Techno-economic analysis of PC versus CFB combustion technology

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Abstract

In the last ten years circulating fluidised bed combustion (CFBC) has emerged as a viable alternative to pulverised coal combustion (PCC) for utility-scale coal power generation, with widespread deployment of 300 MW boilers and the successful demonstration of supercritical units of up to 600 MW. Although CFBC offers a greater degree of fuel flexibility and does not usually require downstream flue gas cleaning, high capital costs and high auxiliary power use have hindered the adoption of CFBC for utility power generation. Recent advances in CFBC unit capacity and steam conditions have led to higher efficiencies and economies of scale, with the result that a CFBC plant may now be more economically favourable than a PCC plant depending on a range of factors such as available fuels and regional emissions limits. This report reviews the state-of-the-art for both technologies and provides a comparison of their relative performances and economic costs. Standard operational parameters such as efficiency, availability, and flexibility are assessed, in addition to relative suitability for biomass cofiring and oxyfuel combustion as strategies for carbon mitigation. A review of recent cost evaluations of the two technologies is accompanied by a breakdown of individual plant expenses including flue gas scrubbing equipment and ash recycle value.

Acronyms and abbreviations

ASU	air separation unit
BEC	bare erected cost
CIUDEN	Fundación Ciudad de la Energía
CF	capacity factor
CFB	circulating fluidised bed
CFBC	circulating fluidised bed combustion
COE	cost of electricity
CPU	compression and purification unit
DOE	US Department of Energy
EHE	external heat exchanger
EPRI	Electric Power Research Institute (USA)
EU	European Union
EC	European Commission
EPC	engineering, procurement, and construction
FBC	fluidised bed combustion (includes bubbling and circulating FBC)
FBHE	fluidised bed heat exchanger
FGD	flue gas desulphurisation
GEC	General Electric Company
HHV	higher heating value
IED	Industrial Emissions Directive
KOSPO	Korean Southern Power Company
LCOE	levelised cost of electricity
LCPD	large combustion plant directive
LHC	lower heating value
O&M	operation and maintenance
PC	pulverised coal
PCC	pulverised coal combustion
PRB	Powder River Basin
NETL	National Energy Technology Laboratory (USA)
SC	supercritical
SCR	selective catalytic reduction
SNCR	selective non-catalytic reduction
SOAPP	state-of-the-art power plant
TOC	total overnight cost
TPC	total plant cost
USC	ultra-supercritical

Contents

1 Introduction

The combustion of pulverised coal for power generation has been taking place since the 1920s, whereas firing coal in circulating fluidised beds (CFB) was first piloted in 1979, and not used for utility power generation until 1985. Since then, the growth in thermal capacity of circulating fluidised bed combustion (CFBC) units has proceeded at a similar rate to the early development of pulverised coal (PC) boilers, with particularly rapid growth during the last decade having culminated in the successful operation of a supercritical 460 MW unit at Lagisza power plant in Poland. A still greater capacity supercritical unit of 600 MW has recently been completed in China, whilst the construction of four 550 MW supercritical units for Samcheok power plant in South Korea, scheduled to begin operation in 2015, constitutes the single largest CFBC utility project to date. The boiler manufacturers involved in these projects are currently offering units of up to 800 MW in size. Whilst units on the scale of the largest PC boilers are not available, these developments have put CFBC firmly within the size and efficiency range of typical utility-scale units, making it a competitive alternative for large-scale power generation. Choosing which of these technologies to apply for a given project could therefore require careful consideration of several factors in order to determine the most appropriate economic and technical solution.

CFBC has traditionally been used as an effective way of burning unconventional solid fuels that are difficult or impossible to use in pulverised coal combustion (PCC). In particular, it has been widely employed to extract energy from coal mining wastes whose high mineral content presents insurmountable problems for PC boilers such as difficulty of pulverising, or slagging and fouling of the boiler. CFBC occurs over longer times and at lower temperatures than PCC, allowing larger particles of fuel to achieve complete combustion whilst mineral impurities remain solid. CFB boilers can therefore be designed to take essentially any solid fuel, hence another major impetus for their development has been their use in firing biomass in the pulp and paper industries of Sweden and Finland. Although CFB boilers are generally designed for a specific fuel, the tolerance of a unit to variation in fuel type is relatively high compared to PCC units, and this flexibility has come to be seen as one of their principal advantages for utility-scale projects. Increasingly liberalised and volatile fuel markets, coal sources of highly fluctuating quality, and the tendency towards biomass cofiring in some regions are all factors which can make CFBC a more attractive technology for coal power generation. For example, if the price of higher quality imported coal becomes too great, a switch to lower grade locally-sourced coal can be made without significantly impinging on the performance of a CFB boiler. In this way, the flexibility of CFBC can act as a contingency against variation in fuel supply and potentially offers an economic edge over PCC.

The other principal distinction between the technologies is their relative emissions of the two most widely regulated products of combustion: SOx and NOx. Production of NOx in CFBC is much lower than in PCC owing to the reduced combustion temperatures and, whilst some flue gas scrubbing may still be necessary to meet modern emissions limits, the expensive catalysts needed for PCC deNOx are not normally required. SO_2 capture in a CFB boiler is carried out by the injection of limestone into the furnace itself, thus avoiding the installation of large downstream desulphurisation units used for PC boilers. These capital and operational savings can represent a significant advantage for CFBC, particularly for high sulphur coals and in regions with strict emissions limits. On the other hand, the introduction of even stricter regulations which go beyond the levels achievable with in-furnace desulphurisation could necessitate additional scrubbers for CFBC and negate this advantage.

The potential benefits of CFBC have previously been offset by the greater specific capital cost of the boiler equipment, smaller unit size preventing economies of scale, and slightly lower efficiencies. However, recent growth in thermal capacity, aided by the move to supercritical steam conditions, and optimisation of the technology have allowed boiler costs to drop more in to line with PCC – a highly mature technology for which further optimisation is challenging. This report will assess the technical benefits of each technology and review cost assessments of their use for utility power generation performed in the past five years. Included in this evaluation will be relative suitability for oxyfuel carbon capture, for which both boiler technologies have been studied at the pilot scale.

2 Status of PCC technology

Pulverised coal combustion (PCC) is the standard technology for coal-fired electricity generation, comprising over 95% of the total global capacity. Coal is ground finely enough to achieve rapid combustion in a high temperature flame (1300–1700°C) when injected with air into a furnace. Stable flames are produced by burners in the furnace walls which control mixing of the coal with secondary air. Heat from the hot flue gases is exchanged with water flowing through tubing lining the furnace walls, and the resulting high temperature steam used to drive steam turbines. Upon leaving the furnace, flue gases flow into a convective pass area, either directly above the furnace (tower boiler) or after a U-turn (two-pass boiler), where further heat exchange surfaces are placed (*see* Figure 1). PC boilers with capacities as high as 1300 MW have been built, but multiple units of 300 to 700 MW are often deployed in modern PCC plants to mitigate the risk of outages. Once relatively inflexible to output cycling, PC boilers have increasingly been developed to meet the demands of liberalised energy markets and currently offer competitive load following capability.

PC boilers have been developing since their first application in the 1920s, and as such are a highly mature technology. This chapter will summarise some of the principal advances to date and outline the current capabilities of the technology.

2.1 Supercritical PCC

As the most effective way of increasing the efficiency of energy conversion, increasing the pressure

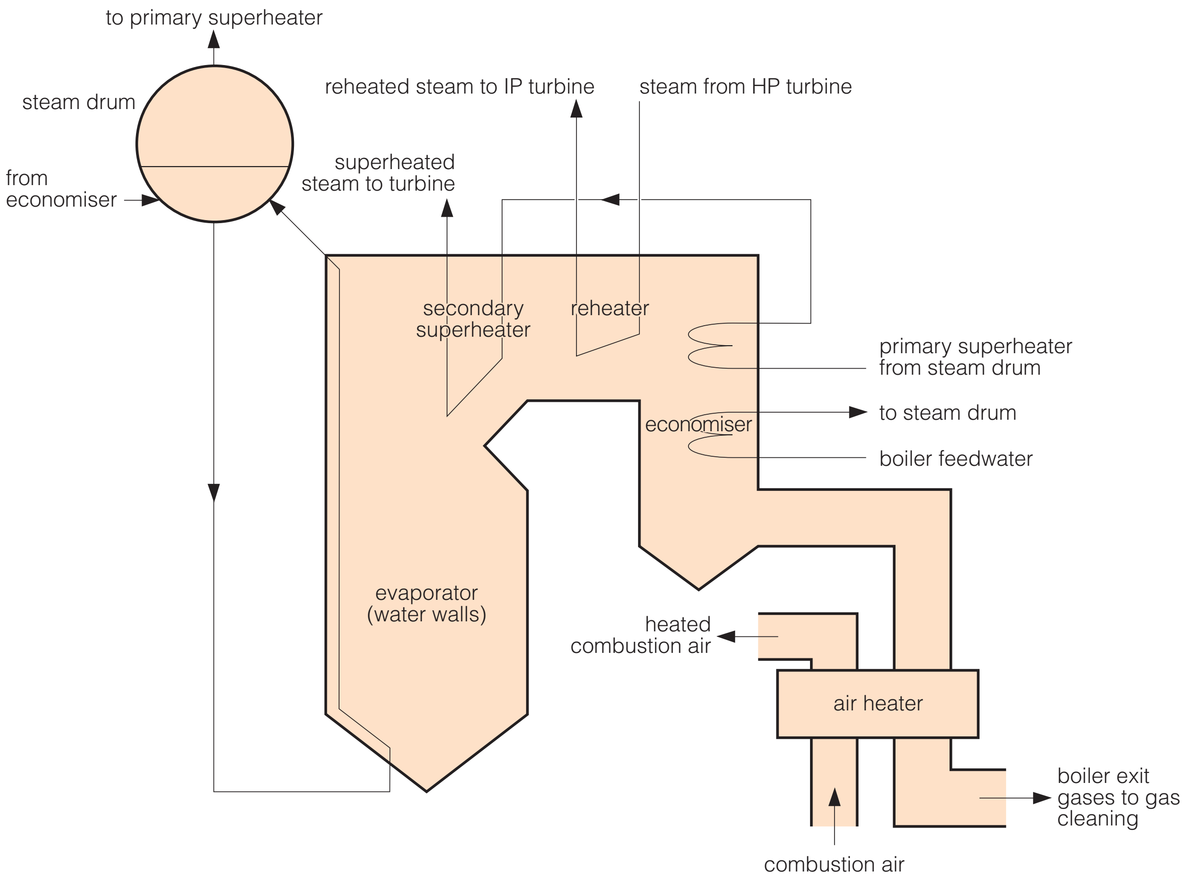

Figure 1 General schematic of a PC boiler (two-pass configuration)

and temperature of the output steam is the principal avenue of research on PC boilers and turbines, with the use of supercritical steam representing the clearest advance in this respect. A supercritical unit eliminates the need for a steam drum to separate steam from water, and can achieve efficiencies of up to 43% (LHV) compared to a practical limit of around 39% for subcritical boilers. Supercritical boilers were first developed in the USA in the late 1950s and were widely built there during the following two decades (over 100 units) despite showing initially poor reliability as well as difficulties with start-up and rapid load following (Saito and others, 2004). Originally, very high temperatures were used and some boiler components were made from austenitic steels which can crack when repeatedly heated and cooled. Milder steam conditions of 560–580°C were eventually settled on, and advances in high temperature metals, development of sliding pressure operation, and application of water purification systems led to steady improvements in supercritical boilers, enabling them to match subcritical units in terms of availability and load following. As a result, the technology was increasingly adopted for new coal plant in Europe and Japan and, more recently, in China, South Korea, and India. However, supercritical steam conditions are still only employed for less than half of new units worldwide, and subcritical boilers constitute the vast majority of existing coal plants (Platts, 2012).

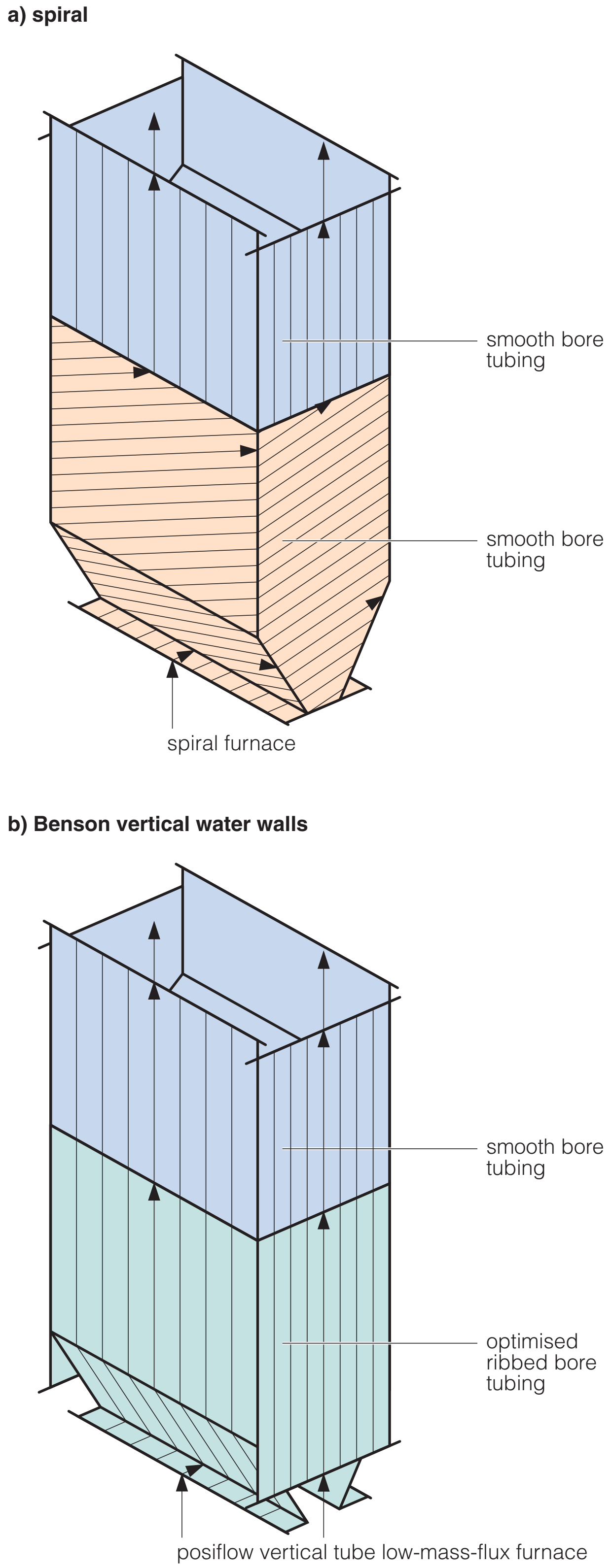

Figure 2 PC boilers with (a) spiral and (b) Benson vertical water walls (Bell and others, 2010)

In subcritical boilers, the marked density difference between water and steam allows a 'natural circulation' of the fluids through the boiler without pumping, and water can make several circuits before it evaporates and is separated in the steam drum. In a supercritical unit, the change in density from water to supercritical steam is continuous and natural circulation is not possible. Instead, the fluid is pumped through the boiler and makes one pass through the waterwalls and other heat transfer surface before arriving at the high pressure turbine. To prevent overheating of the waterwalls under this arrangement a smaller number of tubes can be coiled around the boiler to provide a higher flow of cooling water in each tube (Figure 2a). However, at high flow rates friction effects dominate, carrying the risk that overheating of a section will lead to reduced flow and exacerbate the heating. An alternative design is the Benson vertical once-through boiler, introduced by

Siemens in 2003, in which a low flow rate is used in vertical waterwalls (Figure 2b) (Bell and others, 2010). In this design, a kind of natural circulation occurs, as at low mass flux hydrostatic effects dominate and any local drop in density from overheating will induce an increase in local water flow. Nevertheless, to guard against overheating the interiors of the tubes are rifled to encourage surface wetting and prevent departure from nucleate boiling. Unlike the first generation of supercritical units, both these designs have variable pressure capability, meaning that they can change to subcritical operation for low loads. The capacity for this kind of flexibility has become increasingly important in deregulated electricity markets where power plants are regularly cycled.

2.2 Ultra-supercritical PCC and steam cycle optimisation

The development of higher performance steels during the 1980s, such as the martensitic P91 and P92, led the way for the development of a new generation of supercritical units known as ultra-supercritical (USC) (Viswanathan and Bakker, 2000). This broad term generally includes boilers using steam temperatures over 590°C and pressures over 25 MPa; allowing efficiencies of up to 47% (LHV) to be reached. The first examples of coal plant using this technology were built during the early 1990s in Japan, where it remains the principal choice for coal power generation, and were followed by a small number of units in Western Europe (Nalbandian, 2008). More recently, substantial USC capacity has been built in South Korea and, in particular, China, where rapid deployment of standard supercritical plant has been accompanied by over 70 GW of USC units, including some of the most efficient units currently operating (Long and others, 2013). State-of-the-art PCC units are able to achieve superheat steam temperatures of 600°C, reheat temperatures of 620°C, and pressures of up to 31 MPa, although lower pressures are usually used to allow for greater thermal flexibility (*see* Table 1).

USC boilers employ martensitic steels such as P91 for thick section components (steam pipes and headers) because of their low thermal expansion and higher thermal conductivity, and austenitic steels for superheat and reheat surface which requires high resistance to corrosion on the fireside (Viswanathan and Bakker, 2000). Waterwalls are often made of more conventional low alloy steels such as T12 and T22, which can withstand furnace temperatures whilst offering much better weldability than martensitic steels. More recently developed for higher temperature operation, T24 is a waterwall material with superior creep strength derived from boron and titanium alloying, but problems with weld cracking have been experienced on some boilers.

Introducing a second steam reheat to a plant is a means of further improving the steam cycle efficiency and improving the quality of low pressure steam which was adopted by several of the early supercritical boilers. For these older units it was found to be uneconomical, but at the high steam conditions of modern USC units it can be favourable to introduce a double reheat; particularly if low temperature cooling water is available to fully exploit the available efficiency gain. In Denmark, where cooling water is provided by the North Sea, double reheat has been used to great effect for the Nordjylland 3 unit, where efficiencies of over 47% (LHV) have been achieved (Poulsen and Bendixen, 2006). More recently, there is renewed interest in the technology for retrofitting to 1000 MW USC plants in China, where a demonstration is planned at Guodian Taizhou power plant (Shanghai Electric, 2012). A novel double reheat design proposed by Waigaoqiao power plant aims to reduce the considerable cost associated with the additional length of steam pipe made from expensive alloys. The design, currently undergoing testing by Alstom in Germany, would raise the high and intermediate pressure turbines to the level of the superheater and reheater outlets, whilst the lower pressure turbines remain in the conventional turbine house (Breeze, 2012).

