# A scoping study on Oxy-CFB technology as an alternative carbon capture option for Australian black and brown coals

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# Executive Summary


Circulating Fluidized Bed combustion (CFBC) units use bed materials (such as silica sand) in which to combust coal at about 900°C temperature. CFBCs can tolerate varying particle size (from micron size as in pulverized coal-fired units to coarse feed size around ~10mm), and varying fuel quality (from anthracite to lignite, petroleum coke, biomass, and opportunity fuels). CFBC plants were originally developed for use with low-quality and "difficult-to-burn" fuels – high sulfur, high ash, low calorific value and combinations – or where fuel flexibility was required, such as the availability of variable quantities of wastes for co-firing with more traditional fuels. However, gradually CFBCs have established themselves as being suitable for almost all types of solid and several liquid fuels.

The largest CFBC with supercritical steam parameters and unit size of 460 MWe operates in Poland with bituminous coals. New supercritical steam CFBC boilers between 550-600 MWe size are under construction in China and Korea. Commercial guarantees for units up to 800 MWe are currently available. In contrast, *pf* boilers are now available to 1100 MWe unit size with ultra-supercritical steam parameters.

Apart from demonstrated performance of fuel flexibility, the ability to capture sulfur *in-situ*, eliminate slagging and reduce fouling during operation, and reduced $NO_x$ emission without requiring low-$NO_x$ burner are some of the major advantages of CFBC boilers.

Oxy-CFB operating at atmospheric pressure is emerging as a serious technology option for $CO_2$ capture. This is demonstrated by the rapid design and construction of world's first Oxy-CFB pilot scale facility at CIUDEN in Spain, which was commissioned in September 2011. The facility is designed and operated by Foster Wheeler, and will primarily test non-lignitic coals. In addition to the 30MWth Oxy-CFB unit, the facility also has a 20 MWth Oxy-PF unit and a biomass gasifier. A 300 MWe Oxy-CFB plant is also under consideration in the adjacent Compostilla Power Station.

Among the technology vendors, ALSTOM appears to be dormant in the development of Oxy-CFB following a number of years of pilot scale development work and feasibility studies. B&W is now active in China which has the largest CFBC installations. Foster Wheeler is the primary technology provider for Oxy-CFB. This position will be enhanced due to the Foster Wheeler's involvement in the CIUDEN facility.

Compared to Oxy-PF, Oxy-CFB has potential advantages, including:

- Reduction of flue gas recycling, thereby reducing the size of the boiler island, and some of the auxiliaries consumption. This may potentially allow more compact and less expensive CFB boilers
- Direct (in-bed) sulfur removal in Oxy-CFB may avoid the capital and operating costs associated with an FGD required for Oxy-PF. Direct sulfation of limestone will occur due to the high partial pressure of $CO_2$ and the right thermodynamic temperature for sulfur capture. Calcium conversion under direct sulfation is usually higher than that under calcination/sulfation due to the better porosity of product layer as suggested by several studies.

- Oxygen concentration in the recycled flue gas can be kept to a low and safe level, while additional oxygen can be introduced through oxygen nozzles separate from the burner or the secondary gas inserting points. Thus relative to air-CFBs, Oxy-CFBs do not need new burner design.
- As CFBC's are operated at slightly over atmospheric pressure, possibility of air-in-leakage is greatly reduced.

Oxy-CFB can play a significant role as a technology for $CO_2$ capture. Based on the small and bench scale results from various units around the world, Oxy-CFB appears for the time being to be more suitable for low-rank or high-S or high-ash coals. While Oxy-CFB in principle has the potential to be cheaper than Oxy-PF, there is considerable cost uncertainty, stemming primarily from lack of reliable information on trace pollutant and S-species removal and emissions. This will impact the gas cleaning requirements downstream of the CFBC unit, and hence the overall cost of the system. The long-duration performance results from the CIUDEN facility will be vital to remove or significantly reduce some of these uncertainties.

Pre-drying of coal will be essential if high-moisture coals are to be used in Oxy-CFB.

Targeted bench scale experiments using selective Australian black and brown coals to assess the emission of S-species and trace elements under Oxy-CFB conditions are recommended to allow a definitive economic analysis of the Oxy-CFB system to Australian coals to be carried out. Serious consideration should also be given to carry out testing two representative Australian coals at the CIUDEN facility

Due to the current state of technical maturity of Oxy-CFB, a confident comparison of the cost and energy penalty figures between the two technologies cannot be made at this stage. Published literature is divided on comparative costs, with only scant details being available. A report by NETL (2010) states installed cost (US$/kW) Oxy-CFB to be 8% more expensive than Oxy-PF, while publications from EDF in 2009 based on Alstom and Foster Wheeler data state large Oxy-CFBs to be 10% cheaper than Oxy-PF. Some estimates of differences for Oxy-CFB may be suggested in terms of CAPEX, OPEX and energy penalty, as follows:

**CAPEX:** The CAPEX cost advantage for Oxy-CFB may exceed 5% depending on suitability on in-bed S removal and reduction of flue gas recycling, reduced size of boiler and its auxiliaries. The avoidance of downstream S removal has yet to be proven, and may apply favourably for Oxy-CFB using low-S coal, and the form of S, in particular the organic S which is emitted in the gaseous phase.

**OPEX and energy penalty**: The OPEX advantage is based on air leakage reduction, lower excess $O_2$ operation and lower auxiliary power. Lower excess $O_2$ operation alone may reduce the oxygen supply of the ASU by 10%, associated with a reduction of the Oxy-fuel energy penalty from typically 9% by 0.5%.

**$CO_2$ recovery:** Reduced air leakage for Oxy-CFB may result in increased $CO_2$ recovery of greater than 10%.

A roadmap for future Oxy-CFB deployment is presented, revealing that due to the current status of Oxy-CFB development compared to Oxy-PF, there is greater uncertainty regarding future technology development and deployment. Common drivers include a potential future cost of $CO_2$, and development of higher USC efficiency commercial plant. The roadmap indicates a delayed application of higher temperature steam conditions for CFB compared to PF based on IEA projections. Although Foster Wheeler indicate guarantees can currently be provided for USC CFB units, the commercial risk of their deployment must be considered to be greater. Noted for Oxy-CFB is the current need for more fundamental and applied research related to the uncertainty of coal performance and gas quality control, in order to define the appropriate Oxy-CFB flowsheet.

As operational experience becomes available from CIUDEN, it will be worthwhile to carry out an in-depth cost study on Oxy-CFB using representative Australian coals.

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# Introduction

ANLECR&D is developing an Australian national program for collaborative low emission coal R&D, and will oversee its implementation and operation. The program, initially funded by $75M each from the Federal Government and the Australian Coal Association, is for a seven year period. This R&D will be taken in ANLECR&D research nodes, which will be based on existing research centres or, if necessary, developed for the purpose.

The ANLECR&D construct has seven research nodes – economic studies, fundamentals, brown coal, three capture technologies – oxy-combustion (commonly called Oxy-fuel), post-combustion capture, gasification – and carbon dioxide storage. More details of ANLECR&D activities are available at http://www.anlecrd.com.au/.

The ANLECR&D has sponsored several status reports and scoping studies since 2009. These include Australian R&D on low emission coal technology (Simento and Lowe, 2009), Oxy-fuel scoping study (Wall, 2009), brown coal R&D research (Campisi and Woskoboenko, 2009) black coal IGCC (Harris and Roberts, 2010) $CO_2$ capture (Feron and Hooper, 2009)

This report is a scoping study on coal-fired Oxy-fuel technology based on circulating fluidised beds (Oxy-CFB) as an alternative carbon capture option for Australian black and brown coals. The most common Oxy-fuel technology is based on pulverised coal (Oxy-PF), with oxygen substituting for air, thereby producing a $CO_2$ product with a concentration high enough for compression with adequate recovery and acceptable energy requirement. Oxy-CFB uses a similar approach, with $O_2$ substituting for air and a recycle stream to dampen temperatures and maintain gas flow.

Australia has a current focus on Oxy-PF due to the Callide Oxy-fuel Project which has been developed over a period of several years, but the emergence of Oxy-CFB as an alternative in that period and its relevance has not been considered. The objectives of this report are as follows:

- Report the current technology status and vendor capability for Oxy-CFB with roadmap to deployment, including current research efforts, and planned pilot-plants and demonstrations
- Compare Oxy-CFB to Oxy-PF for $CO_2$ capture in Australia, fired with Australian black and brown coals, with initial assessment of cost and energy penalty differences
- Provide recommendations for inputs to allow Oxy-CFB inclusion in technology comparisons in the Techno-Economic Analyses for Low Emissions Energy from Coal (TEA) program of ANLECR&D
- Provide recommendations for Australian R&D on Oxy-CFB

# CHAPTER 1

## Coal-fired Power Generation and Circulating Fluidized Bed Combustion (CFBC)

Coal is used as fuel for almost forty percent of power generation worldwide (IEA, 2010). This role is set to continue in the foreseeable future. Figure 1 presents the global coal-fired capacity and the age distribution of the units, while Figure 2 presents the age and size distribution of the units (Platts, 2011).

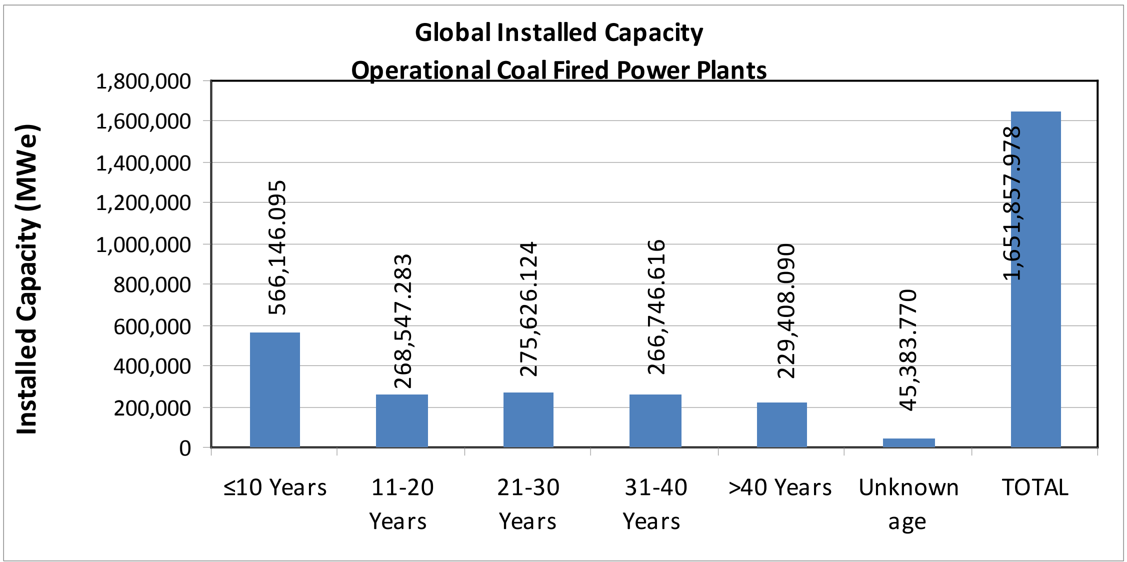


***Figure 1**: Global Coal-fired power generation capacity and age distribution of the units*

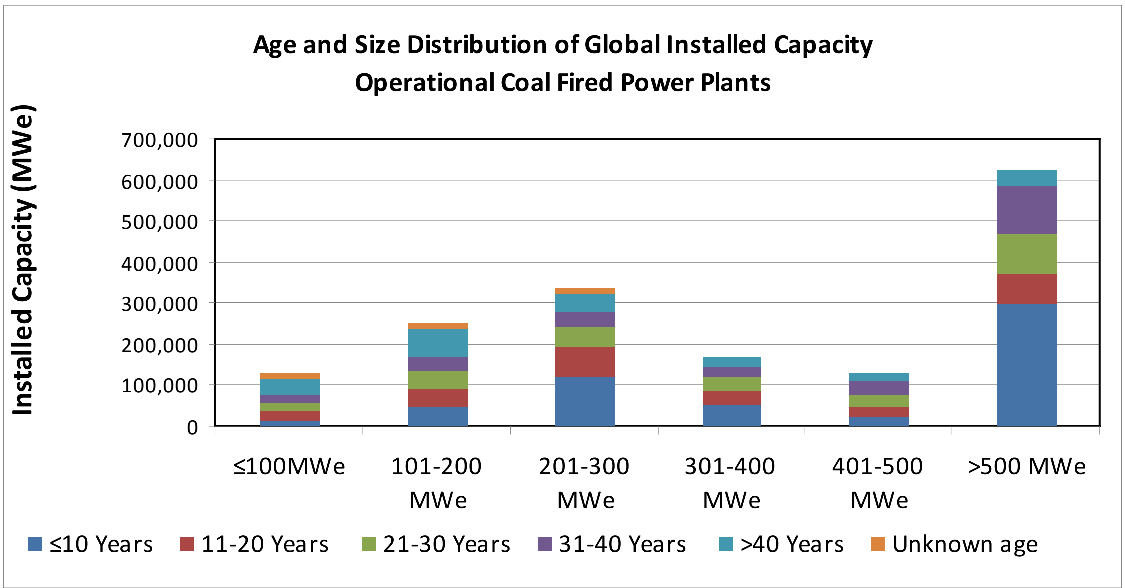


***Figure 2:** Age and size distribution of coal-fired power generation units worldwide*

At the end of March 2011, the global coal-fired power generation capacity was approximately 1650 GWe, which increased from almost 1240 GWe in 2006 (Platts, 2011). Pulverized coal-fired technology is the dominant technology for coal-fired power generation at present, with unit sizes up to 1100 MWe operating in Europe and China. Majority of the new coal-fired capacity additions (~70%) has been in China.

**Coal-fired power generation - Australian context**

*In Australia, black and brown coals generate 77% of our electricity (ESAA, 2010).*

*In 2009-2010, out of 230,674 GWh electricity generation, 53% was sourced from black coal and 24.3% was from brown coal.*

*Out of a total of 52000 MWe generation capacity, black coal power station capacity was just over 22000 MWe, while brown coal based power generation capacity was just over 7300 MWe (ABARE, 2011).*

*Of the total coal (black coal and brown coal) fired capacity, all except 140 MWe was based on the pulverized coal-fired technology.*

## What is Circulating Fluidized Bed combustion (CFBC)

CFBC units use bed materials (such as silica sand) to support the combustion of coal or any solid fuels around 900°C temperature to generate heat. Steam generated inside the combustor can be used for power generation in steam turbines. CFBCs can tolerate varying particle size (from micron size as in pulverized coal-fired units to coarse feed size around ~10mm), varying fuel quality (from anthracite to lignite, petroleum coke, biomass, and opportunity fuels).

Major characteristics and advantages of CFBC are listed in the highlighted box below.

