for the installation of biomass co-combustion in full-scale oxy-fuel utility boilers and to make recommendations how such systems can be optimised in practice. This WP is fundamentally reliant on the data obtained from previous stages that deliver input information for the techno-economic and risk evaluation.

5. Conclusion

There are important benefits on the oxyfuel combustion of large ratios of biomass combined with carbon capture technologies. However, to date there have not been enough studies. These tests carried out demonstrated the large scale feasibility of oxy-co-CFB combustion, however, more operational and fuel tests are needed to reduce uncertainties related to biomass properties. The modification of boiler load, blend dynamic variation, and high ratios of biomass co-combustion have not been carried out yet. The proposed research approach will help to understand uncertainties of biomass combustion with coal in CFB boilers.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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