Optimising feedwater heating is a less costly strategy for enhancing steam cycle efficiency which is more widely exploited by state-of-the-art PCC plant. Steam at different temperatures is drawn from between the turbine stages and used to heat feedwater in a series of stages, increasing the number of which brings the process closer to thermodynamic reversibility and improves efficiency.

Table 1 Efficiencies and steam conditions of some USC and high efficiency supercritical plants (Elsen and Fleischmann, 2008; ENEL, 2011; Mao and Feng, 2012; Peltier, 2010; Platts, 2012; Shanghai Electric, 2012)

Plant	Country	Start-up year	Rating, MW	Fuel	Superheat temperature, °C	Reheat temperature, °C	Second reheat, °C	Steam pressure, MPa	Efficiency, %
Nordjylland 3	Denmark	1998	440	Bituminous	580	580	580	29	47
Guodian Taizhou	China	2008	1000 x 2	Bituminous	605	605	610*	25.5	47.94
Waigaoqiao 3	China	2008	1000 x 2	Bituminous	600	600	610*	25.8	46.5
Isogo 2	Japan	2009	600	Bituminous/ Subbituminous	600	620	–	25.1	45
Torrevaldaliga	Italy	2010	660 x 3	Bituminous	604	612	–	25.2	45
Neurath	Germany	2012	1100 x 2	Lignite	600	605	–	27.2	43
Turk	USA	2012	600	Subbituminous	601	608	–	26.2	40 (HHV)
Wilhelmshaven (planned)	Germany	2014	800	Bituminous	620	620	–	28.0	46

* denotes design value for planned double reheat

Consequently, modern USC plants can incorporate from seven to nine feedwater heating stages, gaining up to 2 percentage points of efficiency as a result (NETL, 2008).

2.3 Advanced USC research

Considerable research effort is currently directed towards achieving so-called ‘advanced ultra-supercritical’ high pressure and temperature steam conditions of 700°C and over 30 MPa which should permit efficiencies of 50% (LHV). As the strength of state-of-the-art martensitic steels is compromised by poor oxidation resistance at temperatures over 620°C, these conditions will require the development of new metal alloys which can provide resistance to corrosion and fatigue at high temperatures and in the presence of flue gas or steam. A number of governments worldwide are supporting research programmes in this field, leading to the emergence of some promising new materials. Several alloying strategies have been identified for extending the operable temperature of martensitic steels, many of which encourage the formation of fine nitride precipitates in the metal (Allen and others, 2013). However, operation at 700°C is still likely to require widespread use of the nickel-based superalloy materials currently used in gas turbines and jet engines. Research is therefore also being conducted into the processing of superalloys into the large parts required for steam pipes and turbines, and their successful integration with steel components (Jablonski and others, 2011).

2.4 Minimising auxiliary power

From 7% to 15% of a PCC plant’s gross power output can be consumed as auxiliary power for the operation of the plant, so optimisation of these processes can have a significant impact on overall efficiency (ABB, 2009). The principal consumers are the water pumps feeding the boiler, which can be optimised to some extent by using variable speed drives. Other major power users are the coal mills used to pulverise the coal feed and flue gas scrubbing equipment such as electrostatic precipitators and flue gas desulphurisation (FGD) (Egbuna, 2013). Pulveriser mill power consumption depends to some extent on the hardness of the coal used, and in general a mill design appropriate to the coal fired should be used to achieve the best performance.

2.5 PCC with difficult fuels: state-of-the-art

PC boiler design tends to be particular to a narrow range of coal specifications as variations in volatile matter, calorific value, and ash quantity and composition often need to be met with appropriate changes to burners, heat transfer surface, or boiler dimensions and geometry. As a result, it can be favourable to maintain a consistent coal feed to a PCC plant or additional capital costs may be incurred for redesign of certain components. Blending of various coal sources can be used to achieve this, as well as beneficiation and cleaning processes to remove impurities. Plants associated with coal mines have a relatively consistent supply to hand, but in some regions this coal may be of poor quality and require significant processing before use. On the other hand, plants using primarily imported coal can count on a generally high quality supply, but one that may be forced to vary according to international markets.

2.5.1 High ash coal

Some coals have ash properties that can cause serious operational problems for PC boilers, as the high furnace temperatures can lead to slagging and fouling: deposits of molten or sintered ash which corrode surfaces, reduce heat transfer, and impede gas flow through the boiler. These issues are greatly exacerbated by coals with high concentrations of alkali metals, which are able to form low melting point species in ash (Barnes, 2009). Excessive slagging and fouling in a PC boiler can be mitigated by altering boiler design (usually including an increase in furnace size) and optimising the use of boiler cleaning systems such as sootblowers. Both strategies are described in more detail in Section 4.4.1.

Coal can also be cleaned of mineral content to some extent before use in PCC. Such separation processes are generally based on the difference in densities between organic and inorganic content, using a dense medium or shaking table. However, it has been found that in some circumstances ash removal can actually increase slagging problems (Barnes, 2009). As Na and Ca are often organically associated and therefore not removed in cleaning, the process may serve to further concentrate these species in the fuel feed.

2.5.2 Low volatile matter

Conventional PC boilers are poorly suited to burning low volatile fuels such as anthracite and petcoke, as the residence time of the fuel at high temperature can be insufficient to achieve ignition and complete burn-out, particularly at low loads. Downshot boilers, in which burners are directed downwards into a refractory-lined space, have been developed to provide longer furnace residence times for these fuels, and have been widely adopted in southern China where large anthracite resources are found. As the first supercritical downshot boiler, Jinzhushuan 3, a 600 MW unit operating since 2009 in Hunan province, China, represents the state-of-the-art of this variety of PCC technology (Bennett and others, 2010). The refractory-lined lower section of downshot furnaces has a more complex geometry than a conventional furnace, widening out to form a larger space for combustion and overhangs in which the burners are placed (*see* Figure 3). As constructing a spiral once-through waterwall around this space would be impractical, a Benson vertical system was employed and the corners of the lower furnace mitred to ensure even heating of the walls. Anthracite combustion in this furnace can achieve an efficiency of around 96%.

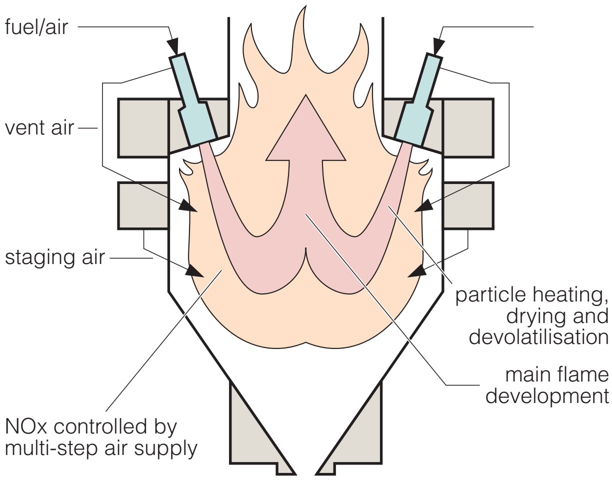

Figure 3 Schematic of a downshot boiler (Bennett and others, 2010)

2.5.3 Lignite

PC boilers are the dominant technology for lignite firing, as high performance can be achieved with appropriate adaptations to boiler size, burners, and coal milling. With low heating value coals, especially with high moisture content, the volume of flue gas is increased and boiler capacity needs to be scaled accordingly. Lignite mills often use recycled furnace gas to dry the fuel with reduced risk of mill fires. PCC with lignite has been extensively developed in Germany, where Alstom have developed a design for large USC units known as 'BoA', denoting 'plant engineering optimised for lignite'. The most recent examples of this design are the two 1100 MW units at Neurath which are currently the largest and most efficient lignite-fired units in the world (Elsen and Fleischmann, 2008). As well as employing the most advanced steam conditions yet used for lignite, their high efficiency stems from a range of optimised plant features, including a high level of automation and firing rate control, nine stage feedwater heating, flue gas heat recovery, and state-of-the-art turbines. The plants have also been designed for high flexibility in order to adapt to the growing renewables capacity in Germany.

Removing the moisture from lignite before combustion could increase plant efficiency by avoiding heat lost in vaporisation of water and allows a reduction in boiler size by reducing the volume of flue gas. A number of technologies for achieving efficient drying exist in varying stages of development (Zhu, 2012). One of the most promising, currently operational at the Niederaussem plant in Germany, uses heat from steam to dry the fuel in a fluidised bed and has the potential to provide up to 4 percentage points gain in plant efficiency (RWE, 2009).

2.6 Reducing PCC emissions: state-of-the-art

As regulations governing coal plant emissions have become increasingly strict and widespread, flue gas cleaning and emissions reductions technologies for SOx, NOx, particulates and, more recently, mercury, are emerging to compete with the well-established combination of calcium sorbent-based FGD and selective catalytic reduction (SCR) deNOx systems. Multipollutant scrubbers employ a single reaction vessel for the removal of several species, thus also allowing potential savings in capital investment. Most notably, a multipollutant system designed for the pioneering Isogo power plant in Japan, is able to reduce emissions to levels equivalent to those of natural gas plants, limiting both SOx and NOx emissions to 15 ppm, as well as removing 90% of mercury (Peters, 2010). This technology, known as ReACT, uses activated carbon as a sorbent which can be thermally regenerated and thus cycled many times through the flue gas, whilst the SO_2 cleaned from the sorbent produces a pure stream suitable for industrial acid manufacture (*see* Figure 4). Fly ash concentrations from Isogo 2 are less than 5 mg/m^3, owing to a low ash coal feed and dual electrostatic precipitators.

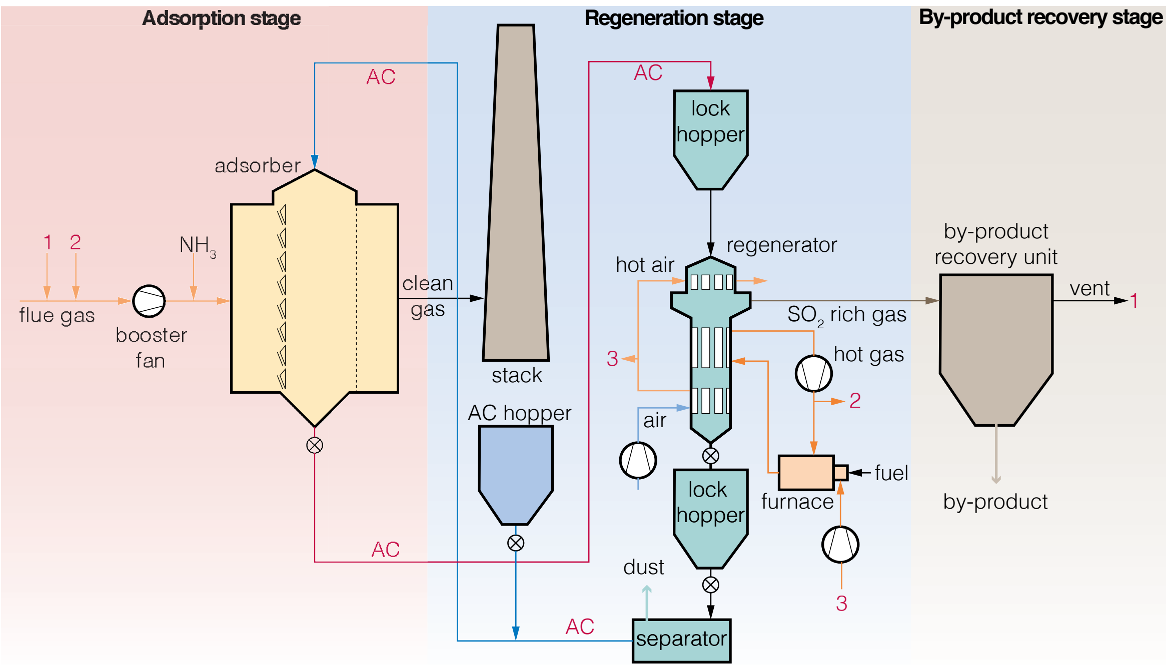

Figure 4 The ReACT multipollutant control system used at Isogo unit 2 (Peters, 2010)

2.7 PCC by region

2.7.1 USA

The USA led the early development of PC boilers, and installed the first ever supercritical unit in 1959. This was followed by extensive deployment of over 100 supercritical plants during the following two decades, most of which are still operational today, and include 1300 MW boilers which remain the highest rated boilers ever built. Subcritical units were built in even greater numbers, particularly during the 1970s and 80s when supercritical units still suffered from reliability issues, and over 340 units rated at over 250 MW are currently operating (Platts, 2012).

Historically, the high sulphur bituminous coal of the Appalachian basin has been the staple of the American coal power industry, and the corrosive effects of high SO_2 have hindered the use of reduced chromium advanced steels such as P91. The introduction of SO_2 emissions limits led to a shift towards the low sulphur, subbituminous coal of the Powder River Basin (PRB) during the 1990s as a favourable alternative to installing wet FGD, and over 40% of the nation's coal output now comes from this region. As a result, lower performance semi-dry FGD technologies have seen increasing use and sulphur corrosion issues at advanced steam conditions have become less of a hindrance, although slagging problems have also become more significant.

A 600 MW boiler at Turk power plant, Arkansas, which began operation at the end of 2012 is the first USC unit to be built in the USA (AEP, 2012). However, in the last five years the use of coal for power generation in the USA has greatly declined due to the emergence of cheap shale gas and the increasing likelihood that CO_2 emissions limits will be introduced in the near future. Consequently, a large number of coal plants are scheduled to be shut and further development of coal power plant technology in the country is becoming increasingly unlikely. On the other hand, the ensuing surge in coal exportation has reduced global prices and had a positive effect on the use of coal power in coal importing countries.

2.7.2 Russia

Supercritical boilers were also adopted early on in the Soviet Union, although on a smaller scale than in the USA. Around 40 units built during the 1960s and 70s are still operational, but development in Russia since then has been very limited due to the loss of Ukrainian coal fields and the exploitation of large oil and gas reserves. Recently, policy has sought to upgrade the ageing coal fleet which still supplies around 19% of Russia's electricity. Along with efficiency improvements to existing plant, four 800 MW supercritical PCC units are under construction and scheduled to come online by 2014 (Rosner, 2010).

2.7.3 Europe

PCC plant currently contributes significantly to baseload power generation in most European countries, with by far the largest capacity in Germany at over 40 GW. Most European plant consists of subcritical PCC units of less than 500 MW capacity built during the 1970s and 80s, but substantial supercritical capacity has also been built in Germany, Denmark, and Italy. Cold seawater cooling in Denmark allows full advantage to be taken of high efficiency plants, encouraging the early adoption of USC technology for the Nordjylland plant in 1998, which also saw the reintroduction of double reheat (Poulsen and Bendixen, 2006). More recently, USC capacity has been added to by the high efficiency lignite 'BoA' units in Germany and the Torrevaldaliga plant in Italy.

The EU Industrial Emissions Directive (IED), which requires all European coal plant to reduce their emissions by 2015 or cease operations, will see 20 GW of the region's ageing coal plant come offline over the coming years, and in much of Western Europe this capacity is to be replaced with other energy sources rather than cleaner coal plant (European Parliament, 2011). In the UK in particular, currently home to the second largest coal power capacity in Europe, a significant proportion of plant has already been forced to close or has been converted to biomass. The focus of coal power development has instead moved to central Europe, where extensive coal resources are being fully exploited to support growing economies. In Poland, two supercritical PCC units have recently come into service, and over 11 GW of coal capacity are planned for construction before 2020, although current falling electricity prices look likely to reduce the actual capacity built (Platts, 2012; Martin 2013; Associated Press, 2013).

Expansion of the coal fleet continues in Germany despite recent policy to move towards producing the majority of the country's power from renewable sources, as a number of USC units are already in advanced stages of construction. In the course of the next year, over 10 GW of USC plant is scheduled to come online, largely firing bituminous coal (Platts, 2012; Patel, 2013). Some of these plants will be at the cutting edge of PCC technology, attaining up to 46.5% and even higher efficiencies when used to provide district heating, as well as high levels of load following flexibility to meet the demands of growing renewable capacity.

2.7.4 Japan

Nearly all Japan's more than 30 GW of coal power capacity is supercritical or USC plant, of which the majority was built less than thirty years ago. Relying exclusively on imported coal, the economic incentive for more efficient plants has helped Japan's PCC power stations to be some of the most advanced and cleanest in the world. Development of high performance metals in Japan during the 1980s led to the world's first USC unit at Tsuruga power plant, operational in 1992. Since then, over 11 GW of USC plant has been constructed in units of 600 to 1050 MW, of which the most recent addition is the benchmark unit for low emissions at Isogo (Platts, 2012).

As nearly all Japan's 50 nuclear reactor units have been taken offline in the aftermath of the incident at Fukushima power plant, Japan may turn to coal as a replacement energy source, despite endangering commitments to carbon emissions reductions. In 2013, the government eased environmental restrictions on construction of new coal plant, although only 3.2 GW of capacity is currently planned (Iwata, 2013). Most recently, a second 1000 MW supercritical unit at Hitachinaka power plant entered service in April 2013.

2.7.5 South Korea

South Korea's over 20 GW of coal-fired capacity is principally supercritical and USC plant built within the last twenty years. Recent energy shortfalls and concerns over the reliability of nuclear plant have led to plans for 10.7 GW of new coal plant, although with strong investment in CFBC technology in the country it remains unclear which boiler technology will provide the majority of this capacity (Williams, 2013).