**Characteristics of CFBC and advantages**

*Lower operating temperature, around 900°C, relative to pulverized coal combustion*

*Bed materials and coal/char particles circulating throughout the furnace and return leg at high velocity, 3-8m/sec*

*Fuel flexibility – from high to low-grade fuels, biomass and opportunity fuels*

*Uniform heat flux*

*Excellent load-following capability*

*In-situ sulfur dioxide capture rather than flue gas desulfurisation as in pulverized coal combustion, and higher calcium utilization*

*Lower $NO_x$ formation relative to pulverized coal combustion due to lower operating temperature*

*Improved combustion efficiency due to longer residence time of the circulating solids, relative to pulverized coal combustion*

*Less erosive ash relative to pulverized coal combustion*

*Compact boiler size*

*Simplified fuel feeding, pulverization is not required, crushing is sufficient*

***Efficiency of CFBC units is similar to pulverized coal-fired units under identical steam conditions***

The high combustion temperatures in pulverised coal fired boilers can be the cause of slagging and fouling problems in the furnace, superheater and reheater sections depending on the coal quality. Therefore regular soot blowing is required to keep these areas clean. On the other hand, combustion temperature in CFBC boilers is low, around 900°C, which reduces slagging or fouling problems. Therefore, soot blowing is not required except in low temperature areas, such as economiser, primary superheater, airheater (Macdonald, 2006)

A typical schematic of a CFBC based power generation plant is presented in figure 3.

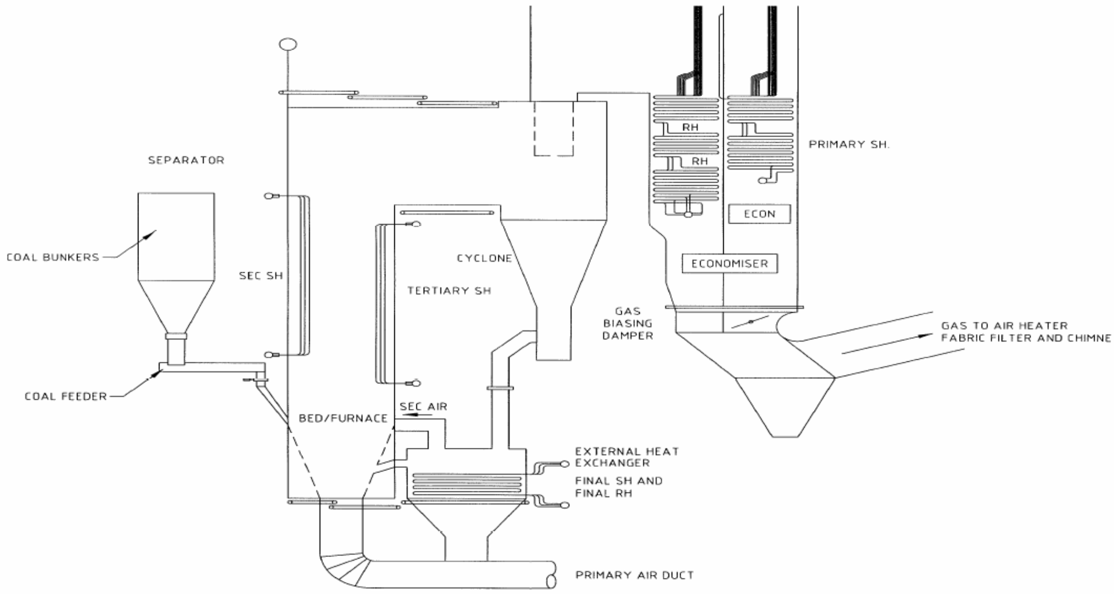


***Figure 3:*** *Schematic of a CFBC boiler plant (Macdonald, 2006)*

## Status of air-fired CFBC technology

Figure 4 presents the regional CFBC capacity for power generation purposes, while figure 5 presents the age and size distribution of these units (Platts, 2011).

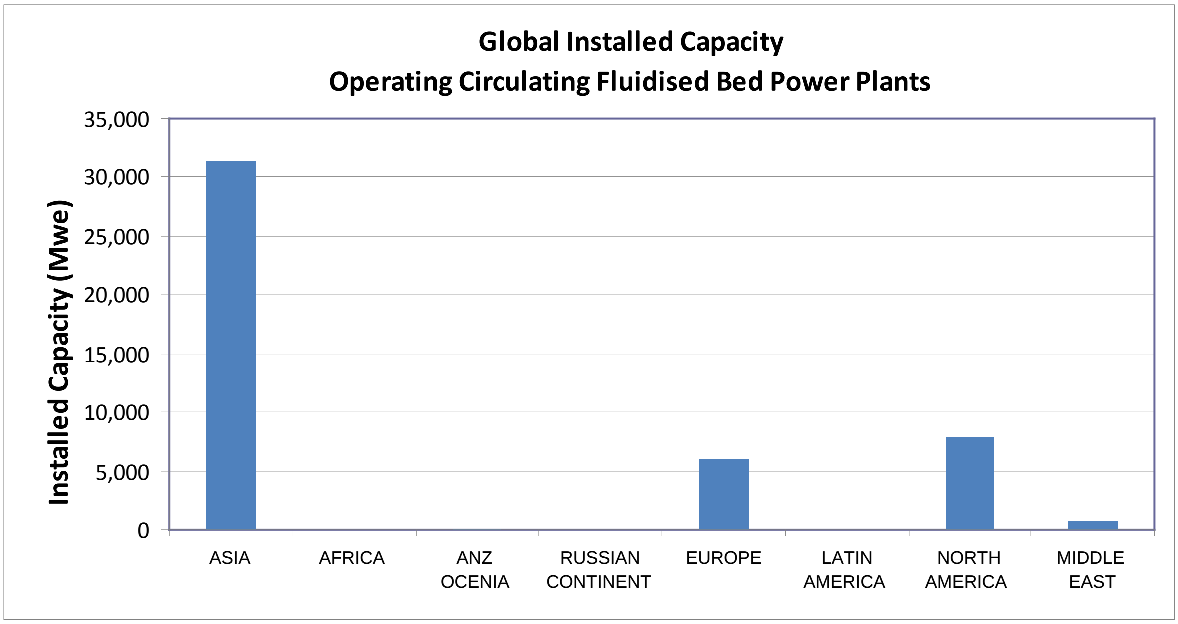


***Figure 4**: Global CFBC power generation capacity*

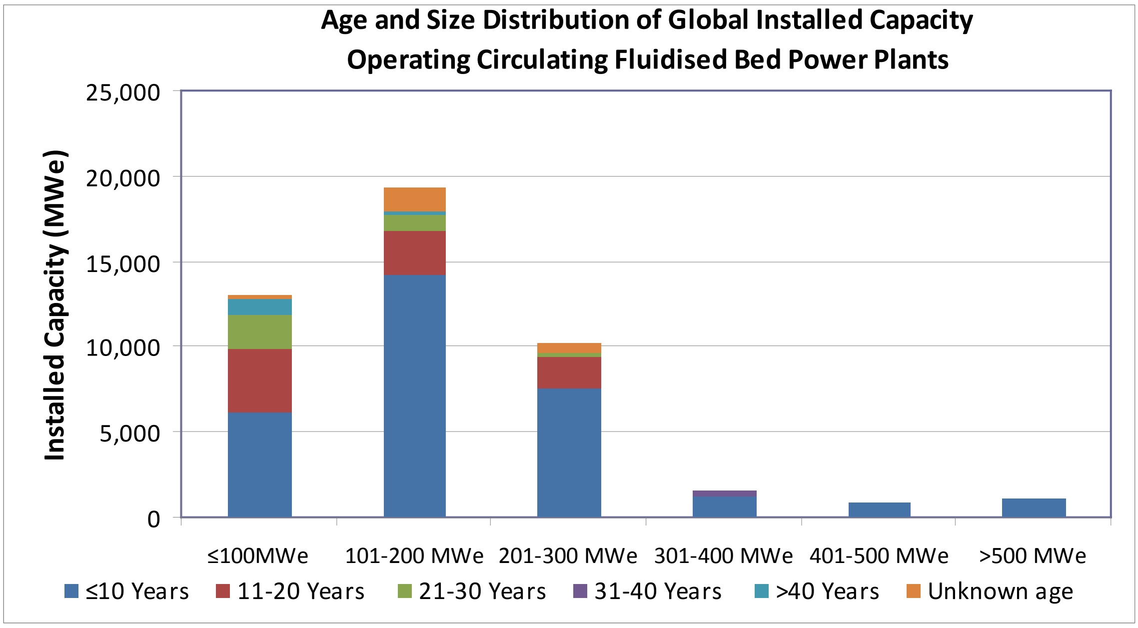


***Figure 5**: Global CFBC power generation capacity, unit and age distribution of the units*

The major points to note in relation to the figures above are the following:

- Global CFBC operating capacity – 46,500 MWe at the end of 2010, approximately 2.7% of the total current coal-fired power generation capacity. This figure was 17000 MWe at the end of 2004, 19000 MWe at the end of 2008, thus signifying a significant rise the new-build CFBC in the recent years.

- Majority of the CFB capacity additions have been in China and to a lesser extent India.
- Largest CFBC to date – Lagisza in Poland, 460 MWe, and supercritical steam parameters (460 MW, 282 bar pressure, 563C superheat/582C reheat temperature), first-of-its-kind. It operates on Polish bituminous coals. Supplied by Foster Wheeler, the unit was commissioned in early 2009, and exceeded the design efficiency of 43.3% (LHV, net) during operation.
- A second supercritical CFB boiler of 330 MWe capacity is slated for commissioning in 2012 Novocherkasskaya GRES facility in Russia (Platts, 2011).
- The largest CFB (600 MWe) with supercritical steam parameters is currently being constructed at Baima, Sichuan, China.
- Hyundai Energy and Construction Corporation and Korea Southern Power Corporation has ordered Foster Wheeler 2 x 550 MWe units with supercritical steam parameters, to be commissioned by 2015. Fuel to be used is bituminous and anthracite coals.
- A major guideline in the 11$^{th}$ five-year plan in China is to build CFB units larger than 600 MW unit size (CEC, 2007).

## *Chronology for scaling up of CFBC*

Figure 6 shows the chronology for scaling up of CFBC.

Foster Wheeler is offering supercritical CFB up to 800 MWe scale for “good quality fuels” with full commercial guarantee (Hotta et al., 2010, Jantti and Parkkonen, 2010) for bituminous coals, with steam conditions of 300 bar, 600°C superheater temperature and 620°C reheater temperature.

The second generation units (in Figure 6) differ from the first generation units in designs that can incorporate supercritical steam conditions and larger unit sizes, and yet within a smaller furnace volume. Figure 7 shows the footprint of scaled-up CFBCs from 35 MWe in 1994 to current 800 MWe design.

However, given an expectation of lower furnace temperatures in general, design improvement will still be required for ultra-supercritical steam parameters much higher than 600°C superheat or reheat temperatures. If such temperatures and main steam pressure to 280 bar are achieved, such units will reach an efficiency of over 45% (LHV, net) or 43% (HHV,net) for black coal.

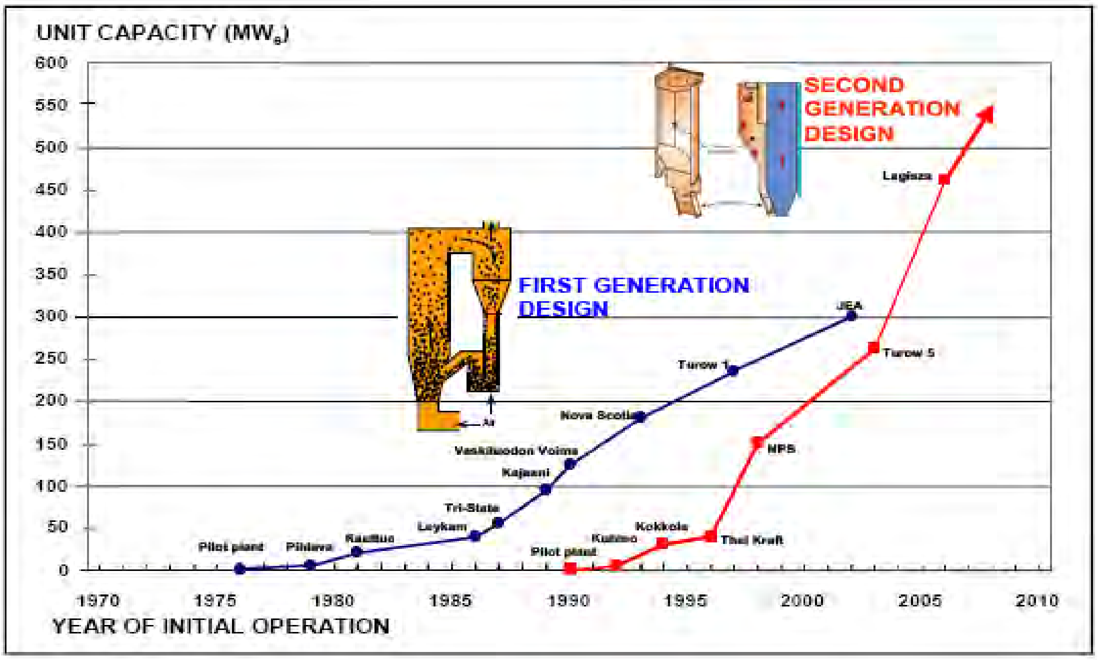


***Figure 6:*** *CFBC Scale-up Chronology for the currently operational units (Utt et al., 2009 )*

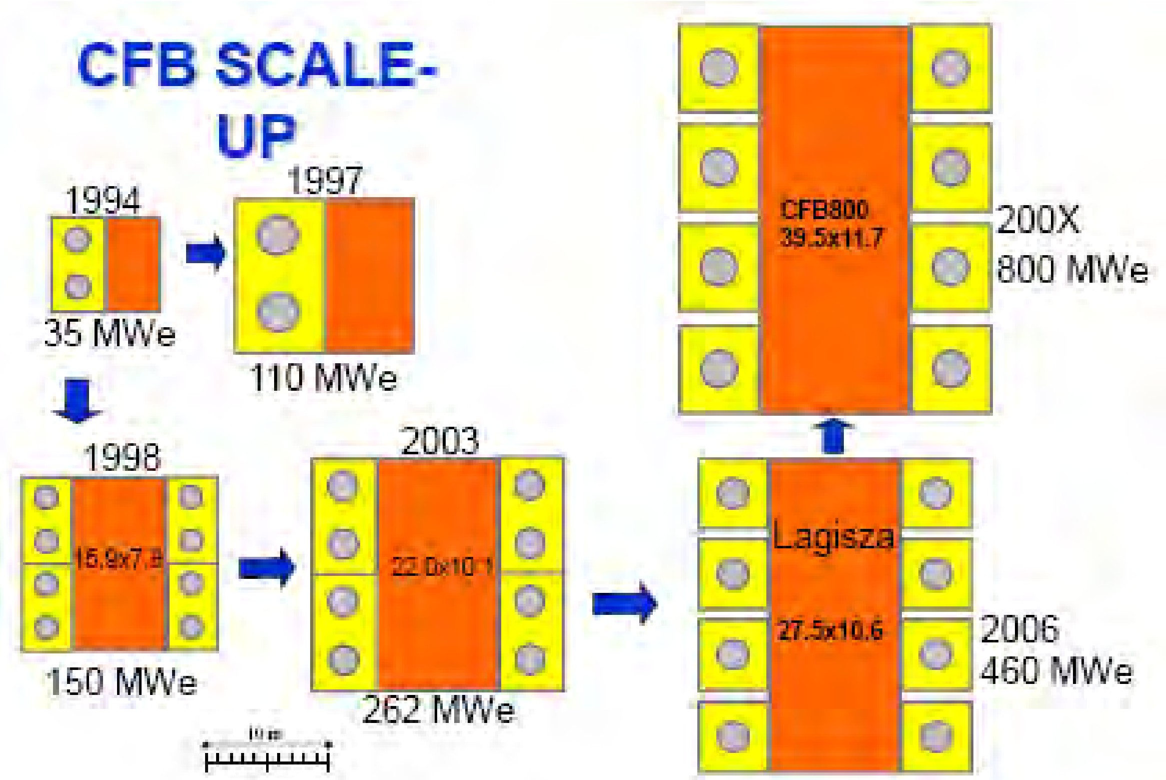


***Figure 7****: Size of scaled-up CFBCs from 35 MWe to 800MWe (Hotta, 2009); developments from 35 MWe to 110-150 MWe took place around the same time*