2.7.6 China

With vast coal resources and a rapidly growing economy, China has witnessed an unprecedented growth in coal power over the last twenty years and currently generates more than the USA and Europe combined. Whilst the majority of this is smaller, subcritical PCC units, expansion of supercritical and USC plant in the last ten years has been equally rapid, totalling over 230 GW and including some of the most advanced PCC plants in the world (*see* Figure 5) (Hu, 2013). As part of the 11th five year plan (2006-10), Chinese government policy has encouraged the replacement of smaller, inefficient subcritical plants with large supercritical and USC units with a view to improving the economics of the coal fleet. More recently, this policy has been extended to promote efficiency gains in existing supercritical units with direct financial incentives to utilities (Hu, 2013). Much of the inspiration for this upgrading will be taken from the example already set by the 1000 MW USC unit Waigaoqiao 3, which has gained 4.4 percentage points in efficiency through a range of optimisation methods such as reducing auxiliary power, and currently holds the record for coal plant efficiency

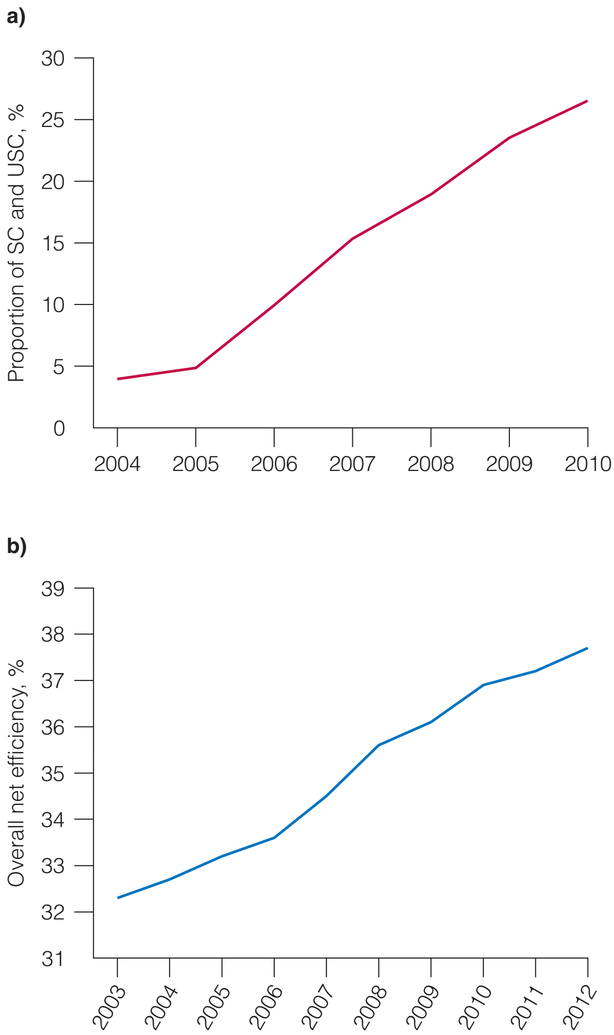

Figure 5 (a) Growth in the proportion of supercritical and USC units in China, and (b) improvements in average efficiency of the coal fleet (Hu, 2013)

without cold seawater cooling (Mao and Feng, 2012). Other plant upgrade technologies being pursued include application of double reheat, lignite drying, and flue gas heat recovery.

Having been long criticised for some of the world's most polluting coal plants, new emissions limits came into force in 2012 which are amongst the most demanding in the world (MEP, 2011). Plants will need to adapt to these by widespread implementation of particulate filters, FGD, and deNOx flue gas scrubbers. A variety of technologies are under consideration, including activated coke-based sorbents as used in the ReACT system, and semi-dry circulating fluidised bed FGD (Long and others, 2013).

Growth of China's coal capacity is set to continue, as at least 400 GW of new plant is estimated to be planned or under construction. This includes two 1000 MW USC units at Taizhou power plant which will feature some of the most advanced steam cycle conditions worldwide, with double reheat at 610°C and a design efficiency of 46% (Hu, 2013). These are scheduled to commence operations in 2013.

2.7.7 India

India's large fleet (over 120 GW) of subcritical PCC plant, mostly built in the last 20 years, places it as the third largest coal consumer in the world, yet the country nevertheless suffers from severe energy deficiencies and a quarter of the population remain without electricity. As part of the last five year plan (2007-12), India's government aimed to set up a series of large, supercritical PCC coal power plants termed Ultra Mega Power Projects (UMPPs) as a means of overcoming these energy shortages (PFC India, 2013). As Indian coal is generally high in ash and transportation over large distances is uneconomical, the plants were to be distributed between mine locations and coastal locations where imported coal would largely be used. Of sixteen plants originally envisaged, only four contracts have so far been awarded to bidding utilities and the 4000 MW Mundra power plant, owned by Tata and located on the Gujarat coast, is the only UMPP to have become fully operational (CGPL). This plant operates five 800 MW supercritical boilers designed by Doosan, and uses mainly coal imported from Indonesia. Two more contracts for coastal plants were awarded to Reliance, who have acquired three Indonesian coal mines to supply them, whilst the company's Sasan UMPP in Madhya Pradesh is to be integrated with three nearby mines (Reliance, 2007; The Times of India, 2013). The first 660 MW unit of five planned at Sasan was commissioned in March 2013.

3 Status of CFBC technology

In fluidised bed combustion (FBC), primary combustion air is injected from beneath a bed of fuel, suspending the particles and giving them fluid-like flow properties. This allows complete mixing of fuel and air and a long furnace residence time for combustion to occur over. In its earliest incarnation, bubbling fluidised beds (BFB) were used, in which low fluidising air velocities are employed to prevent fine particles from being carried out of the bed, but this design has since been restricted to small-scale applications. Circulating fluidised beds (CFB) use higher fluidising air velocities which entrain particles throughout the boiler, but flue gases are fed into solid separators (typically cyclones) which return solid material to the lowest part of the bed and thus prevent unburnt fuel from leaving the furnace (*see* Figure 6). This creates a kind of thermal loop through which fuel particles can cycle 10 to 50 times until complete combustion is achieved. The prolonged combustion time results in much lower temperatures (800–900°C) than those found in PCC.

Typically only 3–5% of the bed material consists of combustible fuel, with the remainder composed of 'inert' bed material such as ash, sand, or limestone, which retains heat and controls the bed temperature. Limestone is most commonly used for utility CFBC as in the furnace it undergoes calcination to CaO which acts as a sorbent for SO_2. This method of in situ desulphurisation, which can achieve over 90% SO_2 removal and avoids the need for downstream flue gas scrubbing, constitutes one of the principal advantages of CFB boilers. In addition, NOx formation is naturally low (normally less than 400 mg/m^3) due to the low combustion temperatures and reducing conditions in the furnace. Consequently, CFBC has often been regarded as a lower emissions technology for coal-fired boilers.

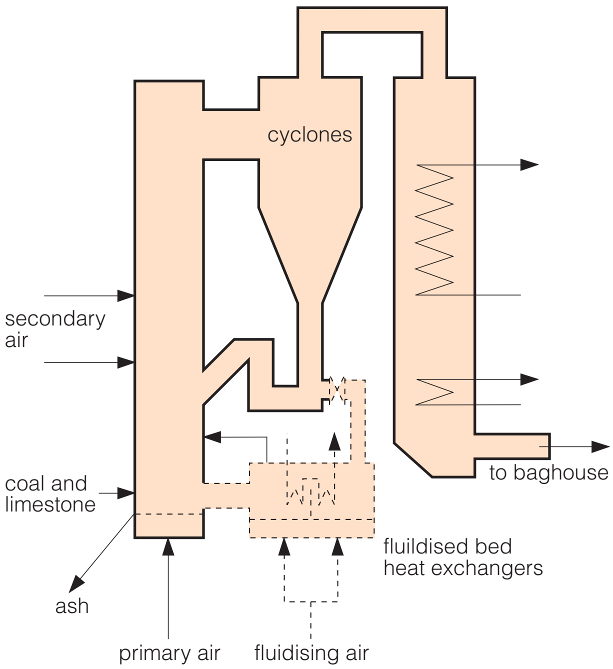

Figure 6 General schematic of a circulating fluidised bed boiler

A principal advantage of CFB over PC boilers is their greater ability to deal with variation in fuel type and quality, and their improved performance with poor quality coals in general. High ash coals present less of a problem than for PC boilers, as the low combustion temperature prevents ash from melting and causing slagging of the boiler components. Low volatile fuels such as anthracite or petcoke are also able to achieve complete combustion over the long residence time in a CFB furnace, and the in situ desulphurisation process allows use of high sulphur coals without installing expensive FGD equipment.

3.1 Scale-up and propagation of CFBC

CFBC technology was developed from bubbling fluidised bed combustion during the mid-1970s, and saw its first commercial use in 1979 for a small industrial boiler firing waste wood and peat (Koornneef and others, 2007). The first utility boiler, a 90 MW coal-fired unit in Germany, followed this in 1985 and led the way for relatively widespread use of similar capacity boilers in utility and industrial power generation. The introduction of stricter controls on SO_2 emissions provided an

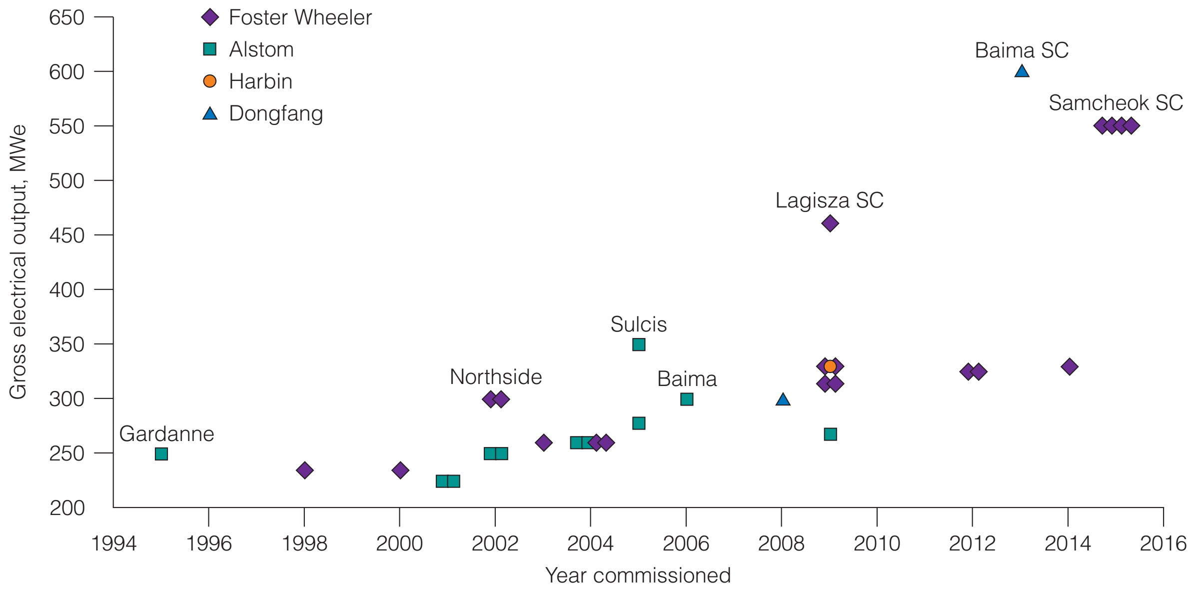

Figure 7 The scale-up of CFB boiler capacity in the last twenty years, with significant plants labelled (Blankinship, 2008; Jäntti and others, 2012)

incentive for the development of larger utility boilers during the 1990s, resulting in the Ahlstrom designed 165 MW unit at Point Aconi, Canada in 1993 (the first utility CFBC unit in North America), and Alstom's 250 MW unit at Gardanne, France in 1995. In the same year, Foster Wheeler acquired Ahlstrom's boiler business and became active in developing CFBC technology towards larger and more efficient units, designing six large capacity units for Turow power station in Poland and, in 2002, two 300 MW boilers for Northside power plant in the USA which became the world's largest. Over the next decade, a small number of similar scale utility CFBC projects were to follow in the USA, using boilers designed by Foster Wheeler or Alstom and usually firing or cofiring 'opportunity fuels' such as lignite, petcoke, or waste coal. Meanwhile, following the acquisition of Alstom's 300 MW CFBC technology by three Chinese manufacturers, rapid deployment of boilers on this scale also began taking place in China from 2006, where they now number over sixty and represent the world's largest share of CFBC capacity (*see* Figure 7).

In 2009, a Foster Wheeler designed 460 MW boiler at Lagisza power plant in Poland became the world's first supercritical CFBC unit. A similar design has been applied to four 550 MW boilers under construction in South Korea, whilst in China, a 600 MW supercritical CFBC unit designed by Dongfang boiler works recently began trial operation in April 2013.

3.2 Technical development

The scaling-up of CFBC units to the utility-scale has been conducted in parallel by Foster Wheeler and Alstom, resulting in two substantially different designs. Increasing the size of a CFBC unit is restricted to increasing the length of the side where the fuel and cyclone inlets are placed, as extending the other dimension could create a central part of the bed which is too far from the fuel feeds and consequently lower in temperature (Fan and others, 2006). Moreover, increasing the height of the furnace is not possible beyond a certain point (about 50 m) above which the concentration of circulating solids, and therefore heat transfer, becomes too low. Equally, the solid separator cyclones become less efficient at large sizes, so it is logical to scale-up a CFBC unit in modules consisting of an additional solid separator for each additional length of furnace, with the possibility of also aligning separators along the opposite wall to double the furnace depth. Figure 8 shows how this principle has been applied by both of the major manufacturers.

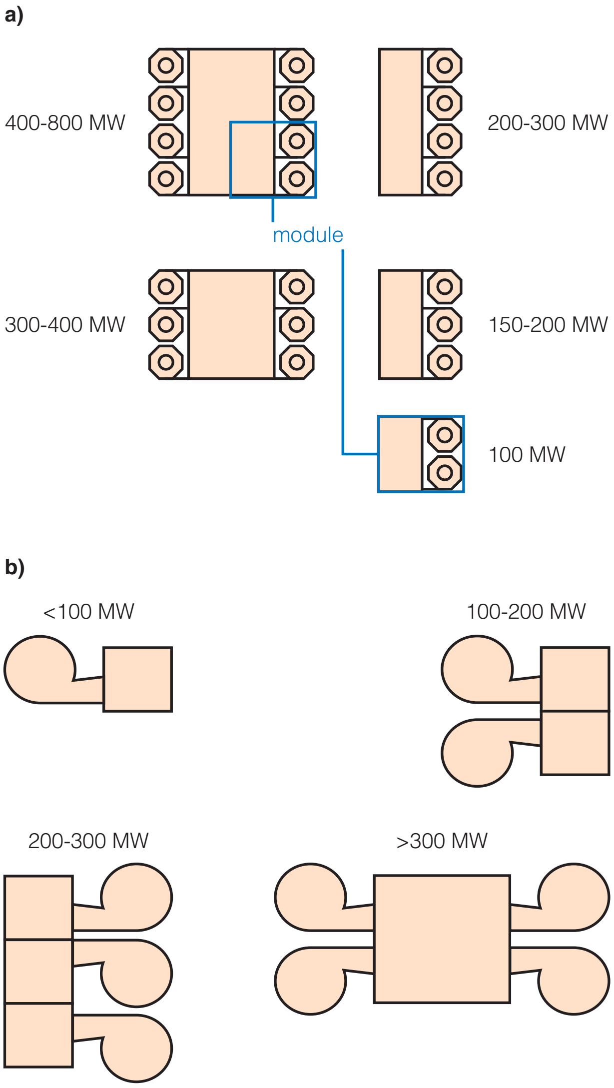

Figure 8 Modular scale-up of CFB boilers by a) Foster Wheeler, and b) Alstom (Jäntti and others, 2012; Morin, 2003)

An initial problem with CFBC was the need for expensive refractory to protect the cyclones from the hot material and flue gases. A significant development was to line the cyclones with curved waterwalls, vastly reducing the need for refractory and allowing heat to be extracted from the separators (Fan and others, 2006). In 1990, Foster Wheeler pioneered a new 'compact' design for CFBC, in which the solid separators are made from a series of straight waterwalls and incorporated into the structure of the furnace itself, allowing much simpler manufacture and a reduced footprint for the boiler, although some loss in cyclone efficiency for smaller particles does result (*see* Figure 9) (Goidich and Hyppänen, 2001). Boilers on this format were developed in parallel with conventional units and reached utility scale in 2003 with three 262 MW units installed at Turow power plant in Poland (Psik and others, 2005). This compact technology has now been adopted as Foster Wheeler's standard boiler design, having been used in the design of supercritical units at Lagisza in Poland, Novocherkasskaya in Russia, and the four 550 MW units at Samcheok, South Korea (Jäntti and others, 2012).

Alstom have also scaled up their CFB boiler design in modules associated with each solid separator, but have adhered to the conventional separate cyclone format. On the other hand, the manufacturer has increased the width of their furnaces by implementing a dual-grate or 'pant-leg' design, in which the bottom of the furnace is split into two sections, with the dividing structure used to introduce more secondary air and prevent a dense bed phase from developing and restricting air flow (*see* Figure 10) (Morin, 2003). This design first featured in Alstom's 250 MW unit at Gardanne in France, and is now standard for boilers of this capacity and upwards (Morin, 2003; Alstom Power, 2012). In the late 1990s Alstom licensed their CFBC technology to the three principal Chinese boiler manufacturers, and it is primarily under these companies that their utility-scale boiler design has been proliferated, often subject to major modifications which will be addressed in the Section 3.5.4 (Li and others, 2010b).

As CFB boilers grow in size, there is clearly less exterior heat exchange surface available for the increased heat output of the furnace. Placing heat exchange surfaces within the fluidised bed itself has proved problematic as they come into contact with a large quantity of circulating solids and suffer severe erosion damage. Both Alstom and Foster Wheeler have introduced extra heat exchange surface in the form of small bubbling fluidised beds placed between the separators and the furnace, which fluidise the hot solids being reintroduced to the furnace at the separator outlet and place them in contact with heat exchangers for superheat or reheat duty. The Foster Wheeler design is known as INTREX (integrated recycle heat exchangers) as it is incorporated into the compact boiler design at the base of the separator units (Goidich and Hyppänen, 2001). The Alstom FBHE (fluidised bed heat

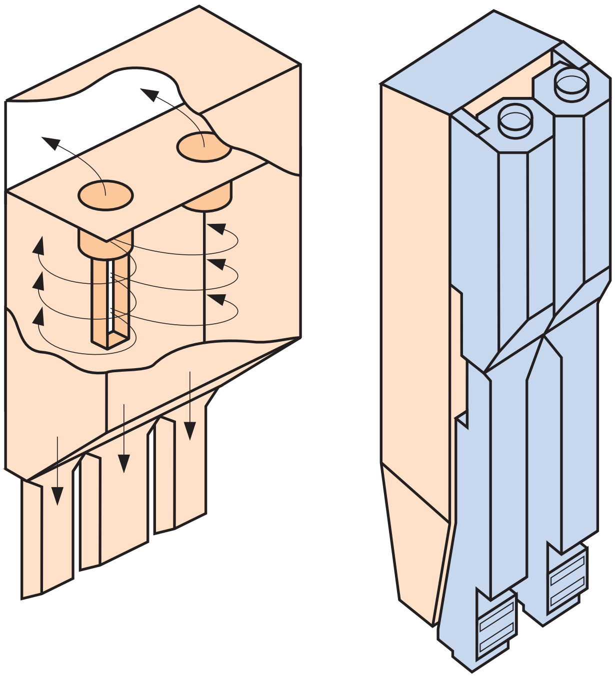

Figure 9 Foster Wheeler's compact cyclone design (Goidich, 2000)

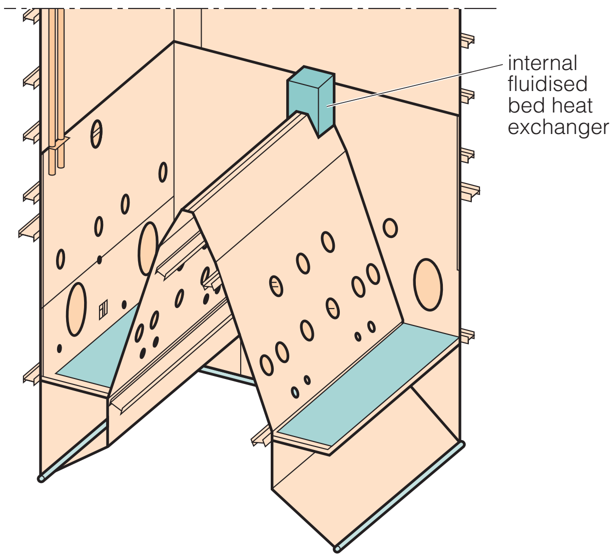

Figure 10 Alstom's dual-grate design (Jestin and others, 1997)

exchanger) design is isolated from both furnace and cyclone, and a control valve allows the directing of recycled solids either directly into the furnace or through the FBHE (*see* Figure 6) (Alstom Power, 2012). Both these designs have the important feature of allowing a greater level of control over superheat and reheat steam temperatures via adjustment of the flow of solids into the external beds or the velocity of the fluidisation air.

Other additional heat exchange surface can be provided by wing walls; protrusions of the waterwalls into the furnace, or pendant tubes hanging from the furnace roof where the lower solids concentration poses less erosion risk. Both these types of surface are often used for superheat or reheat duty in large-scale CFBC.

3.3 Supercritical designs

In 2000, Foster Wheeler proposed a compact CFB boiler using a once-through steam cycle based on Benson vertical technology licensed from Siemens (Goidich, 2000). The spiral wound tubing conventionally used for once-through PC boilers is not a possibility for CFB boilers because the angled tubing would deflect the circulating solids and be subjected to erosion. On the other hand, the relatively low and uniform temperatures in CFB furnaces make vertical once-through tubing particularly suitable for their waterwalls. The low heat flux significantly reduces the risk of tube dry-out and heat damage, with adequate cooling provided by mass flow rates of up to 55% of those used in PC boilers, and no need for rifled tubing. This represents a saving in capital expenditure, as does the lack of expensive support structures used in spiral wound waterwalls.

Despite this technology being available for subcritical compact units such as those at Turow power plant, it was not used until the move to supercritical CFBC at Lagisza, for which a once-through steam cycle was the only option. At Lagisza, wing walls providing extra evaporative surface area use rifled tubing, as they protrude into the furnace and experience heating from both sides (Venäläinen and Psik, 2004). Similar vertical once-through designs have been applied in the supercritical CFBC units at Novocherkasskaya, Samcheok, and Baima, as well as in Alstom's design for supercritical CFBC (Jäntti and others, 2012; Gauvillé and others, 2010). The 550 MW units designed by Foster Wheeler and under construction at Samcheok are notable for employing steam conditions within the ultra-supercritical (USC) range (*see* Table 2 and Section 3.5.5).

Table 2 Steam parameters for supercritical and USC CFBC units currently operational, under construction (*), and at the design stage (†) (Jäntti and others, 2012; Hotta and others, 2012; Li and others, 2010a)

Unit	Output, MW	Superheat temperature, °C	Reheat temperature, °C	Main steam pressure, MPa
Lagisza	460	560	580	27.5
Novocherkasskaya*	330	565	565	24.8
Samcheok*	550	603	603	25.7
Baima	600	571	569	25.5
CFB 800†	800	600	620	30

3.4 600+ MW designs

Both Foster Wheeler and Alstom have made 600 to 800 MW supercritical CFBC commercially available, using designs scaled up from their existing boilers with some modifications. The principal challenge for this continuing growth in boiler capacity is the need for additional evaporative surface in the furnace as the exterior perimeter does not scale with increasing output. The latest Alstom design for a 660 MW lignite boiler, or higher outputs with hard coal, introduces once-through waterwalls and moves from four to eight cyclones and FBHE. Additional evaporative heating surface is introduced to the furnace by a row of square-shaped waterwall columns situated on the central divide of the dual-grate, from which flat, U-shaped panels also extend over each side of the boiler (Gauvillé, 2013). This unit would utilise 600°C superheat and 620°C reheat temperatures corresponding to steam conditions in state-of-the-art USC PCC. The 600 MW supercritical unit currently operating at Baima power plant, designed by Dongfang Boiler Works based on technology licensed from Alstom, is described in Section 3.5.4.

Foster Wheeler designs for 600 MW and upwards are closely based on their existing supercritical CFB boilers, with the eight compact cyclones scaled up in size (Hotta and others, 2012). Particular emphasis has been placed on a boiler rated at 660 MW with a view to competing with the similarly sized PC units employed for large power projects in India (*see* Section 3.5.8) (Utt and Giglio, 2012a). An EU project known as CFB800, which brought together a consortium of research centres and manufacturers, helped Foster Wheeler to develop an 800 MW design with elevated steam parameters (Nevelainen and others, 2010, Hotta and others, 2012). Adhering to the same format as Lagisza, with the same configuration of cyclones but with a 43% increase in furnace width, this unit would also match current USC PC boilers in terms of steam parameters and efficiency (*see* Table 2) (Robertson and others, 2010). Additional heat duty is provided by stacking INTREX heat exchangers in pairs beneath each cyclone, making for 16 in total. In this arrangement, recirculating solids cascade through two fluidised beds before returning to the lower furnace.

3.5 Utility CFBC plants by region

3.5.1 Western Europe

The construction by Alstom in 1995 of a 250 MW CFB boiler at Gardanne, France, represented a significant step-up in boiler size, and could be seen as marking the beginning of truly large-scale power generation with CFBC technology. This boiler was the first to feature Alstom's dual grate design and represented several years of development by Alstom and EDF, motivated by the desire to burn high sulphur domestic coal more cleanly (Lucat, 1997). Despite initial plans by EDF to follow

Gardanne with the development and trial of a 600 MW CFBC unit in France, the utility shifted its focus to hydroelectric power and a plant was never realised even when the technology became available (Sapy, 1998).

In 2005, a 350 MW CFB boiler designed by Alstom was completed at Sulcis, Italy, to replace a decommissioned PC boiler at the same site. CFBC technology was chosen as the best way of meeting the strict local emissions standards of Sardinia with the local high sulphur coal, despite another PCC unit at the site having been previously upgraded with the addition of FGD and SCR (Harghel and others, 2005).

Under the IED, large power plants in the EU will be required to limit their emissions or close by the end of 2015. A recent study by Parsons Brinckerhoff assessed that CFB boilers would be the most economical way of upgrading the large proportion of this generating capacity which uses brown coal (Loyd and Craigie, 2011). Consequently, a new phase of CFBC projects could take place as this emissions directive takes effect.

3.5.2 Poland

In Poland, utility-scale CFBC was adopted early on as part of a large-scale project for replacing six PC boilers at Turow power plant. The new units were required to have lower emissions and higher output than the previous boilers, whilst fitting within the same footprint. The lack of space for a wet FGD system made CFB boilers an attractive choice, in addition to their greater ability to cope with the large variation in Polish lignite. A series of six Foster Wheeler designed units, each over 230 MW capacity, has been built at Turow between 1998 and 2004, in three phases. While the first three units (235 MW each) use conventional separate cyclones, the later three units represent the first utility-scale implementation of Foster Wheeler's compact boiler design, including INTREX superheaters. This technological upgrade allowed an increase in capacity to 262 MW within the same footprint (Psik and others, 2005).

A contract for the first ever supercritical CFB boiler was signed for Lagisza power plant in 2002, despite the original tender having been for a new PCC unit. The Polish utility eventually opted for the newer technology on the basis of a slightly higher design efficiency, the lack of need for additional FGD scrubbers, and the potential for cofiring biomass or other opportunity fuels. The 460 MW unit, commercially operational since 2009, is based on a scaled-up version of the compact boilers at Turow combined with Benson vertical once-through waterwalls for producing supercritical steam. The degree of scale-up required was diminished by the fact that the supercritical boiler is fuelled with bituminous coal rather than the lignite used at Turow (Venäläinen and Psik, 2004). The variability of the coal supply to Lagisza, which comes from ten separate mines and includes coal high in chlorine, was another principal incentive for using CFBC technology (Jäntti and Parkkonen, 2009).

Recent growth in biomass firing for carbon abatement in Poland has also provided a major incentive for the use of CFBC, with one of the largest 100% biomass-fired CFB boilers in the world commissioned in 2012 at Polaniec power plant. In addition to wood chips, this 205 MW unit is capable of firing 20% agricultural waste such as straw and palm kernels, despite the much greater slagging tendency of these fuels (Nuortimo, 2013).

3.5.3 USA

Small-scale FBC spread rapidly in the USA where legislation encouraged its use for extracting energy from the coal waste piles found throughout coal mining regions. However, the Public Utility Regulatory Policies Act, which encouraged utilities to buy electricity from small, industrial FBC, may have stalled the deployment of CFBC for utility boilers during the 1980s (Koornneef and others,

Figure 11 Locations of the seven plants in the USA with dual CFB boilers of over 250 MW each

2007). After large-scale CFB boilers had been successfully demonstrated in France and Poland, the Alstom design was introduced to the USA at the lignite-fired Red Hills power plant (MS) and the Foster Wheeler design scaled-up for two 300 MW units at Northside power plant (FL), where CFBC was chosen for its suitability for cofiring the high sulphur, low volatile petcoke abundant in the Gulf region (Morin, 2003; Dyr and others, 2000). Such dual boiler CFBC power plants became a popular option for coal power over the last decade, with 16 units over eight sites accounting for roughly a third of coal units built during this period (Platts, 2012). Whilst in southern states the technology has primarily been used as an effective means of firing lignite or petcoke, three plants in the Appalachian region have adopted CFB boilers to burn mining waste and help control emissions from the high sulphur eastern coals (Makansi, 2005). Of these, the most recent is the Virginia City Hybrid Energy Center (VA), which started operations in 2012 and also aims to burn 20% wood waste biomass (Martino, 2013) (*see* Figure 11).

Several recently planned CFBC units have been stalled or cancelled as, like other coal burning plants, they are affected by the move to natural gas power generation and increasingly strict emissions standards which disfavour solid fuel combustion.

3.5.4 China

The focus of utility-scale CFBC development has more recently shifted to China, where over sixty 300 MW units have come online over the last six years and a similar number are currently under

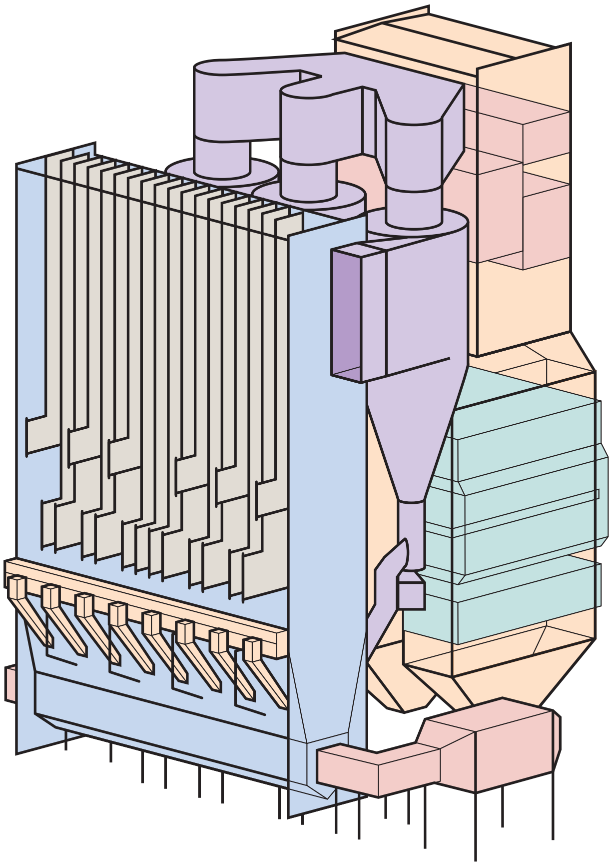

Figure 12 M-configuration 300 MW CFB produced by Dongfang boiler works (Yue and others, 2010)

construction (Li and others, 2013). This CFBC capacity is the largest in the world and constitutes over 10% of China's thermal power. As in other countries, CFBC in China was confined to small-scale industrial and cogeneration boilers during the 1980s and 90s, but its development received considerable impetus from the licensing of technology from foreign boiler manufacturers in the late 1990s (Yue and others, 2010). In particular, 300 MW boiler design from Alstom was adopted by the three major domestic manufacturers: Dongfang, Harbin, and Shanghai Boiler Works. An initial demonstration plant was completed by Alstom at Baima power plant, Sichuan, in 2006, and similar units with collaboration from each manufacturer quickly followed within the same year. This rapid development of 300 MW-scale CFBC in China forms part of the country's general policy to move towards larger and more efficient coal units, within which CFBC is to be directed at using large reserves of difficult coals and coal waste, particularly in regions of water scarcity (Long and others, 2013). The majority of the new CFBC plants are in the south of the country where the local anthracite is high in ash and sulphur and has very low volatile content and reactivity. The large downshot PC boilers conventionally used to burn this fuel can have difficulty achieving high combustion efficiencies without support from oil or natural gas, particularly at low loadings, whereas CFB boilers are expected to operate at 40% loading without supplementary fuels (Morin, 2003). Problems with slagging from the high ash content are also reduced. Utility-scale CFB boilers have also been widely deployed in the heavily coal mined area in the north of the country, where they are largely used in their traditional role of using coal washery wastes, as well as burning the local bituminous coal directly. Amongst the first built, a small number of units situated in Yunnan province are fuelled with lignite.

The original Alstom boiler design was rapidly adapted by the domestic manufacturers to better meet their requirements for Chinese coals. In 2008, the first of these domestic units, produced by Dongfang Boiler Works, became operational at Heshuyuan power plant in Guangdong. The design, developed with Tsinghua University, constitutes a marked simplification of the Alstom boiler as it uses a single rather than dual grate furnace, eliminates the external FBHE, and employs three rather than four cyclones; deployed on one side in an asymmetrical M-shape (*see* Figure 12). The superheat and reheat duty provided by the FBHE is replaced by additional panels in the furnace itself. Harbin Boiler Works have collaborated with the Thermal Power Research Institute to produce another new design, this time for a 330 MW boiler, which first entered service in 2009 (Yue and others, 2010). These units more closely resemble the Alstom design, but feature a single grate furnace and make use of pneumatic external heat exchangers rather than bubbling fluidised beds. Whilst this design is favoured for difficult fuels such as high-ash anthracite, the M-shape boiler can be used with more reactive bituminous coals and lignite.

Many of the design alterations introduced are aimed at dealing with the high ash content in the coals for which Chinese CFB boilers are largely built. Although one of the primary incentives for the spread of CFBC technology, high ash has caused serious operational problems which have encouraged a simpler boiler format and several new design features. Most notably, the fluidised bed ash coolers used by Alstom have been almost entirely replaced with water-cooled rotary ash coolers designed in China to better cope with large amounts of ash with a broad size distribution (Cheng and others, 2011). This modification appears to have largely resolved issues with blockages and agglomeration in ash coolers, which have been one of the main impediments to reliability of the first 300 MW units built.

The largest CFB boiler currently operating or planned worldwide is a 600 MW supercritical unit at Baima power plant designed by Dongfang Boiler works, which began operational trials in April 2013. The design retains the dual grate furnace and external heat exchangers of Alstom boilers, and uses Siemens vertical once-through waterwall technology and six cyclones. A waterwall partitioning the two grates effectively divides the furnace into two sides each resembling a three cyclone 300 MW unit, although openings allow exchange of flue gas and a common pressure. Steam conditions are 25.4 MPa/571°C/569°C and an efficiency of 42% (LHV) is predicted for the unit (Li and others, 2010a). As similar 600 MW supercritical designs have been produced by the other two major boiler manufacturers, the spread of this technology could potentially be as rapid as it has been at the 300 MW scale.

3.5.5 South Korea

As concerns over the cost and safety of nuclear power have grown, South Korea has recently turned to coal power as the principal means of expanding the country's stretched generation capacity over the next decade, and state-of-the-art CFBC features amongst the power plants currently under construction (Blackman, 2012). In 2011, Korean Southern Power Co (KOSPO) commissioned the largest yet supercritical CFBC plant (4400 MW), and a 340 MW subcritical unit has also recently been ordered by Korea South East Power Co. As South Korea is heavily reliant on imported coal, the primary appeal of CFBC is its capacity to provide flexibility to the international coal market whilst retaining the ability to fire the high ash (>35%) domestic coal. The ability to meet the relatively strict emissions standards for new power plants in Korea without expensive FGD units is a further incentive.

KOSPO's Samcheok Green Power Project consists of a first phase of four 550 MW supercritical CFB boilers, scheduled for start-up by 2015, which are to be followed by four more units to bring total capacity to 4400. The Foster Wheeler designed units resemble scaled-up versions of the Lagisza supercritical boiler; each employing eight compact solid separators and Siemens once-through technology, but with USC steam conditions (*see* Table 2) (Jäntti and others, 2012). In order to reduce fuel costs and over-reliance on one supply chain, the boilers have been designed to accept a wide range of imported coals, including lignite, Indonesian subbituminous, and petcoke, as well as up to 5% biomass. Within a design range of up to 1% sulphur coal, the units are expected to be capable of keeping SO_2 emissions below a maximum of 50 ppm without downstream FGD but, unusually for CFBC, SCR scrubbers, rather than selective non-catalytic reduction (SNCR), will be used to keep NOx emissions to the same level. A research centre for carbon capture technology and an additional 600 MW of renewable energy are also planned for the plant site.

3.5.6 Russia

Another supercritical CFB boiler designed by Foster Wheeler is undergoing construction at Novocherkasskaya power plant, Rostov, and will become the first CFB boiler in Russia upon start-up planned for 2014. The 330 MW unit is essentially a slightly scaled-down version of the Lagisza boiler, with the same number of solid separators and a predicted efficiency of 41.5 % (LHV) (Jäntti and others, 2009; Foster Wheeler, 2011a). The boiler is designed to accept a wider range of fuels, including local anthracite culm, bituminous 'Kuznetsky' coal from Siberia, and coal slurry, but is optimised for burning the low volatile, low reactivity anthracite. It is hoped by the utility that this increased flexibility in coal procurement and ability to burn local coal wastes will allow savings of up to 20% to be made on fuel costs (EM Alliance, 2010). CFBC is also easily able to meet Russian emissions limits for SO_2 (400 mg/m^3) without additional FGD. There are indications that two other, similar units are planned in Russia.