## *Table 1: List of major operating CFBC units for power generation and their key parameters*

| **Location** | **Unit size**<br>**MWe** | **Operating from** | **Fuel** | **Steam conditions**<br>**Pressure (bar), superheat & reheat temperature (C)** |
|---|---|---|---|---|
| Lagisza, Poland | 460 | 2009 | Bituminous | 282/567/582 |
| Sulcis 2A, Italy | 340 | 2005 | Bituminous, high S | 169/565/580 |
| Spurlock 3, USA | 268 | 2005 | Bituminous | 165/540/540 |
| Heshuyauan 3 | 300 | 2008 | Anthracite | subcritical |
| Xiaolongtan, China | 300 | 2006 | Lignite | subcritical |
| Yunfu, China | 300 | 2010 | Anthracite | subcritical |

### Australian context

*Of total Australian coal-fired power generation capacity, only Redbank power station has 2 x 75 MW operating CFB units (Addinall, 2011). The now discontinued Lignite CRC had commissioned a Lurgi –designed CFBC pilot plant (350 kWth) and trialed Victorian brown coal and char in 1999-2000.*

*Although Australian experience in CFB is limited, experience globally has improved considerably. Therefore, for this report, we have relied on the experience of the major global vendors and major research institutions.*

### Major CFBC vendors

*Foster Wheeler*
*Alstom*
*Babcock and Wilcox*
**China**
*Dongfang and Wuxi Boiler (collaboration with Foster Wheeler)*
*Harbin/Dongfang/Shanghai Boiler (collaboration with Alstom)*

## *What is Oxy-CFB*

Oxy-CFB combustors are variants of CFBC, where fluidization and combustion is carried out by a mix of oxygen and recycled flue gas (rich in $CO_2$ and water vapour). The latter helps in maintaining the bed and gas temperatures to the same level as in an air-fired CFBC unit. This is analogous to Oxy-PF combustion, where flue gas is recycled to the burners; in Oxy-CFB unit, the recycled gas can be fed into and around the bed region of the CFBC.

Oxy-CFB boilers include all the advantages of CFBC technology, such as fuel flexibility and low-NOx emission. Additional advantages of Oxy-CFB include:

***Oxy-CFB advantages***

- *The strong mixing in the furnace and long residence time due to recirculation of solids allow a good carbon burnout; this clearly suits low-reactive coals.*
- *The recirculation of the cooled solids from the external heat exchanger allow a Oxy-CFB boiler to operate with lower flue gas recycling compared to Oxy-PF systems.*
- *Reduction of flue gas recycling, thereby reducing the size of the boiler island, and some of the auxiliaries consumption. This may potentially allow more compact and less expensive CFB boilers.*
- *Direct sulfation of limestone will occur due the high partial pressure of $CO_2$ and the right thermodynamic temperature for sulfur capture; calcium conversion under direct sulfation is usually higher than that under calcination/sulfation due to the better porosity of product layer as suggested by several studies.*
- *Oxygen concentration in the recycled flue gas can be kept to a low and safe level, while additional oxygen can be introduced through oxygen nozzles separate from the burner or the secondary gas inserting points. Thus relative to Oxy-PF, Oxy-CFBs do not need new burner design.*
- *As also indicated later in Chapter 3, transition from air-mode combustion to oxy-mode combustion is potentially easier relative to Oxy-PF, because CFB has large amount of inert bed material that also helps in controlling the bed temperature.*
- *As CFBC's are operated at slightly over atmospheric pressure, the possibility of air-in-leakage is greatly reduced.*

***Relative to air-CFB, Oxy-CFB is still in developmental stage, hence not all potentially problematic issues are known yet.***

# CHAPTER 2

## The unit operations comprising Oxy-CFB and potential cost impacts

The design of a flow sheet for Oxy-CFB combustion needs to consider both technological performance and economical factors. The design of various Oxy-fuel process flow sheets mainly depends on the flue gas treatment for SOx, NOx, Hg, CO, hydrocarbons, and particulate matter. A conceptual diagram of Oxy-CFB is shown in Figure 8.

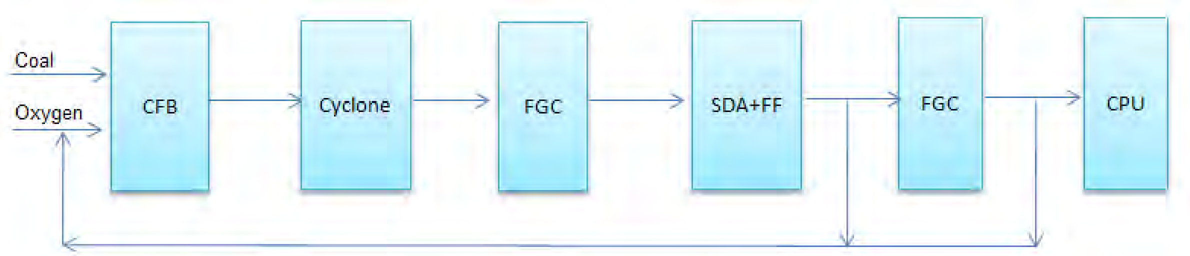


***Figure 8*** *Conceptual diagram of Oxy-CFB process (refer to the list of acronyms on page 40)*

All the $CO_2$ capture and storage technologies increase the cost of electricity. The U.S. Department of Energy (DOE) has adopted a goal of developing a $CO_2$ capture and storage technology with 90% capture rate and no more than 35% increase in cost of electricity. Usually the cost of mature environmental control technologies increases cost of electricity by 10 to 20%. With co-sequestration technology, SOx, NOx and Hg etc can be geo-sequestrated together with carbon dioxide, to avoid expensive flue gas treatment technologies. However, co-sequestration needs to meet the requirement/regulations for $CO_2$ storage sites.

There are several reported studies on techno-economical analysis for Oxy-fuel combustion for black coal and brown coal fired in pulverized coal boilers and circulating fluidized bed boilers (Matuszewski, 2010; Ho, 2011) The costs depend on the selection of air separation unit, types of coal burned, combustor type and configuration for flue gas cleanup.

DOE/NETL study used Aspen Plus software to establish the heat and material balance of power plant, then selected the major equipment specifications from which finally estimated the capital cost and operating cost. The performance is evaluated by gross output and plant energy efficiency. The total plant cost (TPC), 20-year levelized cost of electricity (LCOE, c/kWh), cost of $CO_2$ captured ($/tonne), and the cost of $CO_2$ avoided ($/tonne) were used for techno-economic analysis. The LCOE consists of capital cost, fixed operating cost, variable operating cost, and fuel cost; and it is the economic figure-of-merit.

In this study, parameters evaluated include plant site (North Dakota and Montana), fuel type (sub-bituminous and lignite coal), steam condition (supercritical and ultra supercritical), combustor (pulverized coal furnace and circulating fluidized bed), firing mode (air-firing and

Oxy-fuel firing), environmental control processes configuration (Spray Dryer Absorber vs In-bed desulfurization for DeSOx, Low NOx burner/Overfiring air/Selective Catalytic Reduction vs Selective Non-Catalytic Reduction for DeNOx), air separation unit optimization (normal or advanced ASU), and $CO_2$ purification and compression unit (dehydration, dehydration combined with dry FGD, dehydration combined with dry FGD and flash partial condensation, dehydration combined with dry FGD and distillation for various $CO_2$ purities).

The study found that by combining the technology of advanced air separation unit, boiler material and design, and co-sequestration, the DOE target (90% $CO_2$ capture and <35% increase in cost of electricity) can possibly be achieved. The main added cost comes from ASU, CPU, O&M and fuel cost associated with increased coal flow rate.

## *Oxy-fuel flow sheets*

Compared with conventional air-fired power generation plant, Oxy-fuel processes modify the combustion process, especially the flue-gas system. The Oxy-fuel process do not change the water system, solid system, electric system, and control system. The Oxy-fuel processes include the following main functional blocks:

- Air separation unit (ASU)
- CO2 compression and purification unit (CPU)
- Fuel and sorbent preparation and handling
- Feed water, associated system and equipment
- Boiler and accessories
- Flue gas cleanup
- Heat recovery steam generator (HRSG), ducting & stack
- Steam turbine generator and auxiliaries
- Cooling water system
- Ash/spent sorbent recovery and handling
- Electric plant
- Instrumentation and control

The estimation of the cost and performance of an Oxy-fuel plant depends on the Oxy-fuel flow sheet, especially on air separation unit, combustor type, and flue gas cleaning system.

CFB costs less to capture sulfur compared with PC. The cost of DeSOx includes costs for sorbent handling, sorbent preparation and feed, flue gas cleanup and spent sorbent handling. Because in bed sorbent injection is achieved in CFB, expensive absorber vessels and accessories can be avoided. Table 2 details the costs for DeSOx in PC combustor and CFB combustor. The capital cost for DeSOx in CFB is significantly reduced, although sorbent handling cost increased almost four-fold.. Overall cost of DeSOx in CFB is about 10% of that in PC model. If Spray Dryer Absorber (SDA) is used in Oxy-CFB, then the cost will be similar to that in Oxy-PF with SDA DeSOx, as cases considered in this DOE/NETL report.

***Table 2 :*** *Cost of DeSOx in air fired combustion in PC mode and CFB mode (Matuszewski, 2010)*

| *1000US$ | Air-fired *PF* | Air-fired CFB |
|---|---|---|
| **Sorbent handling** | | |
| Receive & unload | 82 | 209 |
| Stackout & reclaim | 1198 | 5479 |
| Sorbent conveyors | 528 | 1350 |
| Other sorbent handling | 384 | 983 |
| | | |
| **Sorbent preparation and feed** | | |
| Sorbent preparation equipment | | 1859 |
| Storage and feed | | |
| Injection system | | 1348 |
| | | |
| **Flue gas cleanup** | | |
| Absorber vessels & accessories | 107328 | |
| Other FGD | 1727 | |
| PM | 36698 | |
| | | |
| **Total** | 147945 | 11228 |

The available gas cleaning options includes:

- Particulate matter: fabric filter with 99.97% efficiency for environmental emission control and protection of downstream fans for recycled flue gas for PC. Cyclone combined with baghouse with efficiency of 99.8% for CFB.
- SOx: dry lime FGD (Spray dryer absorber, SDA) with 93% DeSOx efficiency for PC and in-bed limestone injection with 94% DeSOx efficiency for CFB. SDA consumes less water than wet limestone FGD system and can use highly alkaline ash as reagent.
- NOx: a combination of low NOx burners (LNBs), over-fire air (OFA), and selective catalytic reduction (SCR) for PC and selective non-catalytic reduction (SNCR) for CFB. Under Oxy-fuel conditions, expensive DeNOx units can be avoided due to re-burning mechanism of DeNOx in Oxy-fuel combustion.

- Hg: co-benefit capture with existing DeSOx and DeNOx units is the cost effective method but with limited efficiency. It is estimated 15-20% co-benefit capture for PRB sub-bituminous coal and 5-10% for North Dakota lignite in PC and about 57% for both coals in CFB. With brominated carbon injection technology, over 90% capture efficiency is expected but with higher cost.

To purify the carbon dioxide in CPU, several configurations can be made, as listed, and there is trade off between the carbon dioxide capture rate, purity and cost: dehydration, dehydration with SO2 polishing scrubber, dehydration with SO2 polishing scrubber combined with partial condensation, dehydration with SO2 polishing scrubber combined with fully condensation

The design of an Oxy-CFB flow sheet needs to compromise between the cost and efficiency. The selection among environmental control options is subject to their suitable with Australian coal combustion emissions.

*The unit operations comprising Oxy-CFB technology are similar to Oxy-PF. However details and associated costs of the operations may differ. For example, a study by NETL indicates that in-bed DeSOx for Oxy-CFB will be substantially less expensive, if adequate removal can be realised.*

# CHAPTER 3

## Facilities Used for the Development and Demonstration of Oxy- CFB technology

Oxy-CFB has recently emerged as a prospective technology for CCS, with the announcement of the feasibility study supported by the EU for the 300 MWe demonstration unit at Compostilla, in Spain. This development is based on the pilot-scale work of Oxy-PF and Oxy-CFB at 30MWt scale at CIUDEN, also located on the Compostilla site. In this chapter, we provide brief description of the various Oxy-CFB facilities - one for technology development, and other facilities for fundamental studies.

### *Technology development facility at CIUDEN*

This section summarises the facility at CIUDEN. More details on the facility are provided in Appendix 1.

The CIUDEN Carbon Capture Technology Development Plant (TDP), situated in Ponferrada, north-western Spain, has been developed as part of the Spanish Government's initiative to drive carbon capture technologies towards commercialisation.

A number of activities other than Oxy-fuel are supported at the test facility. These include large scale testing of Oxy-PF, Oxy-CFB, biomass gasification and post-combustion capture (shown in Figure 9). The facility will have the ability to perform a number of flue gas treatment options (SCR, FGD, Bag filter) or elect to bypass them. The main parameters for the PC and CFB boilers are given in Table 1. The plant does not contain an ASU as it was deemed a mature technology and not in need of demonstration.

The principal focus for the CIUDEN Test Plant is to support and validate the scale-up of Foster Wheeler's Oxy-CFB technology, which will be the basis for Endesa's Compostilla OxyCFB300 project. The OxyCFB300 industrial demonstration has already attracted EU funding of €180M for pre-feasibility studies, with the intention of operating in 2015. The plant is aimed at producing 323MWe with a capture rate of 91%. The investment decision will be made at the end of 2012.