3.5.7 Finland

Much of the early impetus for the development of CFBC technology came from their use for biomass combustion in Sweden and Finland, where they are widely used to burn waste from pulp and paper plants, supplying energy to the plant in turn. Home to leading CFB boiler manufacturers Foster Wheeler Energia Oy and Metso, as well as the VTT technical research centre, Finland remains a global centre for CFBC technology development. Over twenty, mostly smaller-scale units are operational, but also include Metso's 240 MW unit at Alholmens Kraft power plant, currently the largest biomass-fired CFB boiler in the world, and Foster Wheeler's 200 MW peat and biomass-fired boiler at Keljonlahti (Modern Power Systems, 2002).

3.5.8 India

India is the third largest coal consumer and producer in the world and possesses huge reserves of largely poor quality coal, such as high ash bituminous coal and lignite. The frequently unfavourable economics of transporting and burning domestic coal has led India to also depend increasingly on imported coal, mainly from Indonesia. As India experiences rapid economic growth, government policy over the last decade has aimed to introduce large supercritical coal plants to replace the small and inefficient units that currently predominate (PFC India, 2013). To reduce the strain on India's coal supply the government has also required that new plants are designed to burn at least 30% imported coal, and that high ash coal can not be transported over 1000 km. Coupled with this, a proposed introduction of an export tax on Indonesian coal could made it less favourable for Indian plants to rely on using imported coal alone. Whilst the focus of India's investment in large-scale coal power plants remains with supercritical PCC, the country has been identified by manufacturers as an ideal market for utility CFBC due to this inherent reliance on fuel blends incorporating poor quality coal. As in other coal-using countries, small-scale CFBC for industrial generation is already relatively widespread in India, but a potential growth of utility-scale units is in its infancy and largely focused on lignite firing. Two 250 MW units designed by Lurgi-Lentjes and completed in 2012 at Neyveli power plant, Tamil Nadu, are currently the largest CFB boilers in South Asia, but start-up has been delayed for several months by technical problems including the failure of pressure parts before full capacity was reached (The Hindu, 2012; Ramesh, 2013). Intended to burn local lignite, CFBC technology was chosen for these boilers to avoid slagging problems associated with the marcasite (iron sulphide) content in the ash at high temperatures.

In 2011, Foster Wheeler licensed its CFBC technology to Indian construction and energy company Essar, accompanied by the contracting of four 150 MW CFBC units for a plant at Salaya, Gujarat (Bloomberg, 2011; Electrical Monitor, 2011). The boiler manufacturer has targeted India as a market for its supercritical 660 MW boiler design, focusing on the potential economic benefits of increased flexibility to the global coal market provided by the ability to burn blends with domestic coal (Utt and Giglio, 2012a,b).

The potential advantages of CFBC with respect to reducing SOx and NOx emissions are absent in India as neither species is currently regulated, partly due to the low sulphur content of domestic coal. However, as use of higher sulphur imported coal increases and concerns over air quality in population centres grow, it seems likely that some regulation may be implemented in the future. This may prove decisive in whether India embraces utility-scale CFBC.

3.5.9 Vietnam

In 2012, Foster Wheeler was contracted to supply four 250 MW boilers to Mong Duong power plant in Vietnam, with generation scheduled to commence in 2015 (Energy Business Review, 2012). This forms part of a wider programme to build several similar CFBC plants to burn domestic anthracite.

4 Technical comparison of PCC and CFBC

4.1 Efficiency

4.1.1 Combustion and boiler efficiency

CFBC has often been regarded as capable of achieving complete carbon burn-out and exceptionally high combustion efficiencies due to the long residence time of coal particles in the furnace. In practice, the extent to which this can be achieved greatly depends on factors such as coal characteristics, residence time, and excess air. It has been widely found that a combustion efficiency approaching 100% is indeed possible for CFBC of lignite, owing to the relatively high volatile matter and reactivity of the fuel, as has been demonstrated at the 250 MW Red Hills units and lignite-fired 300 MW boilers in China (*see* Table 3) (Morin, 2003; Li and others, 2010b). On the other hand, considerable problems have been experienced in China with poor carbon burn-out in CFBC of other fuels such as the high ash anthracite used at the 300 MW unit at Baima power plant, where 2.43% residual carbon in bottom ash was recorded in 2007 (Li and others, 2010b, 2013). Resolving this issue has become a principal challenge of CFB boiler operation in China, for which increasing the penetration of secondary air, maintaining high bed temperatures, and improving cyclone efficiency have met with some success (Gauvillé and others, 2012; Li and others, 2013). Despite these problems, a 2007 survey of 300 MW PCC ash in China showed similar levels of carbon in bottom ash to CFBC (Mi, 2009). Incomplete combustion has also been experienced at the Gardanne 250 MW unit when using imported bituminous coal, but improvements were found when blending with petcoke (Jaud, 2010). This beneficial effect of petcoke has also been observed at the Northside CFBC plant, although here bituminous coal alone can still be fired with over 98% efficiency (Black and Veatch, 2005). In general, CFBC appears to be capable of combustion efficiencies in a similar range to PC boilers, but some fuel flexibility may have to be sacrificed to achieve the optimal conditions necessary.

High boiler efficiencies (typically 90–93% (LHV)) should also be theoretically possible with CFBC, due to a lower concentration of SO_3 gas exiting the boiler than in PCC which allows lower exit air temperatures to be used without the risk of corrosive condensation occurring (NETL, 2011a). However, this effect only becomes pronounced for high sulphur coals and for most fuels the two boiler types are capable of similar efficiencies.

Table 3 Unburnt carbon content in CFBC ash (Jaud, 2010; Li and others, 2010b; Morin, 2003)

Plant	Coal	Carbon in ash, %
Baima	Anthracite	2.43
Qinhuangdao	Bituminous	0
Honghe (Xialongtan)	Lignite	0.25
Kaiyuan	Lignite	0.70
Xunjiansi	Lignite	0.68
Red Hills	Lignite	0.04–0.61
Gardanne	Bituminous	7.7
Average over 300 MW PCC in China (2007)	Diverse	2.6

4.1.2 Net thermal efficiency and auxiliary power consumption

Net thermal efficiencies of CFB boilers are often less competitive owing to the high auxiliary power consumption by fans used to generate the fluidising air, which can be greater than the power drawn by the coal pulverisers and FGD unit required for PCC. The power consumed by utility-scale CFBC is usually in the range of 8–10% of the total generated output, depending on boiler design and fuel type, whilst PCC plants with FGD are able to approach 6% (*see* Figure 13) (Yang and others, 2012a). As a result, early large-scale CFBC plants have been slightly less efficient than equivalent PCC, falling in the range 37–39%. However, a few more recently constructed subcritical units have been more competitive, with the later 262 MW lignite-fired units at Turow power station achieving over 41% efficiency (LHV), and the 340 MW unit at Sulcis designed for 40% (*see* Table 4).

The application of supercritical steam conditions to CFBC has allowed a similar leap in efficiency to that which accompanied the development of supercritical PCC. The Lagisza supercritical CFB boiler recorded a net efficiency of 43.3% (LHV) after one year of operation, and the design efficiencies of the similar plants under construction in Russia and South Korea are 41.5% and 42.2% (LHV) respectively. As lower mass fluxes can be used in supercritical CFBC waterwalls than in PCC, some energy saving can also be derived from the reduction in water pump power required.

Researchers at Tsinghua University, China, have conducted extensive research into reducing the auxiliary power consumption in CFB boilers, leading to the development of a computational model for determining optimal fluidisation parameters known as 'state specification design theory'. By reducing the quantity of bed material, the pressure drop across the bed and thus the fluidising air fan power required can be reduced. It was found that a significant reduction could be made provided there remain sufficient fine particles to supply heat transfer in the upper furnace and sufficient coarse particles for complete burnout in the lower furnace (Yang and others, 2009). An optimal fluidisation state can therefore be achieved by carefully controlling this size distribution of the fuel feed and fluidisation velocity. This theory was put into practice at the Longyan 300 MW CFB boiler where, in combination with other energy saving measures such as variable frequency fans, an auxiliary power consumption of 4.6% of output was achieved, representing a reduction of 2.3 percentage points over an identical unit at Heshuyuan (*see* Figure 13) (Yang and others 2011). Reducing the proportion of

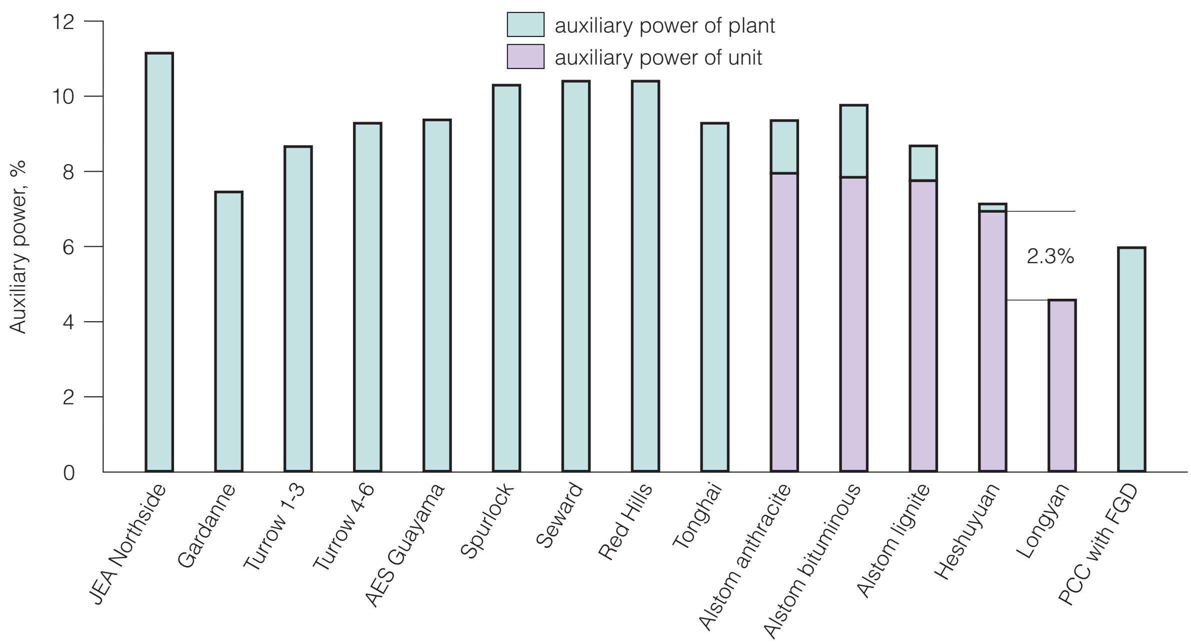

Figure 13 Auxiliary power consumption of large CFBC plants (Yang and others, 2011)

Table 4 Boiler and thermal efficiencies of large CFB boilers with similar capacity PC boilers for comparison (Black and Veatch 2005; Burns and Roe Enterprises, 2007; Foster Wheeler, 2011b; Harghel and others, 2005; Henderson, 2007, 2013; Jäntti and others, 2012; Lu and others, 2010; Morin, 2003; Psik and others, 2005; Yaohua, 2007)

	Country	Power output, MW	Start-up	Manufacturer	Fuel	Boiler efficiency, %	Thermal efficiency, %
CFB boilers							
Gardanne	France	250	1995	Alstom	Bituminous	91.6 (LHV)	37.5 (HHV)
Turow 1–3	Poland	235	1998–2000	Foster Wheeler	Lignite	91.2 (LHV)	40.8 (LHV) 37 (HHV)
Turow 4	Poland	261	2003	Foster Wheeler	Lignite	93.19 (LHV)	41.9 (LHV) 39 (HHV)
Red Hills	USA	250	2002	Alstom	Lignite	82.6 (HHV)	
Northside	USA	300	2002	Foster Wheeler	Bituminous/Petcoke	88.1 (HHV)	39 (HHV)
Sulcis*	Italy	350	2005	Alstom	Bituminous/Biomass	93 (LHV)	40 (LHV)
Seward	USA	260	2004	Alstom	Waste bituminous	–	35 (HHV)
Spurlock 1	USA	278	2006	Alstom	Bituminous	–	36 (HHV)
Baima	China	300	2006	Alstom	Anthracite	91.9 (LHV)	–
Heshuyuan	China	300	2008	Dongfang	Anthracite	89.5 (LHV)	–
Xialongtan	China	300	2006	Shanghai	Lignite	92.8 (LHV)	–
Lagisza SC	Poland	460	2009	Foster Wheeler	Bituminous	–	43.3 (LHV)
Baima SC	China	600	2013	Dongfang	Bituminous	>91 (LHV)	43 (LHV)
Novocherkasskaya SC*	Russia	330	2013	Foster Wheeler	Bituminous/Culm	–	41.5 (LHV)
Samcheok SC*	South Korea	550	2015	Foster Wheeler	Bituminous	–	42.4 (LHV)

	Country	Power output, MW	Start-up	Manufacturer	Fuel	Boiler efficiency, %	Thermal efficiency, %
PCC boilers							
Esbjerg SC	Denmark	415	1992	Stein	Bituminous	95 (LHV)	45.5 (LHV)
Staudinger 5 SC	Germany	510	1992	Borsig	Bituminous	–	43 (LHV)
Opole*	Poland	370	1996	Rafako	Bituminous	91.7 (LHV)	–
Majuba 1	South Africa	657	1997	GEC	Bituminous	90.26 (LHV)	35 (LHV)
Genesee 3 SC	Canada	495	1998	Hitachi	Subbituminous.	87.5 (HHV)	41 (LHV) 40 (HHV)
Suratgarh	India	250	1998	BHEL	Blend	87.78 (HHV)	37.1 (LHV) 35.1 (HHV)
Wangqu 1	China	600	2006	Hitachi	Anthracite	93.72 (LHV)	41 (LHV) 40 (HHV)

* Design values, not tested

coarser material in the lower furnace in this way also has the benefit of reducing waterwall erosion, and improving combustion efficiency by increasing the penetration of secondary air into the bed.

It is difficult to reliably estimate the total energy balance for state-of-the-art PCC and CFBC plants for a general case. It is interesting to note, however, the progression of such estimates in industry and government studies over recent years. In 2007, CFBC technology was often rated as at least 1 percentage point less efficient than an equivalent PCC plant (Black and Veatch, 2007; Jenkins and Brown, 2007). A Parsons Brinckerhoff study in 2011 puts subcritical CFBC 0.2 percentage points behind PCC (500 MW scale), whilst a NETL study of the same year calculates a 0.2 point advantage for supercritical CFBC burning subbituminous coal, and a 0.5 point advantage for lignite (550 MW scale) (Loyd and Craigie, 2011; NETL, 2011a). The NETL study is particularly noteworthy as it provides a breakdown of auxiliary power consumption for both technologies; traditionally seen as a principal drawback of CFBC. For the model coal plants, the load associated with fluidising air fans is less than half that of the coal pulverisers. Together with the power consumed by additional FGD equipment (spray dryers) needed for the PCC case, the CFB boiler is estimated to actually use 4330 kW less of auxiliary power, or only 5.1% of its total output compared to 5.9% for the PC boiler (*see* Table 5). Whilst these estimates for CFBC auxiliary load seem ambitious, it is clear that scaling-up of the technology is reducing the significance of these energy losses.

4.2 Availability and reliability

The reliability and availability of CFB boilers has steadily improved so that they are now widely viewed as comparable to PC boilers, capable of availabilities of around 90%. However, a relatively small proportion of available data concerns the utility-scale CFB boilers that have been built over the past 15 years. As first examples of their kind, some plants initially experienced considerable operational setbacks and low availabilities which have led to operational and design

Table 5 Breakdown of auxiliary power use in modelled 550 MW PCC and CFBC plants using low-rank coals (NETL, 2011a)

	PCC		CFBC	
	Lignite	Subbituminous	Lignite	Subbituminous
Fan power, kW	10770	10660	12140	12020
FGD, kW	2760	2400	–	–
Mills, kW	5140	3850	160	120
Total auxiliary power, kW	34640	32660	28670	28330
Auxiliary power, %	5.9	5.6	5.0	4.9
Net efficiency (HHV), %	37.5	38.7	38	38.9

Table 6 Availability or reliability (unplanned outages only) of large CFBC units (Burns and Roe Enterprises, 2007; Hotta, 2013; Jaud, 2010; Li and others, 2010b, 2013; Thomas and Kang, 2011)

CFB boiler	Measurement period	Availability/(Reliability), %
Northside	2004	59
Northside	2011	(99)
Gardanne	1997–2002	87
Gilbert (Spurlock)	2005	92
Foster Wheeler 7 bituminous units	2012	(98.5)
Foster Wheeler 7 lignite units	2012	(98.3)
Baima	2007	88
Qinhuangdao 1	2007	88
Qinhuangdao 2	2007	61
Honghe 1	2007	91
Honghe 2	2007	94
Kaiyuan 7	2007	52
Kaiyuan 8	2007	79
Xunjiansi	2007	72
China 300 MW average	2012	87

improvements in these plants and newer builds. Problems of ash agglomeration at the two 300 MW JEA Northside CFBC units (the largest in the world when built) resulted in availabilities of 73% and 59% in 2003 and 2004, but the addition of a preventative additive in 2008 has enabled a forced outage rate as low as 1% for 2011 (Thomas and Kang, 2011). The first 250 MW boiler at Gardanne, France, recorded availabilities between 76% and 94% over its first six years of operation (87% average), experiencing outages mainly due to waterwall leakages and ash blockages (Jaud, 2010). On the other hand, recent data from Foster Wheeler units show forced outage rates below 2% when firing conventional fuels such as bituminous coal and lignite, rising to up to 4% for biomass-fired units.

The first few 300 MW CFB boilers in China initially showed very variable reliability, with some boilers experiencing severe erosion problems as a result of high ash fuel or inappropriate boiler design (*see* Table 6). The first plant, built by Alstom at Baima power plant (Sichuan), recorded an availability of 88% in 2007, but other early plants such as Kaiyuan and Xunjiansi (both in Yunnan) recorded availabilities as low as 52% and as many as 12 unplanned outages in the same year (Li and others, 2010b). The eight units surveyed experienced an average of 5.63 unplanned outages per unit during 2007 compared with an average 0.89 outages for similar capacity PCC units in the same year (Mi, 2009). These boiler failures derived principally from the extremely high ash coal used in many CFBC in China (up to 60%), which leads to erosion, ash blockages, and eventually bed agglomeration (*see* Section 4.4). Boiler alterations to suit these conditions such as the rotary ash cooler (*see* Section 3.5.4), and the optimisation of fluidisation parameters according to state specification design theory have allowed improvements to be made. Nevertheless, more recent data from China indicate an average of 87% availability across the 300 MW fleet that is still below the thermal power plant average of 92% (Li and others, 2013; Li, 2013)

4.3 Load following

The load following capability of CFBC can be slightly inferior to PCC, as the large mass of bed material carries considerable thermal inertia when being heated up or cooled down. In the past, large CFB boilers may have been limited to ramp rates of 2–3% MCR/min compared to around 5%/min for PC boilers, but more recently Polish CFBC units at Lagisza, Turow, and Polaniec have successfully met grid requirements of 4%/min. CFB boilers may be restricted to lower rates if problems with SO_2 emissions and incorrect limestone stoichiometry are encountered (Black and Veatch, 2007; Goidich and Hyppänen, 2001; Nuortimo, 2013; Utt and others, 2009).

Starting-up CFBC from cold is more problematic, as ignition of the bed can consume relatively large amounts of oil which can represent a significant economic disadvantage. Particularly in China, ways to reduce the cost of ignition have been investigated, and include ignition from beneath (rather than above) the bed and using heated feedwater from nearby boilers (Li and others, 2010b). The thickness of the bed and quality of the coal should also be optimised at start-up. On the other hand, the bed material and refractory retain heat for long periods, making hot restarts possible after up to 18 hours.

The long furnace residence time in CFB boilers permit the use of harder-to-burn coals at lower loadings (40% MCR) than PC boilers without the need for oil or gas support fuel. This capability is a principal advantage to the use of CFBC rather than downshot PCC boilers for firing Chinese anthracite (Morin, 2003). However, operating a CFB boiler at low loads can also have a negative effect on desulphurisation efficiency as there is reduced mixing in the furnace (Martino, 2013).

4.4 Ash-related operational issues

4.4.1 Slagging and bed agglomeration

Depending on their chemical composition, inorganic impurities in coal can create various problems for both types of boiler. Coal with high concentrations of alkali metals such as sodium and potassium can be particularly problematic, as it produces ash with a lower melting point which leads to serious slagging and fouling of surfaces at the high temperatures found in PCC boilers. These deposits can reduce the efficiency of heat transfer, corrode metal surfaces, and impede gas flow through the convective pass. Reduced heat transfer due to furnace slagging can also create a positive feedback loop by raising furnace temperatures and leading to increased slagging.

There are a number of ways in which a PCC boiler can be designed to accommodate ash with a high propensity for slagging. Larger furnaces can help reduce slagging, or at least produce drier, sintered deposits which can be more easily removed than molten slag, but these gains must be balanced with added construction costs. Use of refractory should also be minimised, for example, by shaping waterwall tubes tightly around burner inlets, and burners themselves can be staggered to avoid local overheating. Pendant superheaters at the roof of the furnace are particularly prone to severe slagging due to their high temperatures. Here, tubes joined by metal membrane (Doosan Babcock design) can be used as large deposits can form as bridges between free tubes (Barnes, 2009).

In CFB boilers, bed temperatures are not usually high enough to completely melt ash but the higher temperatures at particle surfaces can result in stickiness and agglomeration of bed material, particularly if poor mixing and local overheating are allowed to occur. Bed agglomeration is one of the foremost problems of CFB boiler operation, as large masses of material will fail to fluidise properly, potentially leading to further agglomeration and formation of deposits on the fluidisation grid or external heat exchangers. This was a major problem for the first two 300 MW CFBC units, operating at Northside power plant since 2002, where it led to numerous shut-downs in the first years of operation due to deposits on INTREX superheaters and blockage of the bottom ash removal system. Eventually the issue was solved by the addition of an additive to absorb the alkali species (Thomas and Kang, 2011). In general, agglomeration and slagging in CFBC are caused by poor fluidisation, usually as a result of insufficient air, excess bed material, or overly coarse particles. Excessively fine particles can also cause overheating and slagging by undergoing combustion in the cyclones or furnace exit (*see* Figure 14) (Cheng and others, 2011).

Soot blowers, which are commonly used in PC boilers to remove furnace deposits with high pressure jets of water, steam, or compressed air, are often not necessary for CFB boilers unless high ash coal or

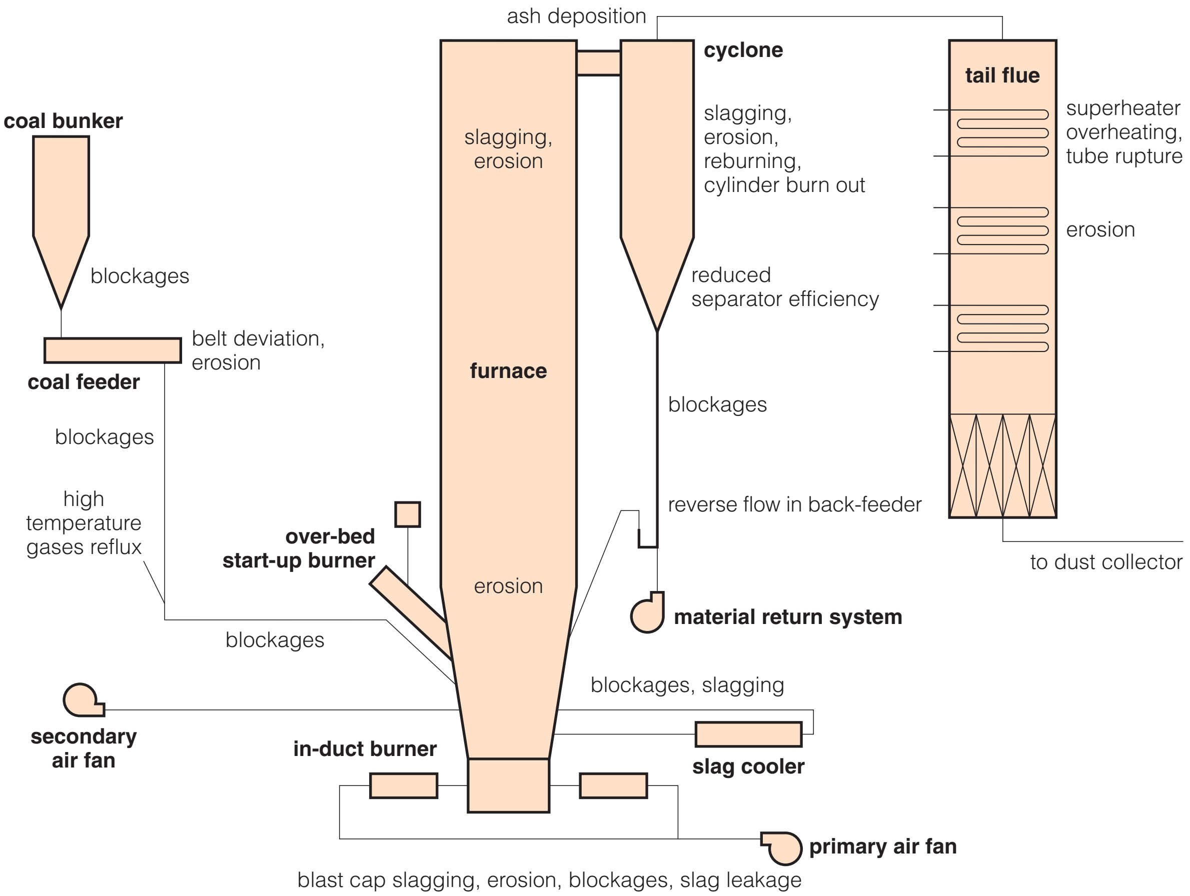

Figure 14 Operational issues affecting the different areas of a 300 MW CFB boiler (Cheng and others, 2011)

biomass is fired. This method of boiler cleaning can be inefficient and risk erosion of the surfaces over time, so more intelligent, automated sootblowing has been developed which is directed at the correct locations and only when sufficient build up has occurred. Such systems can be based on measurements of furnace exit gas temperature, increase in attemperator spray rate, or the weight of pendant superheaters (Barnes, 2009).

4.4.2 Erosion

Hard minerals such as quartz and pyrite are also undesirable impurities in coal as they can cause erosion when they impact upon boiler surfaces as fly ash. In India, where coal is high in ash and hard quartz, erosion is a particular problem and the main cause of coal plant outages. In addition to coal composition, flue gas velocity and temperature are crucial factors in determining the risk of erosion, as over 750°C ash is too soft to cause damage. In a PC boiler, heat exchange surface in the convective pass is therefore at risk, including low temperature superheaters, reheater inlets, and economisers. Non-uniform flow and eddies (often due to fouling deposits) can also exacerbate the problem by increasing ash impacts upon surfaces. Preventative measures include limiting flue gas velocity and the use of metal shielding in problem areas, or introducing refractory lining where shielding is not possible. The erosion resistance of metals in these areas can also be enhanced by coating parts with more resistant alloy materials (Chawla and others, 2011).

In CFB boilers, ash is circulated at high fluidisation velocities through the boiler, often at temperatures at which its hardness is retained, so erosion can be a major concern. Erosion damage accounts for over 80% of boiler shut-downs amongst the 300 MW fleet in China (Li and others, 2010b). Circulating material can deflect off irregularities presented by the boiler interior, damaging heat transfer surface and potentially leading to tube bursts. Areas that are particularly affected are the transition between the sloped and vertical walls at the bottom of the furnace, the external fluidised bed heat exchangers, suspended or projecting waterwall surfaces exposed on both sides, and irregularities in the waterwall associated with fuel feeds and secondary air nozzles. The transition between the sloped and refractory coated lower boiler walls and the vertical waterwalls of the upper boiler can cause vortices and flow of material down the walls which leads to erosion (*see* Figure 14). Bending of the membrane tubes into an S-shape at the junction is a development (known as the ‘kick-out’ design by Foster Wheeler) which has managed to reduce this problem, but ‘splashing’ of the denser, lower bed material above the refractory lined area also needs to be kept to a minimum. This has been achieved to some extent through use of state specification design theory, which limits coarse fuel feed to the boiler and so reduces the height of the dense bed. As for PC boilers, areas subjected to erosion can also be protected by coating with wear resistant alloys, and tubing metal in general should be selected for good resistance to erosion (Cheng and others, 2011).

Hard mineral content in coal also causes problems for the pulverisation process, causing wear to mills and increasing their energy consumption for a given output of ground coal. In CFBC, coal is only crushed before feeding to the boiler and no grinding mills are required, so harder ash does not add to the auxiliary power load of the plant.

4.5 Emissions

The majority of states using coal-fired power generation have implemented legislation to restrict flue gas emissions of SOx, NOx, and particulate matter, due to their negative impact on either public health or the environment. Scrubbing of particulate matter from flue gases is usually performed by electrostatic precipitators, and the process is identical for both PCC and CFBC technologies, although the latter produces proportionally less fly ash and more bottom ash. CFBC has often been presented as a cleaner coal technology because of naturally low NOx levels associated with the low temperature combustion and the capability of removing SO_2 in the furnace itself. However, as most new PCC plant is obliged to include downstream scrubbers which can attain equivalent flue gas concentrations of these species, the potential advantage of CFBC in this respect is primarily economic.

4.5.1 SO_2

Most flue gas desulphurisation technologies for PC boilers employ limestone or lime sorbent to react with SO_2 and are categorised by the amount of water used by the process; namely, wet, semi-dry, and dry. The most widely used process is wet FGD, in which flue gases pass through a vessel containing a limestone slurry. The reaction between calcium ions and SO_2 produces $CaSO_3$, but injection of air, known as a 'forced oxidation', is usually implemented to yield gypsum as a saleable by-product. Wet FGD is generally able to achieve 90–98% SO_2 removal at Ca/S ratios of 1.02 to 1.10, making it the highest performance and most sorbent efficient calcium-based scrubber (European Commission, 2006). However, a high capital cost tends to favour the use of wet FGD for large capacity units or those using high sulphur coal. In the last two decades, semi-dry systems such as spray-dryer absorbers have emerged to compete with wet FGD, particularly for smaller units using low sulphur coal (such as PRB coal), or in water scarce regions. In a spray dryer system, a lime slurry is finely sprayed into the flue gas whereupon the water evaporates and leaves dry lime to be captured by a particle collection device. This technology has been steadily improved to be able to achieve up to 95% SO_2 removal, but it requires a higher Ca/S ratio than wet FGD (at least 1.5) and can struggle with high SO_2 concentrations and large flue gas volumes (European Commission, 2006). More advanced semi-dry FGD systems such as novel integrated desulphurisation (NID) and CFB FGD use hydrated lime as a sorbent and incorporate a mechanism of recirculating the sorbent captured by the particulate collector so as to maximise sorbent utilisation (Buecker and Hovey, 2013). These systems also inject humidifying water separately from the sorbent, which allows sorbent use to be independent of slurry concentrations. This kind of technology can potentially achieve 98% SO_2 removal for a stoichiometric ratio of 1–1.3, and is seeing increasingly widespread adoption in the USA and China.

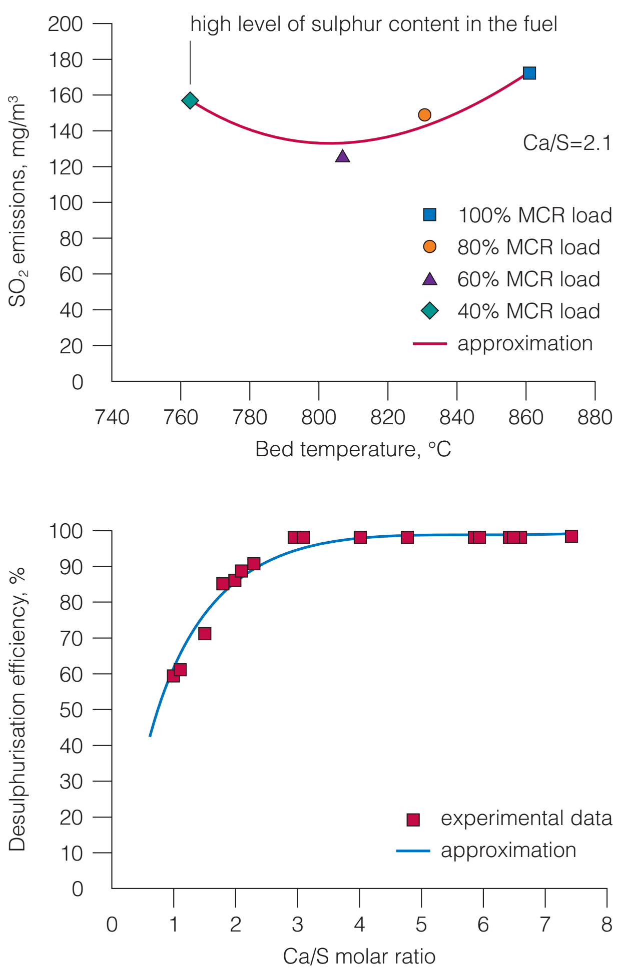

Figure 15 The effect of temperature and Ca/S ratio on SO_2 emissions at the Lagisza CFB boiler. SO_2 removal efficiency remains constant at 99.8% for Ca/S greater than 3 (Blaszczuk and others, 2012)

Desulphurisation can be carried out in a CFB boiler by adding limestone directly to the furnace, where it is calcined to lime before reacting with SO_2 to form primarily $CaSO_3$. The slower reaction kinetics and poorer mixing of this solid-gas reaction compared with the aqueous reaction found in wet FGD result in a less efficient use of limestone. Data from 300 MW CFB boilers in China and the supercritical unit at Lagisza indicate that a calcium to sulphur ratio of 2 can normally achieve 90–95% SO_2 removal and a ratio of 3 is required to reach a maximum of 99.8% removal (*see* Figure 15) (Blaszczuk and others, 2012; Yang and others, 2012b).

However, no additional reaction vessel or water circuitry is required for the process. Several studies have shown that this in situ desulphurisation is highly sensitive to operational parameters and limestone reactivity. In particular, it is important to keep the bed temperature in the range 800–850°C, at which the calcination reaction is thermodynamically favourable, for limestone use to be minimised. Other important factors include the excess air ratio, cyclone efficiency, and the height of the fluidised bed (Blaszczuk and others, 2012).

Strict emissions standards can stretch the capabilities of in situ desulphurisation and require additional downstream flue gas desulphurisation known as 'polishing' which usually takes the form of semi-dry or dry FGD. Nearly all large CFBC units in the USA have been obliged to use FGD spray dryer systems to meet BACT standards, which require power plants to achieve the best economically feasible emissions and can necessitate up to 98.5% sulphur removal (Virginia DEQ, 2008). Whilst in some cases this level of removal efficiency would be possible with in situ desulphurisation, the addition of more limestone yields diminishing returns and can be to the detriment of combustion efficiency as well as catalysing the formation of NOx from ammonia. Foster Wheeler tend to favour spray dryer scrubbers and dry sorbent injection for flue gas polishing, whereas Alstom have installed their own design of flash dryer absorbers at two of their CFBC plants in the USA, and CFB FGD units on two 227 MW CFB boilers in Puerto Rico (Jarvis, 2001). An advantage of these semi-dry scrubbers is that they are able to reactivate the sorbent activity of the unreacted lime left in the fly ash (usually over 30%) and allow it to further react with remaining SO_2. This can reduce the rate of fresh sorbent used by the unit (Nielsen and others, 1999).

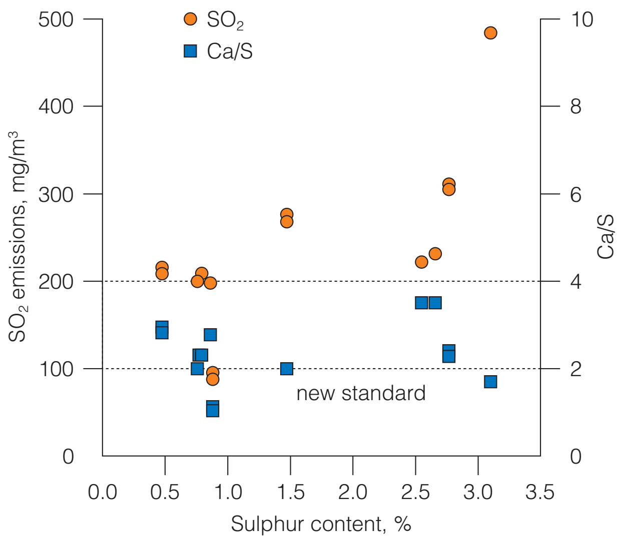

Figure 16 SO_2 emissions from 300 MW CFB boilers in China (Yang and others, 2012b)

In China, recently introduced regulations which impose a limit of 100 mg/m^3 of SO_2 from large coal plants could also require downstream polishing for some of the large number of utility CFB boilers in service. Several 300 MW units using the high sulphur coal found in the south-west of China currently emit well over 200 mg/m^3 even at 95% removal (*see* Figure 16) (Yang and others, 2012b). The addition of CFB FGD to these units is currently amongst the solutions favoured by Chinese utilities (Long and others, 2013).