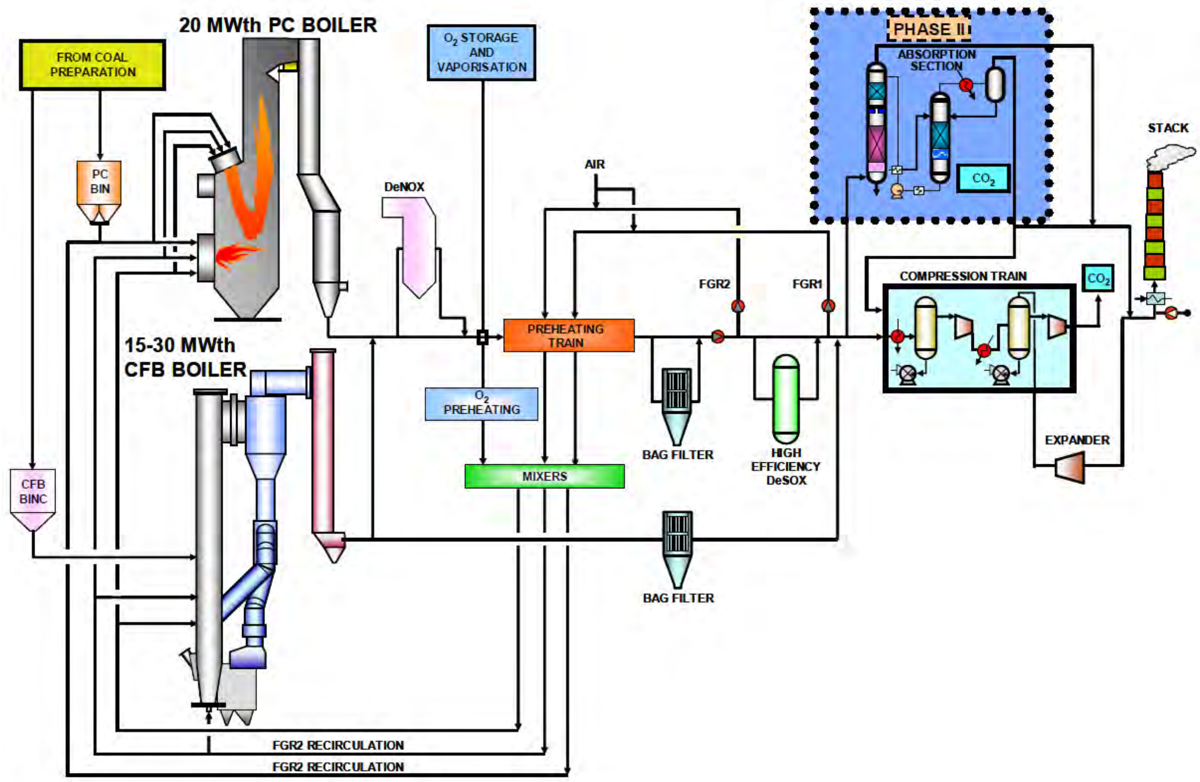


***Figure 9.*** *Simplified diagram of CIUDEN facilities – commissioned in September 2011*

The IP developed at the Oxy-CFB unit may remain with Foster Wheeler who will however pay for the development work at the Oxy-CFB unit. CIUDEN will also target the cement sector, in addition to the power generation sector, join in the Oxy-CFB development work

The facility has three units with one common control room building. The three key units are as follows:

i) 3MWth atmospheric pressure bubbling fluidized bed biomass gasifier, which will supply fuel gas to the pc boiler unit, char to the CFB,

ii) 20MWth Oxy-PC unit with steam generated at 30 bar/420°C at 25 t/hr, this PC unit has the flexibility for both vertical and horizontal firing. The vertical firing will be employed for low-volatile anthracite or lower reactivity coals to achieve longer residence time for combustion. The maximum flue gas flow out of this unit is 26.4t/hr of which up to 17.9 t/hr can be recirculated if required. The PC boiler was designed and constructed by Combustion Biomass Services, a small Spanish company, with the intention of making it flexible.

iii) 30 MWth (21.7mH, 2.7m W, 2.4m L) Oxy-CFB unit, design of it is based on the results from CANMET and VTT facilities which were also funded by Foster Wheeler. The Oxy-CFB unit will run at a maximum coal feed rate of 5.5t/h, and the corresponding maximum $O_2$ feed rate will be 8.8t/h. Oxygen will be supplied from liquid oxygen storage tanks as opposed to ASU. The unit will start-up on air, but under Oxy-CFB condition, it will provide higher capacity as the coal feed rate has to be higher to get the right level of superficial velocity (expected output of 15MWt on air and 30MWt on oxy). $O_2$ will be supplied at concentrations up to 40% at the CFB combustion inlet.

According to Foster Wheeler, the size of the CFB will allow easy scaling-up to 300MWe unit. In particular, the height has been selected so that overall scaling-up becomes easier.

The fuels to be tested at the CIUDEN Oxy-CFB unit include Anthracite (30% ash), bituminous coals, sub-bituminous coals (30 Hardgrove index) and Petroleum coke ( 0.8% ash, 6.5% S, and rich in Vanadium).

The drying of the coal will occur in a separate inertised ($CO_2$) process due to the explosive risk of some brown and sub-bituminous coals. Initially hot gases will be produced for the drying process from natural gas combustion, however this will eventually been replaced by hot recycled flue gases.

## *Facilities for fundamental studies*

There are several facilities from laboratory to bench scale located primarily in research centres and universities around the world. A list of major facilities worldwide is provided in table 3. These are mainly used for generating fundamental data on various aspects – in particular combustion rate, agglomeration, S-capture, trace element emission under Oxy-CFB conditions. Figures 10 and 11 present the schematic of the two bench scale facilities at VTT and at CANMET. These facilities were used by Foster Wheeler to develop the 30 MWt CIUDEN facility.

> *There has been substantial research work covering high and low-grade coals in small bench scale facilities in academic and research institutions leading to the only one technology development facility at CIUDEN. The CIUDEN facility is comparable in size to Vattenfal's Oxy-PF facility and therefore is likely to generate practical information.*

***Table 3: List of major facilities for fundamental research***

| **Facility location** | **Capacity** | **Focus of work** | **Other relevant information** |
| --- | --- | --- | --- |
| Alstom - Windsor, CT, USA | 3MWth | Feasibility study at O2/CO2 atmosphere without recycled flue gas | In 2001, ALSTOM began a two-phase program to investigate the feasibility of CCS technologies. The Phase I study identified the O2-fired CFB as having a near term development potential. The Phase II study consisted of a 3 MWth pilot-scale testing followed by refined performance and economic evaluation of the Oxy-CFB. Following this study, a project entitled “Commercialization development of oxygen fired CFB for GHG control” was carried out. |
| Foster Wheeler - VTT, and Lappeenranta University of Technology,Finland | 0.1 MWth | To provide design and operation data for Oxy-CFB combustion with recycled flue gas (Eriksson et al., 2007) | Foster Wheeler used facilities located in VTT, Finland and CANMET, Canada to study the Oxy-CFB technology. Several coals (lignite, sub-bituminous, anthracite) and sulfur capture sorbents have been tested to support the CIUDEN Oxy-CFB project. |
| CANMET | 0.8 MWth, | To provide operation data for FW Oxy-CFB | |
| CANMET Mini-CFB | 0.1 MWth | To provide operation data for 0.8 MWth Oxy-CFB | |
| Czestochowa University of Technology | 0.1 MWth | Test polish coal and limestone sorbent for Lagisza plant, based from which Oxy-CFB is designed | Supported by Foster Wheeler |
| CIRCE, University of Zaragoza, Spain | 0.1 MWth | To generate fundamental data | |

| | | | |
|---|---|---|---|
| ICB-CSIC, Spain | unknown | To study Spanish limestone sorbent at Oxy-CFB condition | |
| Romeo, Spain | 95 kW | To generate fundamental data | |
| CNR, Italy | unknown | To generate fundamental data | |
| University of British Columbia, Canada | unknown | To generate fundamental data | |
| University of Utah – Salt Lake City, Utah, USA | 0.33 MWth | To generate fundamental data | |
| Southeast University in China | 10 kW | To generate fundamental data | |
| Zhejiang University | unknown | To generate fundamental data | |
| North China Electric Power University | unknown | To generate fundamental data | |
| Chongqing University | unknown | To generate fundamental data | |

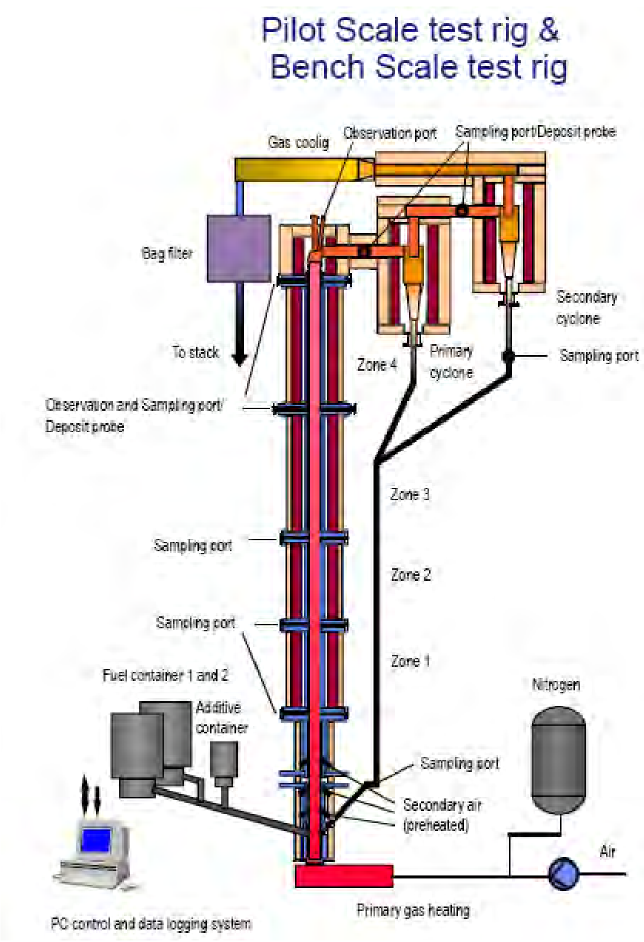


***Figure 10 :*** *Schematic of the VTT facility (VTT)*

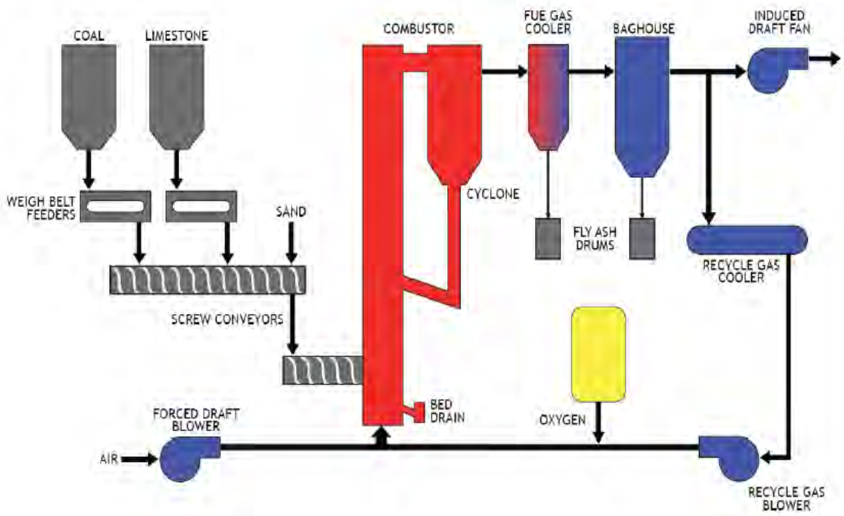


***Figure 11 :*** *Schematic of the CANMET facility (Jia et al.)*

# CHAPTER 4

## Design and operational aspects of Oxy- CFB

Design philosophy of air-fired CFBCs are well established, with units currently offered up to 800 MWe with supercritical steam parameters (Jantti and Rasanen, 2011). The design of Oxy-CFB units is believed to be of similar nature to air-fired CFBC units, except in few aspects. In this chapter, we briefly summarise the major design and operational aspects of Oxy- CFB.

### *Boiler size and volume*

For comparable unit size, an air-fired CFBC is smaller than an air-fired PF boiler. An Oxy-CFB boiler is estimated to be 45% in volume of an air-fired CFBC boiler (Seltzer et al., 2007).

### *Start-up and shut-down*

The sequence is believed to be no different to air-CFBC. Oxy-CFB will need to be started up in air-mode and gradually transitioned to Oxy-fuel mode.

### *Part-load behaviour, and load following capability*

These are believed to similar to established procedures in air CFB which are known to have better load-following capability than *pf* units.

### *Control system*

This is likely to be similar to established procedures for air CFB, however control of the Air Separation Unit and its interlock with the Oxy-CFB boiler and its load will be different. This however is unlikely to be different from Oxy-PF. Compared to Oxy-PF system, better load-following capability and easier turn-down is expected due to the recirculating solids.

### *Environmental control*

The only major difference with air-PF cases is selective non-catalytic reduction (SNCR). In all oxycombustion cases, nitrogen is significantly reduced from the oxidant stream and only present in the boiler due to inherent nitrogen in the coal, small nitrogen in the oxidants and in-leakage air. The in-leakage air is likely to be less in any CFB combustion as CFBs are operated at slightly higher pressure.

The sulphur transformation and emissions from Oxy-CFB units is yet to be fully established. Depending on the level of in-bed $SO_2$ removal, further sulphur clean-up system may be required downstream in the form of spray dryer(Matuszewski, 2010). This will entail additional control and instrumentation. However, this is coal-specific and dependent on the sulphur level and its forms in the coals used.

### *Bed agglomeration*

This is an unknown area requiring targeted research, and may be different from air-CFBC environment. Agglomeration under localized reducing environment (due to the presence of $CO_2$ and water vapour) could be an issue. This will be coal-specific, and likely to be more significant for low-grade coals.

### *Flue gas recycling*

This issue is different from Oxy-PF because of the temperature difference in the two systems. Due to the presence of recirculating solids, Oxy-CFB systems in-principle require lower flue gas recycling (~30%) compared to the Oxy-PF units (~70%). While the power requirements to recycle lower quantities of flue gas will be lower compared to Oxy-PF system.

### *Recarbonation*

This is coal specific, more significant with coals having high Ca levels or high S levels requiring addition of external Ca for sulphur capture. This issue is discussed in the next chapter. The control implication for this is that temperature in the downstream sections (which are prone to form carbonates) need to be monitored carefully and may require dedicated soot blowers along with their controls.

### *Sealing of the boiler and air in-leakage*

CFB boilers are usually operated under slight overpressure, 5-10 kPag; this is likely to minimize or prevent air-ingress into a properly maintained Oxy-CFB boiler.

*The design and operational issues of an Oxy-CFB boiler are unlikely to be substantially different from an air-fired CFB. This is consistent with the views of Foster Wheeler presented in Appendix 1.*

# CHAPTER 5

## Coal Quality Impacts on Oxy- CFB Design

While Oxy-CFB is emerging as a promising technology for capturing $CO_2$ emissions, when utilising both low and high-rank coals, there are several issues associated with these coal quality impacts on Oxy-CFB design. Some of these issues are listed below:

1. Mineral matter in coal
2. High Alkali, Cl and S in some coals

### *Coal devolatilization and ignition delay in Oxy-CFB combustion*

Ignition is an important combustion characteristic of coal. There have been some studies on coal devolatilization and ignition under Oxy-CFB condition (Czakiert et al., 2006),(Zhao et al., 2010).

It has been observed that at the initial stage of coal feeding, the dense phase (in the fluidized bed) temperature decreased slightly, this behavior could be due to ignition delay resulting from the endothermic reactions from $CO_2$ and water vapor present near the coal. However, devolatilization and ignition delay is unlikely to be a significant practical issue for any coals.

### *Combustion characteristics in Oxy-CFB*

CFBCs are inherently suited to low reactivity coals. This is due to the recirculation of the unreacted or partly reacted char to the combustor.

Using brown coal in an Oxy-CFB combustor, Czakiert et al. found an increase in carbon conversion ratio with the increase in the oxygen concentration in the gas mixture delivered into the combustion chamber. However, few studies have been carried out focusing on the combustion characteristics of low-rank coals during Oxy-fuel CFB combustion.

### *Mineral matter and bed agglomeration*

Agglomeration could be an operational problem in Oxy-CFB combustion, since this problem affects the fluidization characteristics of the bed (Kuo et al., 2010, Lin et al., 2009, Kuo et al., 2009, Lin and Wey, 2004). If agglomeration remains undetected for a time, it may propagate to partial or total defluidization of the bed materials, which in turn may lead to a lengthy and expensive unscheduled shutdown (Bartels et al., 2008). It was also suggested that high fluidization velocity and the large excess of inert ash could prevent this problem (Liljedahl et al., 2006a). Hence, several studies have been covered on the agglomeration phenomena in air-CFB combustion (Bhattacharya and Harttig, 2003, Manzoori and Agarwal, 1994, Li et al., 2010, Anthony and Jia, 2000, Anthony et al., 2000, Westberg et al., 2002, Skrifvars et al., 1998, Skrifvars et al., 1994, Steenari et al., 1999, Skodras et al., 2009, Bartels et al., 2010, Leng et al., 2010).

Agglomeration is mainly caused by various elements, such as alkali metals (Na and K), and alkali earth metals (Mg and Ca), sulfur, chlorine, silicon, vanadium, and nickel (Lin et al., 2009, Lin and Wey, 2004). In some low-rank coals, the quantities of these elements are relatively higher compared to that of high-rank coals. Therefore, the possibility of agglomeration occurring is high in brown coals/lignites and less in black coals. When using high-sodium lignite, however, it was suggested that agglomeration could be mitigated by using a nonreactive bed material (e.g., coarse coal ash) instead of sand, operating at slightly reduced temperatures and using additives (Dahlin et al., 2006). Though a few studies have been carried out to study the agglomeration characteristics of low-rank coal in air-CFB combustion (Skrifvars et al., 1994, Bhattacharya and Harttig, 2003, Manzoori and Agarwal, 1994, Leng et al., 2010), there is a little research available on this issue for Oxy-CFB combustion using brown coal (Roy et al., 2011a).

Therefore, in order to explore this issue, it is essential to conduct both small scale experiments (to screen coals) to assess the behavior of the agglomeration using certain types of low-rank coals during Oxy-CFB combustion.

## *Sulfur sorbent utilization efficiency*

While using high sulphur coal in an Oxy-CFB, limestone or similar Ca-bearing sorbents can be used for the sulfation reaction between $SO_2$ and limestone particles. This reaction can proceed via two different routes depending on whether calcination of the limestone takes place under given reaction conditions. There are subtle differences between Oxy-PF and Oxy-CFB combustion system in that respect.

For an Oxy-fuel-fired PF system, the $CO_2$ partial pressure in the system is lower than the equilibrium decomposition pressure of limestone. Therefore, the limestone first decomposes to form CaO, which then reacts with $SO_2$ and $O_2$. This process is called indirect sulfation of limestone and is expressed by the following overall reactions:

$CaCO_3$ (s) $\rightarrow$CaO(s) + $CO_2$(g)

CaO(s) + $SO_2$ + 0.5$O_2$$\rightarrow$$CaSO_4$(s)

For an Oxy-CFB system, the limestone calcination is normally prevented due to large partial pressures of $CO_2$ (800–900 °C temperature and the $CO_2$ concentration around 80-90%). Therefore, at least theoretically, the limestone is subject to direct sulfation (Chen, 2009) :

$CaCO_3(s) + SO_2 + 0.5O_2 \rightarrow CaSO_4(s) + CO_2\ (g)$

However, as the following Figure (12) suggests, literature is divided on the extent and route of sulphur capture under Oxy-CFB conditions.

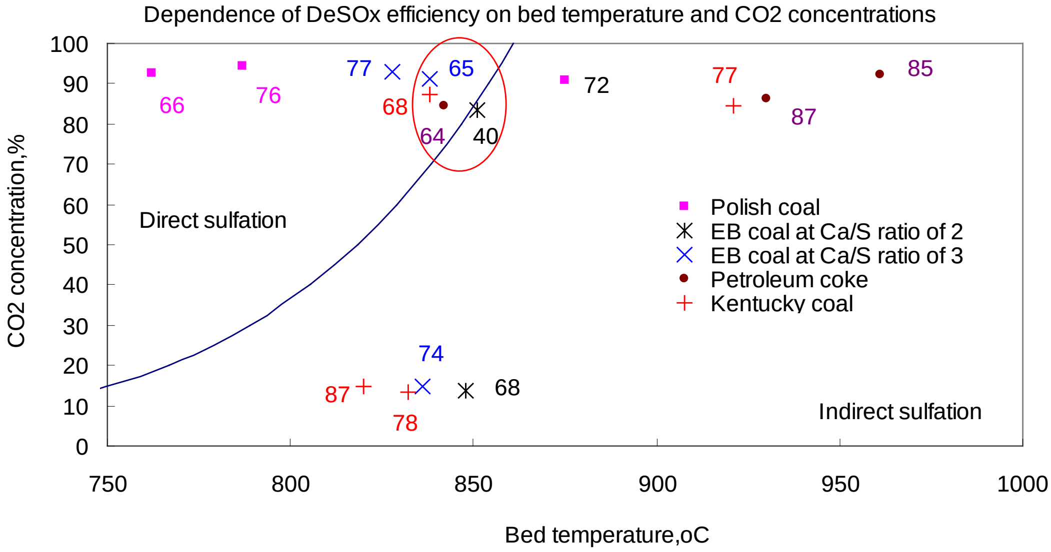


***Figure 12*** *Lower sulphur capture efficiency under the direct sulfation mechanism, compared to indirect sulfation mechanism in Oxy-CFB, with numbers next to data points indicating the sulphur capture efficiency. Data is obtained from CANMET experiments and replotted (Anthony, 2010)*

Therefore, targeted research is recommended to carry out bench scale experiments with high-sulphur Australian coals. The extent of in-bed S-capture has important ramifications for the need and otherwise of subsequent deep cleaning, hence on cost and control issues.

## *Recarbonation of fly ash*

In circulating fluidized bed combustion using high-sulfur coal, limestone is added to capture $SO_2$ from the flue gas. At high temperature, the calcination of the limestone occurs to form calcium oxide. In some locations (e.g., cyclone, dipleg, sealpot, external heat exchanger), where the temperature drops below the calcination temperature, the unreacted calcium oxide is recarbonated to form calcium carbonate, which may cause fouling.

Wang et al. (Wang et al., 2008) investigated that carbonation of fly ash under Oxy-fuel CFB combustion conditions and found that water vapor in the gas phase also had an important role on carbonation. No carbonation occurred without the presence of water vapor, when the temperature is less than 400°C. With the water vapor, however, carbonation was observed even at 250°C.

Due to the high $CO_2$ partial pressure (see Figure 13), limestone does not calcine under typical Oxy-fuel CFB combustion operating temperature (Wang et al., 2008). However, at 80-85% $CO_2$ concentration, the limestone calcines, but when the fly ash cools to below the calcinations temperature, recarbonation of fly ash occurs. Moreover, the high $CO_2$ concentration in the flue gas under Oxy-CFB combustion condition facilitates the carbonation to occur. It was also suggested that fluidizing the external heat exchanger, with air or nitrogen rather than recycled flue gas (mostly $CO_2$) and/or maintaining the sealpot temperature at least as high as the furnace temperature, it was possible to avoid recarbonation (Liljedahl et al., 2006a).

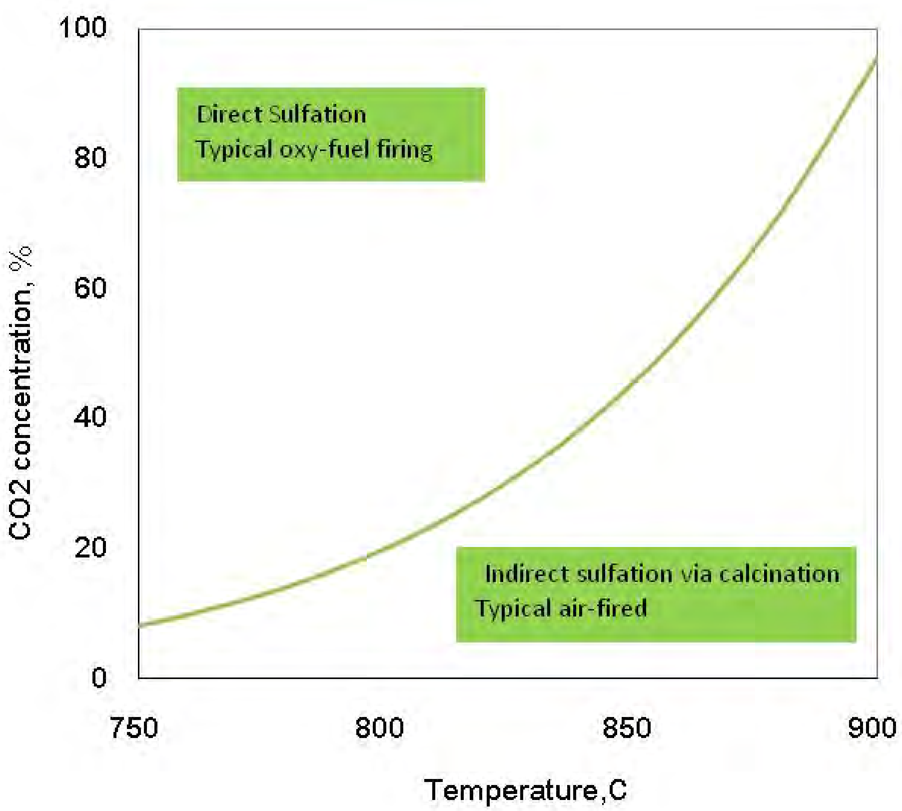


**Figure 13** : *Equilibrium temperature for calcination (Alstom Power Inc., 2003)*

In a pulverized coal-fired power plant after high-calcium lignite combustion, it was found that calcite ($CaCO_3$) is one of the dominant calcium mineral phase in the deposits (Fernandez-Turiel et al., 2004). Though little studies have been carried out on the recarbonation of fly ash under Oxy-CFB combustion(Liljedahl et al., 2006b),(Wang et al., 2008) this phenomena, however, is completely unexplored in low-rank coal context.

Therefore, it is essential to experimentally determine the recarbonation behavior under Oxy-CFB combustion conditions using low-rank coals, particularly having high calcium content.

In order to explore this issue, it is essential to conduct small scale experiments to assess the recarbonation behavior using certain types of low-rank coals during Oxy-CFB combustion.

## *$SO_x$ and $NO_x$ emissions characteristics*

The gaseous emissions characteristics are very important for the operation of Oxy-CFB combustion technology using different types of coals. Czakiert et al. (Czakiert et al., 2006) studied fuel conversion during Oxy-CFB combustion using brown coal and found a significant reduction of fuel nitrogen conversion to $NO_x$ compared to the air combustion (see Figure 3). However, there was an increase in the conversion of sulfur to $SO_2$ under oxygen-enriched conditions.

During the Oxy-CFB combustion using Chongqing industrial coal with the oxygen concentration of 21-35%, Xin et al. (Xin et al., 2010) found that with increasing oxygen concentration, the furnace temperature increased, and the concentration of $SO_x$ and $NO_x$ also increased. The researchers concluded that the fuel containing high sulfur and nitrogen content increases the emission concentrations of $SO_x$ and $NO_x$ respectively under the same combustion atmosphere.

Since the emissions of SOx and NOx depend on coal characteristics, there is a necessity to conduct both targeted experiments and thermodynamic equilibrium modeling to know the emission characteristics using certain types of coals (high S, high N) during Oxy-CFB combustion.

## *Particulate matter, heavy metals and trace elements partitioning between solid and gas phase*

It is well known that mercury in flue gas must be captured prior to $CO_2$ compression. Speciation of mercury, elemental ($Hg^0$)or oxidized (such as HgO or HgCl), is important with elemental mercury reacting with aluminium heat exchangers. The only reported data on mercury emission under Oxy-CFB conditions (Fry, 2011) indicate that additional measurements are necessary.

The issue of trace element emissions during coal combustion has important implication to the operation of Oxy-CFB combustors using different types of coals. The fate of trace elements (TEs), which are present in coal at very low concentrations (below 100 ppm)(Vejahati et al., 2010), are an important consideration as the inclusion of excessive amounts of these elements in the gas is harmful to the environment. The combustion of coals containing only several parts per million of TEs could result in the release of several tons of pollutants into the environment(Vejahati et al., 2010). Therefore, knowledge of trace element reactions and behaviour during Oxy-CFB combustion is important for the control of pollutants and emissions. Though a few studies have been carried out to study the distribution of trace elements in air-CFB combustion (Koukouzas et al., 2011),(Wang et al., 2010),(Duan et al., 2010) few experimental data are available on Oxy-CFB combustion (Roy et al., 2011b). Using chemical thermodynamic software (F*A*C*T), Zheng and Furimsky found that the distribution of trace elements (As, Pb, Hg, Cd and Se) in Oxy-fuel combustion with Eastern Canadian coal was unaffected in compared with that in air combustion (Zheng and Furimsky, 2003). In Oxy-CFB combustion using low-rank coal, these behaviors could remain the same or different.

Therefore, it is essential to have targeted research to establish the particulate matter, heavy metals and trace elements emission during Oxy-CFB combustion using Australian coals.

### *Moisture content in the coal*

Although CFBCs can handle high-moisture coals without drying, pre-drying of coal will be essential for Oxy-CFB. If flue gas has high moisture content (which can be as high as 40% in the flue gas without coal pre-drying), flue gas recycle will bring more moisture back to the boiler and increase moisture content in flue gas; that in turn will require the flue gas temperature in the fabric filter to be increased to avoid acid dew point. Therefore, the ideal take-off point for flue gas recycle in such systems will be after the second flue gas cooler (FGC) as shown in Figure 8.

A lower moisture content in the flue gas will also improve the overall process efficiency. The relationship between moisture content in flue gas and acid dew point will depend on the moisture content, sulphur and chlorine level in coal; such relationship can be established by process simulation.