Additional downstream scrubbing has the potential to reduce the competitivity of CFBC compared to PC boilers with wet FGD units that are already able to achieve up to 99% removal. Once seen as ideally suited for high sulphur coals, more stringent emissions limits may instead place CFBC as better suited to lower sulphur coals for which in situ desulphurisation is still sufficiently effective. The planned 550 MW CFBC units at Samcheok in South Korea represent perhaps the most ambitious SO_2 emissions targets for in situ desulphurisation alone, designed to emit 50 ppm (140 mg/m^3) within the specified fuel range of 0.1–1% sulphur (Jäntti and others, 2012). This limit has been set lower than the national standard in order to demonstrate the green capabilities of the new plant. Slightly higher EU limits of 200 mg/m^3 are currently met by the large CFB boilers at Sulcis and Lagisza using furnace limestone alone. The Italian plant burns a proportion of high sulphur coal, but cofiring with biomass has a mitigating effect on SO_2 emissions.

4.5.2 NOx

The majority of NOx produced by the combustion of coal derives from the oxidation of nitrogen present in the fuel (fuel NOx), with a smaller contribution from the oxidation of nitrogen gas at high temperatures (thermal NOx). In PC boilers NOx can be significantly reduced by adjusting combustion parameters, known as primary measures, which include low NOx burners, overfire air and reburning. These are all based on similar principles of promoting lower flame temperatures and the introduction of combustion air in stages, avoiding the oxygen rich combustion which promotes NOx formation. Together, primary measures are able to achieve up to 55% NOx reduction. Nevertheless, in order to meet emissions limits lower than 200 mg/m^3, additional, secondary measures are often required to remove already-formed NOx from the flue gas. These scrubbers inject either ammonia or urea into the flue gas where they react with NOx to form nitrogen and water. A solid catalyst such as vanadium can be employed to promote this reaction in a process known as selective catalytic reduction (SCR), which is able to achieve 80–90% reduction with a 1:1 stoichiometric ratio of ammonia to NOx. Alternatively, selective non-catalytic reduction (SNCR) avoids the expense of catalyst and separate reaction vessel by injecting ammonia or urea into hot flue gases (over 800°C). This process is less effective, generally managing 30–50% NOx reduction at 1–1.5 stoichiometry, and carries the risk of 'ammonia slip' where unreacted ammonia reaches unacceptable levels in the flue gas.

The extent to which reagent can be mixed with flue gases is a crucial limiting factor for SNCR, and consequently SCR has been widely adopted by large PC boilers needing to comply with NOx emission limits. Despite this, improvements in injection technology and flue gas modelling have led to increasing adoption of SNCR for boilers up to 320 MW in size (Schuettenhelm, 2013; Von der Heide, 2013). Combining SNCR with primary measures such as low NOx burners can in some cases present an alternative means of achieving similar removal rates to SCR with less capital investment. High-ash coals also favour the use of SNCR as certain inorganic species can contaminate and damage the catalyst used in SCR.

NOx emissions from CFBC are inherently lower than from PCC as the low combustion temperatures effectively prevent thermal NOx formation and reducing conditions in the lower bed minimise fuel NOx. Similarly to PCC, air staging is used to further reduce fuel NOx, with secondary and tertiary air introduced higher up the furnace walls. Consequently, all of the large CFBC units operating in Europe have managed to meet emissions limits of 200 mg/m^3 without the use of scrubbing. However, as for SO_2 control, strict emissions standards and certain types of fuel can mean that downstream NOx treatment is also needed for CFBC. In these cases, SNCR offers a sufficient level of NOx reduction, and this technology has been fitted to nearly all large CFB boilers operating in the USA in order to meet BACT requirements (Sargent and Lundy, 2005). Notable exceptions are the two Red Hills 250 MW units, which benefit from the lower temperatures and air flow needed for lignite combustion to meet NOx limits without flue gas scrubbing (Morin, 2003). The Foster Wheeler units at Turow and Lagisza are also designed to allow ammonia injection to counter increased NOx that may result from using fuels outside of specifications (Jäntti and Parkkonen, 2009).

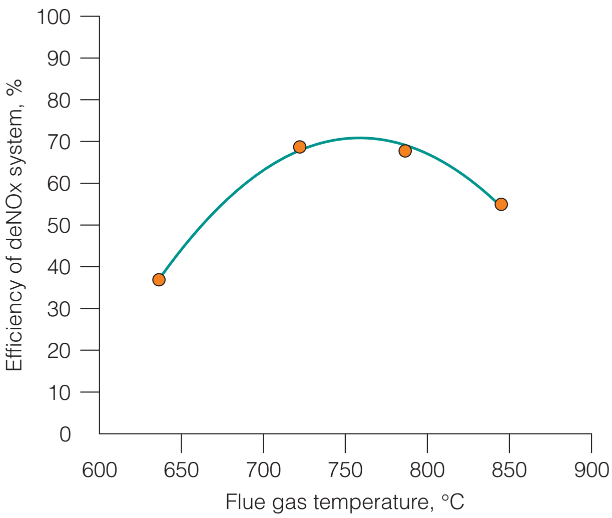

Figure 17 The efficiency of the SNCR deNOx system at Lagisza as a function of flue gas temperature (Blaszczuk and others, 2013)

There is evidence that SNCR is more effective in CFB boilers than PC boilers, as the temperature window of the NOx conversion reaction corresponds well with CFBC operating temperatures (Wojichowski, 2002; Blaszczuk and others, 2013). Below 800°C the reaction with ammonia is significantly slower, but at over 1150°C the reagent can itself be oxidised to NOx. In a PC boiler, a delicate balance must therefore be achieved between injecting the reagent into too hot a region of the furnace, and injecting too far downstream to achieve sufficient residence time (more than 0.5 s) in the temperature window. In CFBC, the reagent is normally injected at the inlet to the cyclones at the top of the boiler, where some proportion can be expected to circulate back through the furnace and have more than enough time for complete reaction. Injection at the cyclone outlets is also possible and was indeed shown to be considerably more effective for NOx reduction at the two 227 MW units in Puerto Rico, with urea as the reagent. However, at low loadings, the boiler temperature can fall below the required window and significantly reduce the efficiency of NOx removal (*see* Figure 17) (Blaszczuk and others, 2013).

The 550 MW units at Samcheok are the first CFB boilers to incorporate SCR technology into their design, probably due to a combination of a strict NOx emissions limit (50 ppm or 100 mg/m^3) and the large boiler size (Jäntti and others, 2012).

The low temperatures and reducing conditions responsible for low NOx production in CFBC have the adverse effect of elevated N_2O emissions, which can be ten times higher than from PCC. As a potent greenhouse gas, N_2O has been incorporated into some emissions trading schemes and there is the potential for stricter regulations in the future to reduce the competitivity of CFBC. Researchers in China have investigated the possibility of removing this pollutant with ammonia scrubbing at the cyclone inlets, exploiting the inherent catalytic properties of the circulating ash (Hou and others, 2006). Reburning is an alternative abatement approach for which gasified biomass has been studied as a secondary fuel (Hu and others, 2012).

4.5.3 Multipollutant control

The development of multipollutant control systems that are able to remove SOx, NOx, and other species in a single reaction vessel has the potential to reduce the advantage offered by CFBC pollutant control. Although use at the commercial scale is currently very limited, the ReACT system at Isogo power plant has demonstrated the potential of such systems by achieving very high levels of SO_2 and NOx abatement using a thermally regenerable activated coke sorbent for both pollutants. Although there is a high capital cost currently associated with ReACT, the system offers similar advantages to CFBC desulphurisation with respect to low power consumption (60% of wet FGD) and water use (Peters, 2010). Significantly, the process also absorbs mercury, for which emissions limits currently exist in North America and have recently been introduced in China. The advantage of in situ desulphurisation in CFBC may become less pronounced as larger boilers and increasingly strict legislation require the use of several downstream scrubbers, whilst the emergence of multipollutant control systems offers a lower cost alternative.

4.6 Cofiring biomass

As carbon emissions become increasingly regulated, many coal-fired power plants, particularly in the USA and the EU, are turning to biomass cofiring as a means of reducing their carbon footprint. Burning biomass also effectively reduces the levels of SOx and NOx emitted and thus reduces the demand on flue gas scrubbers. On the other hand, cofiring biomass can raise a number of difficulties for coal boilers which necessitate alterations in design or operational practice. As biomass is much less energy dense, there is a significant capital requirement for separate fuel storage, preparation, and feeding installations, although existing coal mills and conveyors can be adapted for use with biomass to some extent (Mahr, 2011). A major operational concern is the usually high alkali metal and chlorine content in biomass ash, which promotes slagging and fouling whilst increasing the corrosive nature of these deposits. The wide range of biomass types that have been used for cofiring are associated with highly variable combustion and slagging characteristics. Most notably, woody biomass, which is lower in Cl and has higher melting point ash, causes fewer problems than agricultural, herbaceous biomass such as straw, which produces very low melting point ash and corrosive deposits.

These issues have an impact on both boiler technologies, but PC boilers are somewhat more restricted by the need to inject biomass through burners, which limits particle sizes to about 6 mm and requires milling. The most straightforward approach to adding biomass to a PC boiler is to simply add the material to the raw coal feed and use the same mills and burners for both fuels. However, biomass is usually fibrous so does not grind very effectively in coal mills and can accumulate over time. Biomass also has a much higher percentage of volatile matter than coal and. as a result, milling needs to be carried out at lower temperatures than usual to avoid combustion, incurring a slight efficiency loss. In most cases, up to 5% (by mass) biomass can be cofired simply by this method, although up to 15% has been demonstrated with specific biomass, such as wood pellets, and mill types (Fernando, 2012). Cofiring over 15% biomass in PCC requires separate, dedicated biomass mills, followed by mixing with the pulverised coal feed or separate injection to the furnace. As the biomass feed remains relatively coarse, both these approaches will usually require burners to be modified accordingly (Moulton, 2009). Retrofitting an entirely separate biomass handling system involves considerably more capital expenditure for fuel preparation, burners, and potentially boiler modifications to allow for altered flue gas flow and slagging properties. The power generation potential of this approach has been successfully demonstrated at projects converting large PC boilers to 100% woody biomass, such as the 180 MW Rodenhuize power station in Belgium and the 750 MW Tilbury power station in the UK, but extensive use of other biomass types in PC boilers is likely to remain limited.

Much of the early development of FBC was aimed at burning wood, peat, and pulp and paper wastes in Sweden and Finland, where both BFB and CFB boilers are still widely used for this purpose. Some of these, such as the Alholmens Kraft 240 MW unit (Kvaerner) and the Jyvaskylan 200 MW unit (Foster Wheeler) are amongst the largest biomass-fired boilers in the world. Use for cofiring with coal is also widespread, using the full range of possible fuel ratios (Fernando, 2012). The longer combustion times of CFBC allow much coarser biomass feed of up to 75 mm to be used, meaning that most biomass can be added to the boiler without further preparation and using similar delivery apparatus to the coal feed (Mahr, 2011). Several of the newer utility-scale CFB boilers designed by Foster Wheeler have also incorporated the capability of cofiring a proportion of biomass, including the two 325 MW units at Virginia City, which can take up to 20% biomass, the six Turow units and Lagisza in Poland (up to 10%), and Samcheok in South Korea (up to 5%) (Martino, 2013; Psik and others, 2005; Venäläinen and Psik, 2004). The 350 MW Alstom unit at Sulcis, Italy, is an example of a boiler which was designed purely for coal but has since been adapted to fire 15% (thermal) wood chips with the relatively straightforward addition of a separate delivery system. This has helped to reduce emissions from the high sulphur coal used (Mahr, 2011).

However, cofiring biomass is still able to present serious difficulties for CFBC, and in particular the increased risk of bed agglomeration when using high alkali fuels with low melting point ash such as straw or other cereal waste (Barisic and others, 2009). Refractory is also at greater risk of corrosive damage by alkali species when firing certain biomass, but this can be countered to some extent by the use of more resistant, low-cement refractory materials. Foster Wheeler have produced designs for biomass-fired CFBC up to 400 MW, with a range of material and operational modifications aimed at preventing agglomeration and corrosion when firing agro-based biomass. These include superior control of bed temperature and reduced flue gas velocity (Jäntti and others, 2013).

4.7 Ash utilisation

The majority of coal ash worldwide is still disposed of as waste in landfills and settling ponds, but as this becomes more expensive, and concerns over environmental damage grow, there are increased

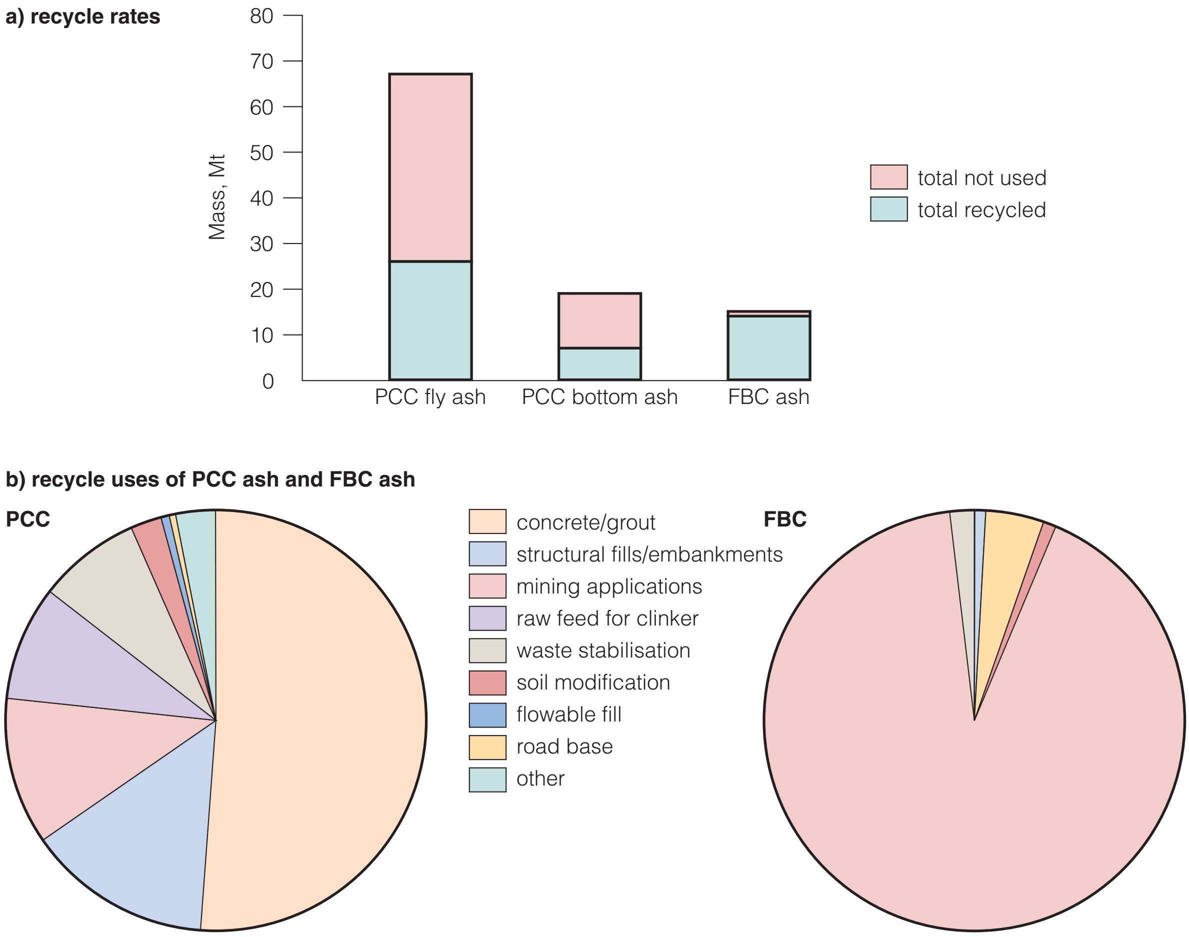

Figure 18 a) Production and recycle rates of coal ash, and b) the recycle uses of PCC and FBC ash in the USA in 2011 (ACAA, 2011)

efforts to expand the proportion recycled. In regions where coal use is particularly high, such as China, India, and the USA, this can pose a greater challenge and recycle rates are generally lower.

The most common recycle use of fly ash is as a replacement for Portland cement in concrete or grout, and this also usually represents the highest value application. However, in most regions the composition of fly ash for concrete must meet strict specifications with respect to CaO, silica and alumina, and carbon content in particular. Roughly half of the total PCC ash recycled in the USA is used for this purpose, and around 30% in the EU (*see* Figures 18 and 19) (ACAA, 2011; Feuerborn, 2011). The remainder is primarily used for lower grade applications with less strict specifications including use as a raw material (clinker) for cement production, and for construction as structural fill and road base material. Particularly in China, recycle rates for these low grade construction applications have grown rapidly in the last twenty years (Fu, 2010). In the EU, the major part of coal ash production is used in the rehabilitation of opencast mine sites. Another important by-product of most PCC plant is the gypsum produced by forced oxidation wet FGD. This is able to replace mined gypsum for a range of applications, but is most commonly recycled as plasterboard in the USA. Other uses include structural fill or in cement, where it acts as a set retardant.