### *Fluidization velocity*

Fluidization velocity is one of the most important parameters for Oxy-CFB boiler design and operation, which can affect the bed temperature distribution, heat flux, heat surface arrangement, agglomeration and corrosion (Zhao et al., 2010). So, there is a need to know the effect of fluidization velocity on Oxy-CFB operation using different types of coals.

*While we have identified the major coal quality impacts on Oxy-CFBC design, there is a need for targeted bench scale research on some of these issues. In particular, the issues of emission of Sulphur and trace element species require to be established. These issues will only affect the design of the gas clean-up system for $CO_2$ disposal, and none of these issues will be show-stoppers for the Oxy-CFBC technology.*

# CHAPTER 6

## Oxy-CFB and Oxy-PF – Cost issues

In terms of technology development, Oxy-CFB is less developed compared to Oxy-PF; however, it is developing rapidly, in particular with the commissioning of the CIUDEN facility. Due to this state of technical maturity, a confident comparison of the cost and energy penalty figures between the two technologies cannot be made at this stage.

Here, we compare new build Oxy-CFB and Oxy-PF.

During the study we initially considered that if in-bed sulphur capture can be proven to satisfactorily reduce sulphur gas levels in Oxy-CFB then its capital cost would be less than the known cost of including FGD units in Oxy-PF for high-S coals. In addition, the expectation that Oxy-CFB would operate with lower air in-leakage and lower excess O2 would result in lower operating costs.

After a detailed review, we now conclude that published literature is divided on comparative costs, with only scant details being available. As an example, a report by NETL (2010) states installed cost (US$/kW) of Oxy-CFB to be 8% higher than Oxy-PF, while publications from EDF (2009) based on Alstom and Foster Wheeler data state large Oxy-CFBs to be potentially 10% cheaper than Oxy-PF.

In Chapter 1, potential advantages of the Oxy-CFB technology were identified. Based on those advantages, there are a number of characteristics of Oxy-CFB that lead to differences in capital cost (CAPEX), operating cost (OPEX) and energy penalty associated primarily with the energy requirements of the ASU and $CO_2$ compression when compared to Oxy-PF. Table 4 lists some differences considered to be of significance in terms of cost and efficiency penalty.

Other advantages for Oxy-CFB with cost impacts include suitability of CFB technology for use with poor quality coal, some of which could be of lower cost than higher-rank coals, and reduced operating cost due to inherently lower impurity levels in $CO_2$, such as NOx.

Regarding efficiency without CCS, it should also be noted that the current state-of-the-art of CFB is the 460MWe supercritical Lagisza plant, with reheat steam temperature of 580C, below current ultra-supercritical PF technology which has unit operating sizes of 1100MWe and steam conditions of 630C. Foster Wheeler indicate that guarantees can be given for future CFB plant of 620C reheat. The Baima plant, currently approaching commissioning in China, is 600 MW with supercritical steam temperatures 580C.

Some estimates of differences for Oxy-CFB may be suggested in terms of CAPEX, OPEX and energy penalty, as follows:

**CAPEX:** The CAPEX cost advantage for Oxy-CFB may exceed 5% depending on suitability on in-bed S removal and reduction of flue gas recycling, reduced size of boiler and its auxiliaries. The avoidance of downstream S removal has yet to be proven, and may apply favourably for Oxy-CFB using low-S coal, and the form of S, in particular the organic S which is emitted in the gaseous phase.

**Table 4** Some differences between Oxy-PF and Oxy-CFB with cost and energy penalty impacts

| Differences not advantageous to Oxy-CFB, compared to Oxy-PF | | |
|---|---|---|
| Difference | Cost/efficiency impact | Comments |
| Steam conditions and resultant efficiency of plant without energy penalty for CCS | New PF plant currently with 630C steam reheat (with development to 700C in progress, compared to FW (Hotta, private communication) indicating guarantee of new CFB plant of 620C | Similar steam conditions and efficiency without CCS, but is risk is considered greater for CFB. Development to higher steam temperatures for CFB is more challenging due to lower furnace gas temperatures |

| Differences potentially advantageous to Oxy-CFB, compared to oxyPF | | |
|---|---|---|
| Difference | Cost/efficiency impact | Comments |
| Direct SO2 removal in in-bed for CFB, to avoid need for FGD | CAPEX: FGD has significant cost for Oxy-PF for high S coal, ~7% CAPEX | Suitability of in-bed removal alone yet be proven. Current designs in assessments of Oxy-CFB have S removal exterior to bed in addition to in-bed removal |
| Reduction of air in-leakage | CAPEX and OPEX of compression plant: Reduces N2 removal need and increases $CO_2$ recovery | Leakage for Oxy-CFB potentially 1% for operation at positive pressure, compared to possibly around 5 % for Oxy-PF, so $CO_2$ recovery will increase. OPEX improvement uncertain. |
| Reduction of flue gas recycle, reduced size of boiler and its auxiliaries | CAPEX and OPEX of boiler island | In Oxy-PF, flue gas recycle ratio is typically 70%. In Oxy-CFB, it is around 30% as the cooled circulating solids assist in moderating temperature inside the boiler. This is expected to result possibly in a 50% lower cost for the associated ductwork, and a smaller reduction in CFB boiler size. |

| | | |
|---|---|---|
| Reduced fan and blower power | CAPEX and OPEX. | Due to lower flue gas recycle, Oxy-CFBs are expected to lower the cost of fan power (associated with the recycled flue gas) possibly by 50% |
| Reduced excess $O_2$ | Potential reduced flue gas $O_2$ of 1% compared to 3% | Reduced $O_2$ supply required with reduced energy penalty. |

**OPEX and energy penalty**: The OPEX advantage is based on air leakage reduction, lower excess $O_2$ operation and lower auxiliary power. Lower excess $O_2$ operation alone may reduce the oxygen supply of the ASU by 10%, associated with a reduction of the Oxy-fuel energy penalty from typically 9% by 0.5%.

**$CO_2$ recovery:** Reduced air leakage for Oxy-CFB may result in increased $CO_2$ recovery of greater than 10%.

The only quantitative cost comparison between Oxy-PF and Oxy-CFB is presented in a NETL report (2010). For nominal 550 MW net output, supercritical steam parameters of 600C/600C, Powder River Basin sub-bituminous coal and without considering $CO_2$ transport and storage, the installed capital cost are as follows:

- Oxy-PF - US$ 3070/kW
- Oxy-CFB – US$ 3290/kW – making Oxy-CFB about 8% more expensive than Oxy-PF

For other coals, the relative difference is expected to be similar.

The NETL study appeared to consider mature technology for Oxy-PF boiler based on existing developments, and also relatively larger sized PF units available commercially to 1100 MWe. For Oxy-CFB, first-of-its-kind (FOAK) technology has been considered, based on relatively recent technology development and also the largest commercial size of the CFB currently available, to 460 MWe. These considerations have some impact on the cost figures above.

In addition, the NETL study did not consider any in-bed S-capture, rather consideration was given to downstream S-capture through Alstom's proprietary Flash Drying Absorber (FDA) coupled with the bag filter unit. However, the cost of the FDA unit is not known.

The operational experience gained in CIUDEN will shed insight into S-capture under large scale Oxy-CFB operation. In particular, the issue on the need for downstream S-capture in addition to in-bed S-capture is expected to be resolved.

It is likely that for low-S coals, in-bed S-capture will be sufficient, while for high-S coals and those having large proportion of organic-S, additional downstream S-polishing might be required.

The NETL study also did not specifically indicate the effects of trace element emission (see chapter 5) on downstream gas cleaning prior to $CO_2$ separation. While, the emission of these elements under Oxy-CFB condition is yet to be conclusively known for a range of coals, the downstream cleaning requirements could at worst be similar to that required in Oxy-PF. Therefore the cost and energy penalty issues will likely be similar to Oxy-PF.

In summary, current knowledge indicates that the cost of a mature Oxy-CFB technology is likely to be of the same order for the Oxy-PF technology. At the very least, for lower-S or lower grade coals, Oxy-CFB may have a cost advantage over Oxy-PF.

As operational experience begins to appear from CIUDEN, it will be worthwhile to carry out an in-depth cost study on Oxy-CFB using representative Australian coals.

# CHAPTER 7

## Oxy-CFB - Relevance to Australia and Recommended R&D

CFBC plants were originally developed for use with low-quality and "difficult-to-burn" fuels – high sulfur, high ash, low calorific value and combinations – or where fuel flexibility was required, such as the availability of variable quantities of wastes for co-firing with more traditional fuels. However, gradually CFBCs have established themselves as being capable of handling almost all types of solid and several liquid fuels. The largest CFBC with supercritical steam parameters and unit size of 460 MWe operates in Poland with bituminous coals. New supercritical steam CFBC boilers between 550-600 MWe size are under construction in China and Korea. Commercial guarantees for units up to 800 MWe are currently available. In contrast, *pf* boilers are now available to 1100 MWe unit size with ultra-supercritical steam parameters.

Apart from demonstrated performance of fuel flexibility, ability to capture sulfur *in-situ*, eliminate slagging and reduce fouling during operation, and reduced $NO_x$ emission without requiring low-$NO_x$ burner are some of the major advantages of CFBC boilers.

Oxy-CFB is emerging as a serious additional technology option for $CO_2$ capture. This is demonstrated by the rapid design and construction of world's first Oxy-CFB pilot scale facility at CIUDEN, which has been commissioned in September 2011. The facility is designed and operated by Foster Wheeler, and will emphasise testing of non-lignitic coals. In addition to 30MWth Oxy-CFB unit, the facility also has a 20 MWth Oxy-PF unit and a biomass gasifier. A 300 MWe Oxy-CFB plant is also under consideration in Compostilla, Spain.

Among the technology vendors, ALSTOM appears to be dormant in the development of Oxy-CFB following a number of years of pilot scale development work and feasibility studies. B&W is now active in China which has the largest CFBC installations. Foster Wheeler is the primary technology provider for Oxy-CFB. This position will be enhanced due to the Foster Wheeler's involvement in the CIUDEN facility.

We have reviewed the results from several small and bench scale facilities around the world operated under Oxy-CFB conditions. While, performance from longer-duration tests at CIUDEN will shed more insights, the following observations can be made:

- Combustion of coal particles under Oxy-CFB conditions is unlikely to be a problem.
- Agglomeration of minerals (from low-rank, high-alkali or high-S coals) under elevated levels of $CO_2$, $SO_2$ and water vapour may be a problem; targeted measurements using such coals in bench scale would provide definitive answers and identify remedial measures, if any.
- Recarbonation in the back-pass of the boiler could be a problem, particularly for coals which have high Ca-content or coals that require added Ca for S-control. Again, targeted measurements using such coals in bench scale would provide definitive answers and identify remedial measures, if any.

- The extent of in-bed removal of sulphur gases in CFB and the need to sulphur removal by an additional operation exterior to the bed requires clarification.
- There is a lack of reliable information on emission of S-species, heavy metals and trace element emissions under Oxy-CFB conditions. It is not possible to speculate the extent of their emissions for Australian black and brown coals as no thermodynamic database can reliably make predictions under these conditions.

  Mercury speciation is not expected to be substantially different from Oxy-PF combustion, but data from only one study has been cited.

  The concentration of S-species, trace elements have significant implications for the gas cleaning requirement for $CO_2$ capture and transport.

  Therefore, targeted measurements using such coals in bench scale would provide definitive answers and identify remedial measures. These will also allow accurate estimation of cost for Oxy-CFB systems for $CO_2$ capture.
- A detailed analysis should be undertaken to establish the economics of Oxy-CFB technology under supercritical and ultra-supercritical steam conditions and using Australian coals.
- The economic evaluation should consider a sensitivity study on the unit operations employed, particularly the gas cleaning operations and their relevance to Australian coals and emission regulations. In particular, sensitivity to in-bed sulphur removal must be clarified.
- Results from Vattenfall's Oxy-PF, CS Energy's Oxy-PF and CIUDEN's Oxy-CFB and Oxy-PF will resolve many of these uncertainties as performance results from longer-duration performance trials become available.
- In addition to the above, continued development of membrane separation technology in parallel is essential, in particular high temperature $O_2$ separation membranes

**Oxy-CFB roadmap**

A roadmap for future Oxy-CFB development has been developed based on the roadmap previously developed for Oxy-PF (Wall and Stanger, 2010),(Wall et al., 2011),(Henderson and Mills, 2009), and is given on Figure 14.

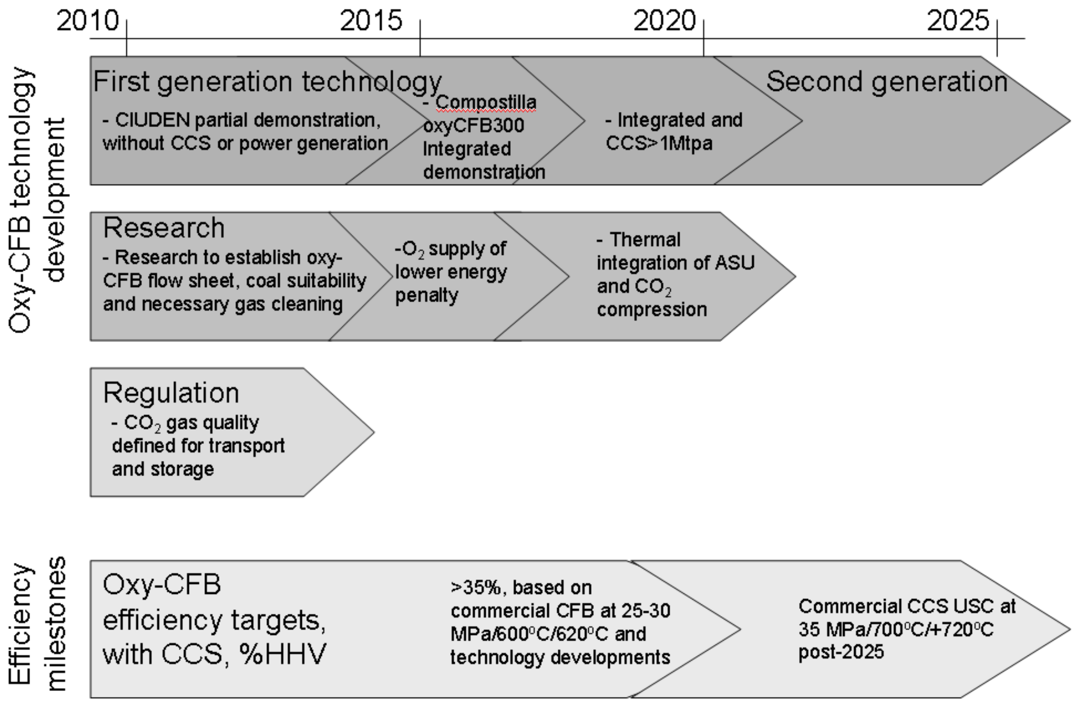


**Figure 14**: *Oxy-CFB roadmap*

Due to the current status of Oxy-CFB development compared to Oxy-PF, there is greater uncertainty regarding future technology development and deployment.

Common drivers for Oxy-PF and Oxy-CFB include a future cost of CO2, and development of higher USC efficiency commercial plant (suggested to be >500MWe). The roadmap indicates a delayed application of higher temperature steam turbines for CFB compared to PF based on IEA projections (Henderson and Mills, 2009). Although Foster Wheeler indicate guarantees can currently be provided for USC CFB units, the commercial risk of their deployment must be considered to be greater.

Other common aspects include technology improvements such as O2 supply with lower energy penalty and thermal integration of plant, and regulations defining CO2 gas quality for transport and storage.

Noted for Oxy-CFB is the current need for more fundamental and applied research related to the uncertainty of coal performance and gas quality control, in order to define the appropriate Oxy-CFB flowsheet. Currently the CIUDEN plant is expected to provide the applied research. The extent of targeted basic research and economic analysis using Australian coals are spelt out earlier in Chapter 7.

*Oxy-CFB can play a significant role as an additional technology for $CO_2$ capture. Based on the small and bench scale results from various units around the world, Oxy-CFBC appears for the time being to be more suitable for low-rank or high-S or high-ash coals. While Oxy-CFB in principle has the potential to be cheaper than Oxy-PF, there is considerable cost uncertainty, stemming primarily from lack of reliable information on trace pollutant and S-species emissions. This will impact the gas cleaning requirements downstream of the CFB unit, and hence the overall cost of the system. The long-duration performance results from the CIUDEN facility, (which incidentally tests primarily non-lignite coals) will be vital to remove or significantly reduce some of these uncertainties.*

*We recommend targeted bench scale experiments using selective Australian black and brown coals to assess the emission of S-species and trace elements under Oxy-CFB conditions. This should allow a precise economic analysis of the Oxy-CFB system to be carried out.*

*Also, serious consideration be given to carry out testing two representative Australian coals at the CIUDEN facility.*

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# List of Acronyms

| | |
|---|---|
| ABARE | Australian Bureau of Agriculture, resources, and energy |
| ACALET | Australian Coal Association Low Emissions Technologies Limited |
| APP | Asian Pacific Partnership |
| ANLECR&D | Australian National Low Emissions Coal Research and Development |
| ASU | Air Separation Unit |
| CAPEX | Capital expenditure |
| CCS | Carbon Capture and Storage |
| CEC | China Energy Council |
| CEI | Clean Energy Initiative |
| CFB | Circulating fluidized bed |
| CFBC | Circulating fluidized bed combustion |
| CPU | CO2 Purification Unit |
| DeSOx | A collection of sulphur removal technologies |
| DeNOx | A collection of nitrogen oxides removal technologies |
| DOE | Department of Energy |
| EDF | An electricity generation company |
| ESAA | Energy Supply Association Australia |
| FDA | Flash Drying Absorber |
| FGC | Flue gas cooler |
| FGD | Flue Gas Desulfurization |
| HRSG | Heat Recovery Steam Generator |
| IEA | International Energy Agency |
| LNB | Low NOx Burners |
| OFA | Over-Fire Air |

| | |
|---|---|
| OFWG | Oxyfuel Working Group |
| OPEX | Operational expense |
| Oxy-CFB | Oxy-fuel combustion using a circulating fluidized bed |
| Oxy-PF | Oxy-fuel combustion fired with pulverized fuel |
| PF | Pulverized Fuel |
| MWe | Mega Watt electricity |
| NETL | National Energy Technology Laboratory, USA |
| NOx | Nitrogen oxides |
| LCOE | Levelized Cost of Electricity |
| SC | Super Critical |
| SCR | Selective Catalytic Reduction |
| SNCR | Selective Non-Catalytic Reduction |
| SDA | Spray Dryer Absorber |
| TEA | Techno-economic analyses |
| TPC | Total Plant Cost |
| USC | Ultra Super Critical |

# Appendix 1 Report on a visit to the CIUDEN facility

Photograph taken in front of CFB during CIUDEN site visit from left: Rohan Stanger, Inaki Alvarez Gutierrez, Sankar Bhattacharya, Jesus Ramos Lage, Terry Wall, Jon Lopez Diaz and Arto Hotta.

# Appendix 1

## The status of Oxy-CFB technology for CCS:

## Report on a visit to the CIUDEN Carbon Capture Technology Development Plant and discussion involving Foster Wheeler Oy, January 31 and February 1, 2011

**Prepared by Terry Wall, Sankar Bhattacharya and Rohan Stanger**
**University of Newcastle and Monash University**

**March, 2011**

## Summary

A site visit to the world's largest pilot Oxy-CFB facility, at CIUDEN in Spain, was organised and coupled with a discussion meeting with the facility's management and the technology developer, Foster Wheeler.

The reason for the facility is due to the current domestic fuel sources reaching the end of the easily minable coal seams and the variability in the spot price of petroleum coke, the emphasis on fuel versatility has led the use of fluidised bed combustion to provide electricity generation.

The principal focus for the CIUDEN Test Plant is to support and validate the scale-up of Foster Wheeler's Oxy-CFB technology, which will be the basis for Endensa's Compostilla OxyCFB300 project. The OxyCFB300 industrial demonstration has already attracted EU funding of €180M for the pre-feasibility study, with the intention of operating in 2015. The plant is aimed at producing 323MWe with a capture rate of 91%. The investment decision will be made at the end of 2012.

The CIUDEN PC and CFB rigs are in parallel, with common gas treatment units. When operating with $CO_2$ capture, only one rig can be used. A fluidised bed biomass gasifier, which sits between the PC and CFB rigs, and a $CO_2$ gas pipeline transport rig which will follow the compression units are also included. CIUDEN has now selected Praxair as the vendor for liquid oxygen supply & Air Liquide for the CO2 Processing Unit through a competitive bidding process involving Praxair, Air Products, Air Liquide. In future, CIUDEN will consider allowing other vendors to test their systems on a slip-stream.

Through discussion, it appears that ALSTOM is now not active in Oxy-CFB, but that B&W is now active in China where there are many CFBs. Foster Wheeler is therefore the primary technology provider for Oxy-CFB. This position will be enhanced due to the Foster Wheeler involvement in the CIUDEN facility. A summary of technical discussions during the meeting is included.

## Overview

Oxy-fuel Combustion is a CO2 capture technology currently being developed in order to abate anthropogenic CO2 emissions from the power generation sector. In general the majority of oxy-fuel projects (research, pilot scale) has been focussed on pulverised coal combustion as this represents the dominant form of electricity utilities world wide. However, with many countries facing aging infrastructure and diminishing supplies of current coal feed stocks, new build oxy-fuel circulating fluidised bed combustion (Oxy-CFB) could provide a viable alternative to oxy-fuel pulverised coal (Oxy-PC).

Oxy-CFB has recently emerged as a prospective technology for CCS, with the announcement of the feasibility study supported by the EU for the 300 MWe demonstration unit at Compostilla, in Spain. This development is based on the pilot-scale development of Oxy-PF and Oxy-CFB at 30MWt scale at CIUDEN, also located on the Compostilla site.

The benefits of fluidised bed combustion are well known; fuel versatility, in-bed SO2 capture, uniform heat flux, stable load following), however under oxy-fuel combustion other benefits are presented (possibly lower air leakage, high $O_2$ concentration ≈ reduced boiler size).

As part of an ANLEC Oxy-CFB scoping study, a site visit to the worlds largest pilot Oxy-CFB facility, CIUDEN, was organised and coupled with a discussion meeting with the facility's management and the technology developer, Foster Wheeler.

The visit was organised by Monica Lupion, through the Asia Pacific Partnership Oxyfuel Working Group (OFWG) with an APP project supporting travel costs.

Foster Wheeler has emerged as the primary Oxy-CFB vendor, and their R&D expertise is in Finland. Therefore we were very gratified that Arto Hotta, Director R&D, Foster-Wheeler Global Power Group, Finland was able to visit CIUDEN for the meeting. Dr Stanley Santos of IEAGHG was to have also joined the group but due to visa problems he was not able to attend. Those present included:

- Foster Wheeler
    - Arto Hotta, Directo R&D, Foster Wheeler Energia Oy, Finland
    - Jon Lopez Diaz, Foster Wheeler Energia, S.L.U, Spain
- CIUDEN
    - Jesus Ramos Lage, Technical Adviser, $CO_2$ Capture Programme
    - Pedro Otero Ventin, Technical Director, $CO_2$ Capture Programme
    - Monica Lupion, External Relations Director, $CO_2$ Capture Programme
- Australia
    - Professor Terry Wall, A/Professor Sankar Bhattacharya, Dr. Rohan Stanger

The report has two parts, the first outlining the facility, the second giving a brief summary of the discussions.

## The CIUDEN facility

### Background

The CIUDEN Carbon Capture Technology Development Plant (TDP) has been developed as part of the Spanish government's initiative to drive carbon capture technologies towards commercialisation. The CIUDEN project is funded by three Spanish government departments (Science and Innovation, Industry and Trade, Environment). The project also includes an Energy Museum located on the site of the first Compostilla power station which began operation in the 1920's and was decommissioned in the 1940's. The regional fuel source has historically been based on anthracite with the addition of petroleum coke as a secondary fuel. Domestic coal makes up around 30% of Spain's power generation. With the current domestic fuel sources reaching the end of the easily minable coal seams and the variability in the spot price of pet coke, the emphasis on fuel versatility has led the use of fluidised bed combustion to provide electricity generation. Furthermore, with only one power station built in Spain in the last 20-30 years and the current international push towards CCS technologies, supporting the commercialisation of oxy-fuel will prevent new-build utilities from being "locked-out" of capture technology.

### The CIUDEN Facility

The CIUDEN facility is situated in Ponferrada, north-western Spain (Figure 1). A number of activities other than oxy-fuel are supported at the test facility. The intention is to facilitate large scale testing of Oxy-PC, Oxy-CFB, biomass gasification and post-combustion capture (shown in Figure 2). The facility will have the ability to perform a number of flue gas treatment options (SCR, FGD, Bag filter) or elect to bypass them. The main parameters for the PC and CFB boilers are given in Table **A1-**1. The plant does not contain an ASU as it was deemed a mature technology and not in need of demonstration.

### Supporting Oxy-CFB Demonstration

The principal focus for the CIUDEN Test Plant is to support and validate the scale-up of Foster Wheelers Oxy-CFB technology, which will be the basis for Endensa's Compostilla OxyCFB300 project. The OxyCFB300 industrial demonstration has already attracted EU funding of €180M for pre-feasibility studies, with the intention of operating in 2015. The plant is aimed at producing 323MWe with a capture rate of 91%. The investment decision will be made at the end of 2012.

Figure 3 indicates the historical development of oxyfuel technology indicating the CUIDEN PC and CFB and Compostilla CFB300 projects.


**Figure A1-1.** Location of Test Facility in Ponferrada in the north-west of Spain

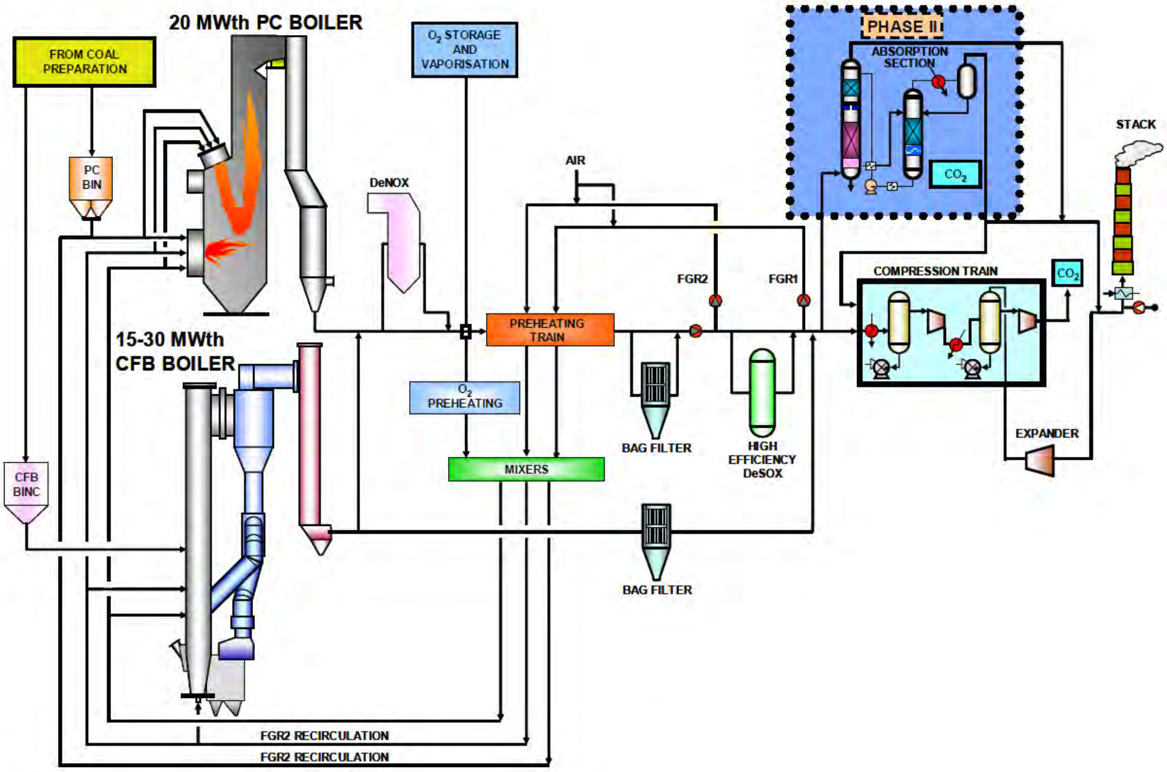


**Figure A1-2.** Simplified diagram of CIUDEN facilities

Figure A1-2 gives the flow sheet for the PC and CFB rigs in parallel, showing the common gas treatment units. When operating with CO2 capture, only one rig can be used.

Not shown on Figure A1-2 is the fluidised bed biomass gasifier, which sits between the PC and CFB rigs, and a CO2 gas pipeline transport rig which will follow the compression units. We did not inspect or discuss this latter facility, but it may be unique.

Figure A1-4 gives gives a photograph of the facility looking at the coal feeding conveyor, and the PC and CFB rigs indicating there is still construction work proceeding. Our hosts were confident that the mid-2011 opening would be realised.

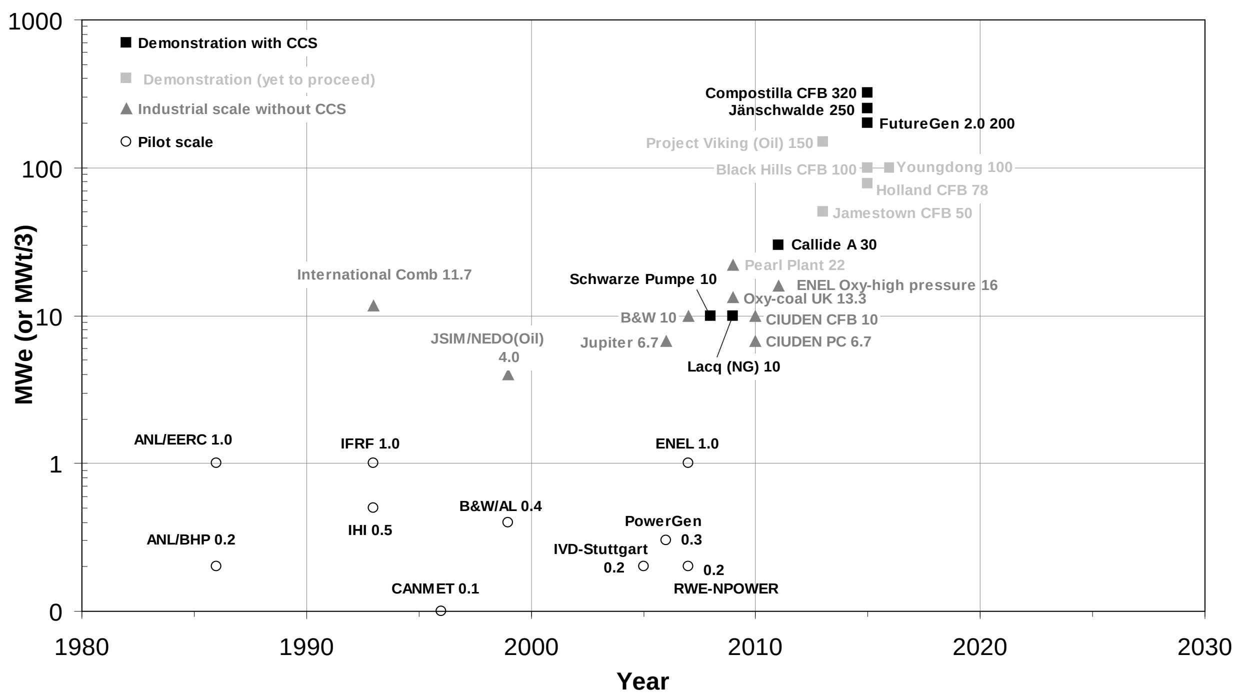


**Figure A1-3:** Historical development of oxyfuel technology indicating the Ciuden CFB and Compostilla CFB300 projects **(*Note that the Janschwalde Project is currently on hold*)**

### The facility

The CIUDEN facility was built with 100million€ CAPEX from the European Commission. The current operating budget is 8million€ per year, decided every year depending on the operating programme. At present, the facility will be run by CIUDEN with Foster Wheeler involvement. In future, they will consider participation by other organisations/research institutions/universities in the research programme.

The facility is expected to be operating mid-2011, with Figure 4 indicating the state of construction during the visit.

The IP developed at the Oxy-CFB unit may remain with Foster Wheeler who will however pay for the development work at the Oxy-CFB unit.

CIUDEN will also target the cement sector, in addition to the power generation sector, join in the Oxy-CFB development work

- The facility has three units with one common control room building. The units are as follows:

  … a 3MWth atmospheric pressure bubbling fluidized bed biomass gasifier, , which will supply fuel gas to the pc boiler unit, char to the CFB, a 20MWth oxy-PC unit with steam generated at 30 bar/420°C at 25 t/hr, this PC unit has the flexibility for both vertical and horizontal firing. The vertical firing will be employed for low-volatile anthracite or lower reactivity coals to achieve longer residence time for combustion. The maximum flue gas flow out of this unit is 26.4t/hr of which up to 17.9 t/hr can be recirculated if required. The PC boiler was designed and constructed by Combustion Biomass Services, a small Spanish company, with the intention of making it flexible.

  … a 30 MWth (21.7mH, 2.7m W, 2.4m L) Oxy-CFB unit, design of it is based on the results from CANMET and VTT facilities which were also funded by Foster Wheeler. The Oxy-CFB unit will run at a maximum coal feed rate of 5.5t/h, and the corresponding maximum $O_2$ feed rate will be 8.8t/h. Oxygen will be supplied from liquid oxygen storage tanks as opposed to ASU. The unit will start-up on air, but under Oxy-CFB condition, it will provide higher capacity as the coal feed rate has to be higher to get the right level of superficial velocity (expected output of 15MWt on air and 30MWt on oxy). O2 will be supplied at concentrations up to 40%.
- According to Foster Wheeler, the size of the CFB will allow easy scaling-up to 300MWe unit. In particular, the height has been selected so that overall scaling-up becomes easier
- The fuels to be tested at the CIUDEN Oxy-CFB unit include Anthracite (30% ash), bituminous coals, sub-bituminous coals (30 Hardgrove index) and Petroleum coke ( 0.8% ash, 6.5% S, and rich in Vanadium)
- The drying of the coal will occur in a separate inertised (CO2) process due to the explosive risk of some brown and sub-bituminous coals. Initially hot gases will be produced for the drying process from natural gas combustion, however this will eventually been replaced by hot recycled flue gases.
- Tapping point for flue gas recycle in the Oxy-CFB unit – several options will be tried, before and after the FGD unit
- Flue gas cleaning system in the Oxy-CFB unit involves the following:

  Cyclone → SCR → bag filter -→ ID fan -→ FGD-→ Stack

- CIUDEN selected Praxair as the vendor for liquid oxygen supply & Air Liquide for the CO2 Processing Unit through a competitive bidding process involving Praxair, Air Products, Air Liquide. In future, CIUDEN will consider allowing other vendors to test their systems on a slip-stream.

- Among the key research needs nominated during the visit to be addressed by the facility are:
    - Identify and quantify the trace elements released into the gas phase under Oxy-CFB condition is important
    - Assess the recarbonation propensity at the external (INTREX) heat exchanger
    - Agglomeration under Oxy-CFB conditions
    - Sulfation under Oxy-CFB conditions
    - Lignite issues need to be identified
    - 

**TABLE A1-1 –** Main Operating Parameters for CIUDEN Facility

| | PC Boiler | CFB Boiler |
|---|---|---|
| **Size (m)** | 24 x 7.6 x 4.5 | 21x2.7x2.4 |
| | | |
| **MWth - max oxycombustion mode** | 20 | 30 |
| **O2 (kg/h)** | 6600 | 8775 |
| **Flue Gas Recycle (kg/h)** | 17900 | 25532 |
| **Flue gas flow (kg/h)** | 26400 | 28800 |
| **Coal flow rate (kg/h)** | 3350 | 5469 |
| **Steam (t/h)** | 25 | 44.6 |
| | | |
| **Burners** | 4 horizontal burners<br>2 vertical burners | |
| **Limestone feed (kg/h)** | | 720 |
| **P(bar) / T (°C)** | 30 / 420 | 30 / 250 |
| | | |


**Figure A1-4.** Photograph taken of CIUDEN facility at sunset, January 31, 2011

## Discussion during meeting

The meeting agenda is given at the end of the appendix, and involved presentations from CIUDEN, Foster Wheeler and the Australian delegation. Prior to the meeting seven areas were identified for discussion, with questions for each area. Here, the areas and questions are given with summary discussion points given in italics where reasonable discussion occurred.

Most of the questions were answered by Arto Hotta, Director R&D, Foster-Wheeler Global Power Group, Finland.

Through initial discussion, it appears that ALSTOM is now not active in Oxy-CFB, but that B&W is now active in China where there are many CFBs. Foster Wheeler is therefore the primary technology provider for Oxy-CFB. This position will be enhanced due to the Foster Wheeler involvement in the CIUDEN facility, as many questions asked in discussion were answered on the basis that operational experience with the CIUDEN rig will resolve the issue in one way or the other.

## 1: CFB technology for coal-fired power generation

| |
|---|
| Issues: Current status – air-fired CFB, and Oxy-fuel CFB; steam conditions, scale, efficiency, market share |

**Discussion**

- What is the maximum size at present that the vendors will be willing to provide guarantee with any coal? *Depends on the outcome of the results from CIUDEN facility which under the CFB facility is 40MWth. Foster Wheeler (FW) is of the view that Oxy-CFB units of current air-CFB units can be designed.*
- What are the maximum steam conditions at present that the vendors will be willing to provide guarantee? *FW sees the possibility of the supercritical (SC) steam conditions (similar to their Lagisza air-CFB unit in Poland) in Oxy-CFB offering.*
- What's needed to increase both size and steam conditions? – *eventually to air-CFB size for which they have design up to 800MWe SC unit. The current largest operating air-CFB is in Lagisza, Poland which was built by Foster Wheeler and has SC steam conditions.*
- Are there any issues (*eg.* government "policy push" or "technology pull") to accelerate the development – *not discussed explicitly, but quite obvious that without government support (as in CIUDEN) such developments would not be possible.*

## 2: Development and demonstration of Oxy-fuel CFB technology for CCS

Some of the current known bench to pilot scale demonstrations are:

- Foster Wheeler used facility at CANMET, Canada
- Alstom facility at Connecticut, USA
- CUIDEN, Spain
- Flexi-Burn CFB
- CANMET Mini-CFB: 0.8 MWth, 5kg/h coal feed
- WP 3.4 in ENCAP $CO_2$ program
- Unit at the University of Utah
- Unit at the VTT, Finland

Laboratory scale facilities

- CANMET - TGA: sulfation, ash characteristics
- Southeast University in China
- Huazhong University of Science and Technology (HUST)

**Discussion**

- Who are financing these developments/demonstrations at present? – *private or predominantly public? –predominantly public.*
- Are these developments/demonstrations sufficient leading to commercial demonstration? – *According to FW, the CIUDEN facility is of a size that would allow them to scale up to 300MWe size.*
- If not, what else is required, at what scale and when? Are we ready for a larger scale demonstration? *Depends on the results from CIUDEN unit.*
- What is required before a Lagisza-scale Oxy-CFB unit can be built and when? *Depends on the results from CIUDEN unit.*

## 3: Design and operation of oxy-fuel CFB

Some of the issues, relative to air-fired CFB and Oxy-PF are:

- Start-up and shut-down – *no different to air-CFB*
- Part-load behaviour, and load following capability – *same as air-CFB*
- Control system – *no different from air-CFB; however, control of the ASU could be important*
- Bed temperature and heat transfer – *agglomeration could be an issue, but otherwise no different from air-CFB*
- Fluidization velocity, excess oxygen requirement – *same as air-cfb, yet to be demonstrated but expected to be around 2% excess oxygen*
- Cyclone separator performance - *same as air-cfb as fluidization velocity will be similar*
- Sealing of the boiler – *air leakage could be issue, see Horst Hack (of USA Foster Wheeler) presentation at the Clearwater conference 2010, see note # below*
- Erosion
- Flue gas looping - hot or cold. *– no reduction in FG recirculation expected, but a number of recycle options are being studied at CIUDEN*

**Discussion**

- What are the design implications of these issues to the key components for introducing oxy-firing to CFB design
    - Furnace
    - Cyclone
    - FBHE
    - Economiser surfaces

*Will depend on the results from CIUDEN, but any impliations are likely to be similar to those in air-CFB*

- Differences, if any, among Oxy-CFB, Oxy-PF, and air-CFB expected in respect of the above issues on their design and control system. *Under oxy-fuel conditions, the CFB output (MWth) will be higher than in the air-CFB. This is because in order to maintain the CFB velocity in presence of O2/CO2 and to maintain a low excess O2 in the flue gas, the coal feed rate will have to higher.*

## 4: Coal quality impacts on Oxy-fuel CFB design

Some of the relevant issues are:

Fluidization velocity – *same comment as before in item 3*

Coal devolatilization, ignition delay in Oxy-CFB – *unlikely to be an engineering issue*

Char combustion in Oxy-CFB - *unlikely to be an engineering issue*

Mineral matter, bed agglomeration – *will require research for certain types of coals*

Recarbonation of fly ash - *will require research for certain types of coals particularly those which have high Ca and/or Mg*

SOx and NOx emissions and their control in Oxy-CFB – *likely to be equal to or better than air-CFB; NOx will be reburnt by recirculation into the bed*

Particulate matter and heavy metals, trace element partitioning between solid and gas phase - *will require research for certain types of coals*

Black coal vs. brown coal – *was not discussed*

**Discussion**

- To what extent coal quality (high levels of S, Cl, alkali, high-Si ash, mineral matter in coal) affect unit sizing, steam conditions and operating conditions (temperature, air/$O_2$ staging, agglomeration)? – *unknown at present, needs to be investigated*
- Will the above issues significantly affect the design of an Oxy-CFB relative to that of an air-fired CFB? - *unlikely*

## 5: Comparison between Oxy-fuel *pf* and Oxy-CFB

| |
|---|
| Some of the technical issues are:<br><br>Air separation issues<br><br>Safety issues $O_2/CO_2$ handling<br><br>Implementation of advanced steam conditions in Oxy-CFB<br><br>Cost and efficiency |

## 6: Issues related to retrofitting or replacing existing older *pf* and/or air-CFB units

### Discussion

- What are the prospects of <u>replacing</u> the existing air-CFB or *pf* boilers with an Oxy-CFB boiler? Are there any specific issues (such as sealing). Are there any government policy issues to accelerate the development. *Oxy-CFB was seen as a new build option*
- To what extent the existing auxiliary systems and major piping be retained? Can there be any generic criteria or could this predominantly involve a case-by-case analysis? *Needs to be decided on a case-by-case basis. But in general, FW sees Oxy-CFB as being used mostly for new-builds*

## 7: Relevance to Australia and recommended R&D for Australia *–this is Australia specific and was not discussed*

| |
|---|
| Some of the issues to address here are:<br><br>i) Could global development and overseas demonstration be the driver for Oxy-CFB entry to Australia?<br><br>ii) Research on coal quality impacts – experimental and modeling work; what are the major issues to address here?<br><br>– recarbonation, sulfation, emission of trace elements<br><br>iii) Most coal-fired units in Australia are sub-600MW units, almost all are sub-critical, what proportion of these can be replaced by Oxy-CFB?<br><br>iv) Establishing the economics of retrofitting existing *pf* units by Oxy-CFB vs. new built Oxy-CFB |

**Attachment : Meeting agenda**

**Workshop: Oxy-CFB technology for CCS development**

GOBIERNO DE ESPAÑA

ciudad de la energía

**Date and time: 31st January/ 1st February 2011, 09h30**

**Venue: CIUDEN headquarters, II Avenida de Compostilla nº2 24400, Ponferrada, Spain**

**Participants**

Terry Wall, university of Newcastle and Oxy Fuel Working Group

Sankar Bhattacharya, Monash University, Brown coal CFB expert

Rohan Stanger, University of Newcastle and OFWG

Arto Hotta, Director R&D, Foster-Wheeler Global Power Group, Finland

Jon Lopez Diaz, Project Engineer, Foster Wheeler Energia, Spain

Stanley Santos, IEAGHG, Cheltenham, England

José Angel Azuara, CIUDEN

Pedro Otero, CIUDEN

Monica Lupion, CIUDEN

**Agenda**

1. Introduction and welcome

2. Presentation: CIUDEN Technology Center for CO2 Capture and Transport (TCCT):OXYCFB technology

3. Presentation: OXYCFB300 Compostilla Project

4. Presentation: OXYCFB initiatives in Australia

5. Presentation: Latest development on OXYCFB technology. FOSTER WHEELER Oy

6. Presentation: International vision of OXYCFB technology from IEAGHG

7. Discussion

8. Conclusions

9. Visit to CIUDEN´s TCCT