CFB boiler ash is of a substantially different composition to PC boiler ash as it contains materials derived from the limestone added to the furnace; principally CaO and $CaSO_3$ (*see* Table 7). The tendency to use more varied fuel sources in CFBC can also lead to wider variation in ash chemistry, and the coarser fuel feed results in larger ash particles. These differences have presented some barriers to the use of CFBC ash for conventional coal ash applications, particularly as a cement substitute, for

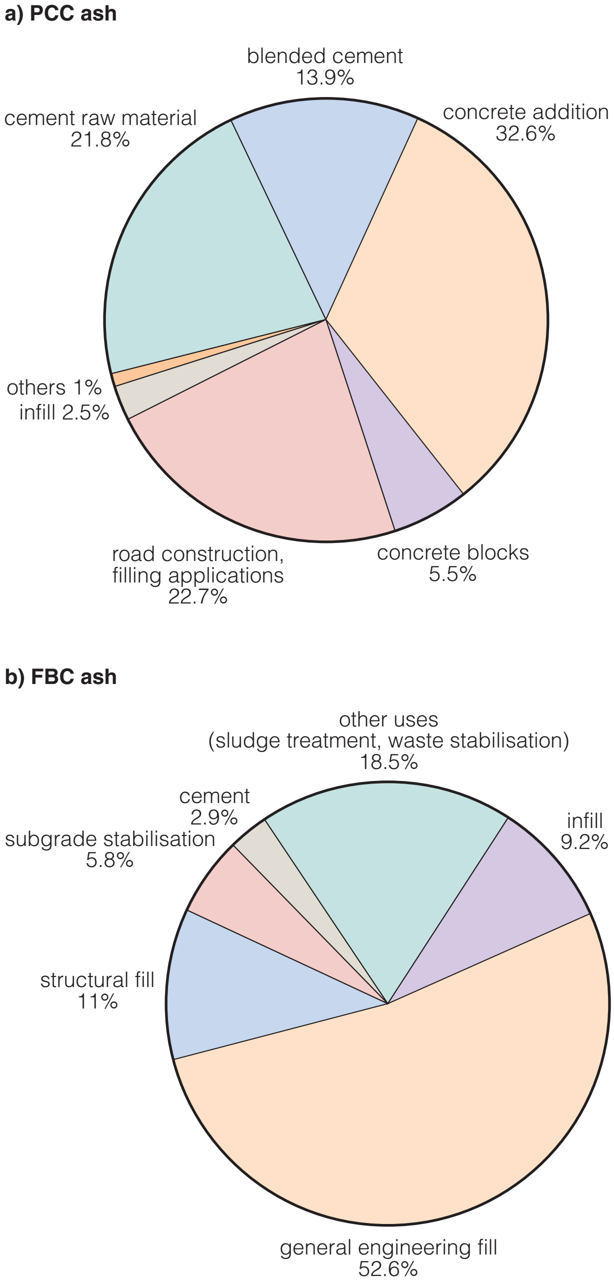

Figure 19 Construction and underground mining uses of PCC fly ash (17.7 Mt) and FBC ash (0.2 Mt) in the EU in 2008 (Feuerborn, 2011)

which excessive levels of CaO (often 30%) and sulphur, and reduced pozzolanic activity, place it outside of EU and US specifications (Stevens and others, 2009; Sear, 2001). Although the high free lime content in CFBC ash renders it self-cementitious, hydration is slow and can lead to unwanted expansion as minerals such as ettringite form from anhydrous calcium sulphate. Despite this, research is ongoing into safely incorporating CFBC ash into concrete, with more promising results from blends with PCC fly ash or even completely by-product-based concrete using blends of CFBC ash, PCC ash, and FGD gypsum (Robl and others, 2011; Rathbone and others, 2010). On the other hand, CFBC ash has found greater acceptance in construction applications with less stringent specifications, such as in soil stabilisation, as structural fill, and road base material. In the EU, use in these areas accounted for around 18% of FBC ash produced in 2008 (*see* Figure 19) (Feuerborn, 2011). In the USA, a notable construction use is the 'EZbase' product produced by the 300 MW Northside CFB boilers which is used to replace limerock for forming road bases (Jackson and others, 2009). A similar application has been trialled for the ash from the 300 MW CFB boiler at Baima, China (Lu and Amano, 2006). For these applications the self-cementitious nature of the ash is usually desirable, but unwanted expansion can also present problems for clay soils and high humidities. Methods devised to mitigate this problem include stockpiling the ash before use to allow hydration to occur, or blending with sufficient quantities of PCC ash (Adams, 2004; Reyes and Pando, 2007; Thenoux and others, 2009).

In the USA, where CFBC is primarily used as a means of extracting energy from coal waste piles, a high proportion of the resulting alkaline ash is used to neutralise acidic soil remaining at the site and allow their complete rehabilitation. The material is also widely used for preventing acid drainage from mined areas as it can self-harden to form an impermeable seal and expansion during hydration may actually be desirable (Schueck and others, 2001). These applications largely account for the impressively high recycle rate for the 13 Mt of FBC ash produced in the USA; at 94% compared to 38% for PCC fly ash (ACAA, 2011). Restoration of opencast mines and quarries is also the principal use for FBC ash in the EU, where it accounts for over 60% of the total production (not included in Figure 19).

An effective strategy to capitalise on the high residual lime content in the ash is to use it as a substitute in conventional applications of lime itself. The primary examples of this type of use are in

Table 7 Principal components of PCC fly ash and CFBC bed ash taken from boilers in Kentucky, USA (Rathbone and others, 2010)

Oxide, %	PCC fly ash	CFBC bed ash
Silica	12.77	52.75
Alumina	5.25	22.94
Iron oxide	3.15	14.92
Lime	48.23	2.67
SO_3	27.83	0.64

stabilisation of waste sludge and in 'liming' acidic soils to increase crop yields. In sludge stabilisation, the hydration of lime by water reduces fermentation and helps produce a solid material which can itself be used as a soil additive with the additional benefit of organic matter. CFBC ash has been found to be particularly suitable for this application, as the fine carbon content absorbs odours. Some research has also been conducted into the possibility of exploiting the residual lime by reusing the ash as a sorbent for SO_2 capture. This involves 'reactivating' the ash, usually with steam treatment, which hydrates the lime and increases porosity (Montagnaro and others, 2008). Researchers at the Turow CFBC plant have also introduced a mechanical activation step as a precursor to potential use as desulphurisation sorbent or road base material (Kobylecki and others, 2003).

4.8 Oxyfuel combustion

Oxyfuel combustion is one of three principal technologies proposed for the capture of carbon dioxide emissions from fossil fuel burning power plants. To circumvent the difficulty of capturing the relatively low concentrations of CO_2 (typically 20% by mass) found in flue gases, combustion air is replaced with a mixture of purified oxygen and recycled flue gas, effectively eliminating the nitrogen which makes up the major part of air. The resulting flue gas is almost entirely made up of CO_2 and water, of which the latter can be easily separated by condensation, allowing the pure CO_2 to be compressed for transport and sequestration. The energetic penalty of this process comes from the air separation units (ASU) required to produce pure oxygen and, to a lesser extent, the CO_2 compression and purification unit (CPU), which together are estimated to reduce coal plant efficiency by 9–11 percentage points (Jukkola and others, 2005; Hack and others, 2009 NETL, 2010). Nevertheless, oxyfuel is currently considered one of the most promising carbon capture technologies and a number of pilot plants are operational using both PCC and CFBC, with demonstration-scale units in advanced stages of planning. As the dominant technology in coal power, PCC has received significantly more attention, but it is clear that CFBC could offer some unique advantages when applied to oxyfuel.

In PCC oxyfuel, oxygen is normally diluted with recycled flue gas to concentrations which best mimic the combustion and heat transfer characteristics of air combustion, thus minimising changes to boiler design. For air-like combustion temperatures, higher than atmospheric concentrations of oxygen (31%) are required due to the high specific heat capacity and density of CO_2. On the other hand, the higher emissivities of the CO_2 and water molecules result in more efficient heat radiation, favouring the use of slightly lower combustion temperatures provided by oxygen concentrations of around 28% (Scheffknecht and others, 2011). Higher oxygen concentrations than air come with the benefit of reduced boiler sizes due to the reduced volume of gas flow, but further increases lead to high temperature combustion and greater risk of slagging. Furthermore, higher temperatures and reduced gas flow present a challenge for providing sufficient heat transfer duty in the boiler. In CO_2-rich conditions flame propagation is also slower, so a principal consideration in oxyfuel PCC is the redesign of burners to maintain flame stability and similarity to air-firing (Doosan Power Systems, 2013).

An important development for oxyfuel PCC was the 2008 start-up of a 30 MWth pilot at Vattenfall's Schwarze Pumpe power plant in Germany. Demonstrating a full capture chain with oxygen separation from air and CO_2 compression, this pilot has achieved over 93% CO_2 capture and is scheduled to operate for another five years (Stromberg, 2011). Since then, a number of pilot-scale projects have started up, including a 20 MWth unit at the CIUDEN oxyfuel research site in Spain, operational since 2011. The first example of an oxyfuel retrofit to an existing PC boiler was carried out at Callide power plant, Australia, resulting in a full capture chain 30 MWe pilot which has operated since December 2012. Other large pilots include the Doosan 40 MWth burner demonstration in Renfrew, UK, and the Babcock and Wilcox 30 MWth pilot at Alliance, Ohio. Essentially, oxyfuel PCC is now well studied and understood, and is awaiting financial and political support for a full-scale demonstration plant. Plans for a 300 MW Vattenfall plant at Jänschwalde have been scrapped due to a lack of legislation for onshore carbon storage in Germany. Other large-scale demonstrations that are still in planning include the 168 MW retrofit project, Futuregen 2, in the USA, the 426 MW White Rose project in the UK, and a 100 MW boiler conversion project at Young Dong Power Station in South Korea (Mills, 2012).

With its lower combustion temperatures and, most significantly, a means of taking heat from circulating solids which is independent of gas flow, CFBC technology is potentially ideal for running oxyfuel combustion at high oxygen concentrations and thus further reducing boiler size and fan power needed for flue gas recycling. This idea has been pursued by Alstom, who developed a design for an oxyfuel CFBC using 70% oxygen which takes up slightly more than half the volume and area of an air-fired boiler (*see* Figure 20) (Jukkola and others, 2005). The reduced gas flow means that the heat transfer from solids circulating through the external heat exchangers (EHE) is significantly increased to about 3.4 times greater than in an air-fired CFBC, while heat transfer in the furnace and convective pass is correspondingly much lower. To accommodate this demand on the EHEs, Alstom have implemented moving bed heat exchangers instead of the conventional bubbling fluidised beds, in which solids move under gravity and no fluidising air is used. The design has been constructed at a pilot scale of 3 MWth in Windsor, CT, which was successfully tested for 300 hours and with up to

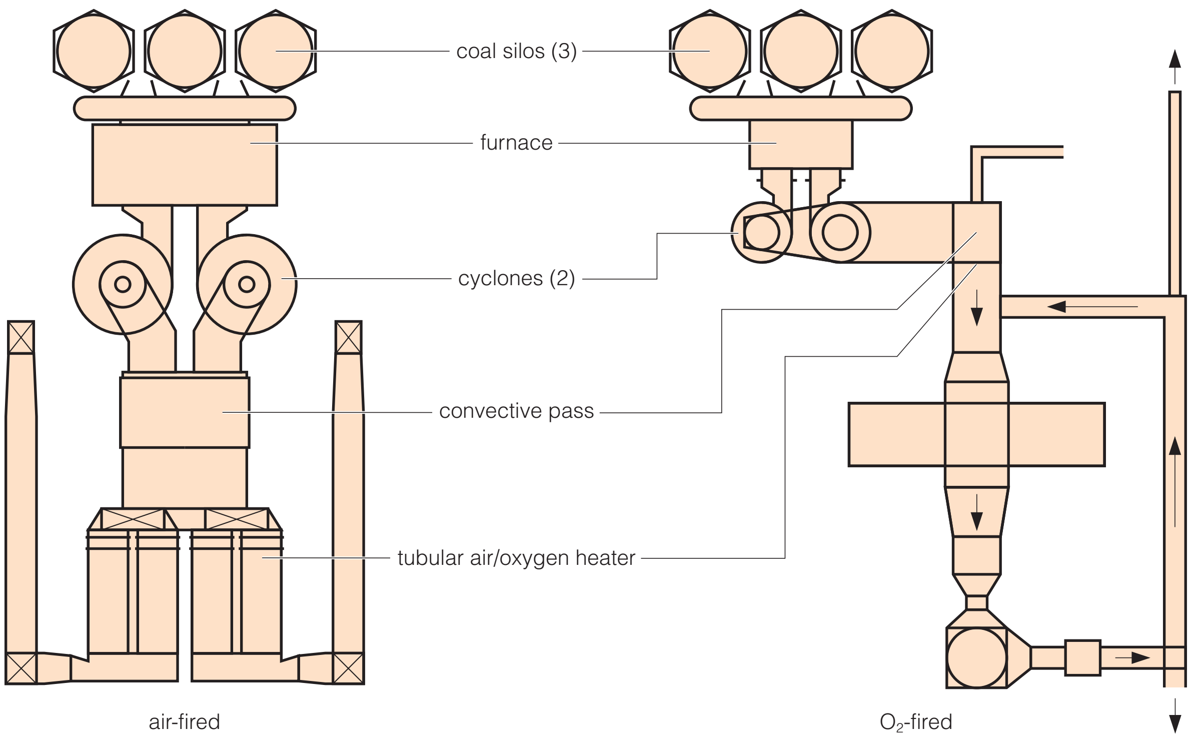

Figure 20 Plan views of 210 MWe air-fired and 70% oxygen-fired CFBC plants (Levasseur, 2009)

70% O_2 (Levasseur, 2009). However, Alstom have since abandoned their research into oxyfuel CFBC.

Foster Wheeler have sought to exploit another potential advantage of CFBC oxyfuel combustion by designing a boiler which can be easily switched between air and oxyfuel modes, known as Flexiburn technology (Hack and others, 2009). The control of temperature via the circulating bed material in CFBC should also permit relatively easy switching between the two firing modes without large changes in the bed temperature. However, maximising the output under both modes would preclude the benefit of reduced boiler size. Such flexible operation has been presented as a useful way of allowing higher energy output when demand is high, for use when air separation or CO_2 compression units are not operating, and as a contingency against uncertainty in carbon credits. As part of the CIUDEN project in Spain, a 30 MWth pilot version of the design operates using 24–28% oxygen, although the boiler rating is halved when under air-firing (Gomez and others, 2013). Operational since September 2011, initial results from this unit have demonstrated a smooth transition between both firing modes over around half an hour and reduced emissions which are discussed in the following section (Lupion and others, 2013). This research represents the first phase in an EU-sponsored programme to construct a 300 MW supercritical oxyfuel CFB boiler at the Compostilla power plant, which would also be based on the Flexiburn concept. An investment decision for this project is expected in 2013, with a view to commence operations in 2015. O2GEN is a closely-related EU research programme, also using Foster Wheeler for boiler design, which aims to develop a second generation of oxyfuel CFBC optimised for exclusively oxyfuel firing (Romeo, 2012). The research is directed at maximising the potential for reduced boiler size, with use of 40% O_2 seen as a realistic target, as well as reducing the energy penalty associated with air separation and CO_2 compression.

Further potential advantages to using CFBC for oxyfuel include the positive boiler pressures employed which, in contrast to slightly negative pressures in PC boilers, will reduce the ingress of air that contaminates the CO_2 stream and increases the energy demand of CPU (Wall and others, 2012). In addition, CFBC is able to use lower excess air than PCC due to the recirculation of unburnt material, which translates into a lower oxygen demand in oxyfuel firing. An excess of 1% oxygen is thought to be possible for oxyfuel CFBC, as opposed to 3% for PCC, reducing the energy consumption of the ASU by around 0.5% (Wall and others, 2012).

4.8.1 Oxyfuel emissions

NOx formation is reduced in oxyfuel combustion due in part to the absence of nitrogen gas which prevents thermal NOx formation and, more significantly, to the decomposition of NOx under reducing conditions as it is recycled through the boiler. Whilst the absence of thermal NOx is likely to have more of an impact on PCC emissions, the latter, more important, effect appears to take place both in the reducing atmospheres of a CFBC bed and a PCC flame. Reduced NOx has been observed at most oxyfuel PCC pilots, including Schwarze Pumpe, where NOx showed a reduction of 50% from air-firing, and primary NOx reduction measures such as air staging also appear to continue to provide a similar level of abatement under oxyfuel conditions (Kluger and others, 2011). In early trials at the CIUDEN CFBC pilot NOx was reduced from 300 to 100 mg/m^3 when going from air- to oxyfiring conditions (Lupion and others, 2013).

The effect of oxyfuel firing on SO_2 emissions is less well understood, but also of high importance, as the concentrating effect of recycling hot flue gases inevitably leads to elevated SO_2 levels in the boiler. A boiler environment rich in water and acid gases can lead to an increase in acid dew point by up to 30°C, exacerbating the risk of corrosion and potentially requiring the use of more resistant materials. On the other hand, the actual rate of conversion of sulphur to SO_2 is generally found to be lower in oxyfuel PCC; by up to 40% according to some studies (Wall and others, 2009; Scheffknecht and others, 2011). This is itself thought to be due to the concentrated levels of SO_2 in the furnace, which favour the sulphation of species in ash such as CaO and $CaCO_3$; in effect, mimicking to some extent the in situ desulphurisation of CFBC. However, it is likely that the exact fate of sulphur in oxyfuel firing depends to a great extent on coal type, particularly volatile matter, and combustion conditions.

In contrast to oxyfuel PCC, at the lower temperatures found in oxyfuel CFBC the sulphation enhancing effect of the SO_2 rich atmosphere is less significant. Instead, the high levels of CO_2 render the calcination of the limestone much less favourable, potentially altering the mechanism of desulphurisation which takes place in the bed. In these conditions, calcination is not significant below 870°C and in situ desulphurisation is instead thought to proceed via direct sulphation of the limestone. This mechanism has much slower kinetics than the sulphation of calcined lime, or ‘indirect’ sulphation, and as a result the desulphurisation process becomes much less efficient. This effect has been observed in results from the CIUDEN oxyfuel CFBC pilot, where desulphurisation efficiency was poor at temperatures below 870°C but can be restored to 98% at higher temperatures as calcination becomes favourable (*see* Figure 21). Conversely, air-firing at over 870°C is no longer optimum for calcination and poor desulphurisation efficiencies of around 80% were recorded (Gomez and others, 2013). There is also evidence that the indirect sulphation mechanism can be even more effective in oxyfuel conditions due to higher levels of SO_2 and water vapour, which aids the diffusion of reactants (Stewart, 2009). However, the ability to maintain CFBC at temperatures favourable to indirect sulphation will depend on fuel type and may not be possible at lower loadings.

The performance of a wet FGD unit is also likely to be influenced by the change in flue gas composition in oxyfuel combustion. A study has shown that the effect of high levels of CO_2 in flue gas on limestone dissolution depends strongly on pH. At pH greater than 5.4, there is a significant reduction in limestone dissolution in oxyfuel conditions, and the resulting increase in residual limestone particles in the absorber can actually improve desulphurisation performance by up to 3 percentage points (Hansen and others, 2011). Results from the FGD unit at the Schwarze Pumpe pilot show high rates of desulphurisation but no effect of CO_2 on rates of limestone dissolution, presumably because the unit operates at relatively low pH, at which little difference with air firing conditions is observed (Faber and others, 2011).

Elevated CO_2 concentrations also introduce the risk that CaO will carbonate in cooler sections of the boiler or convective pass and remain as surface deposits (Wang and others, 2008). Whilst possible in oxyfuel PCC where fly ash is calcium rich, this problem is likely to be far more important for oxyfuel CFBC, in which temperatures are lower and limestone is introduced to the boiler. Dedicated sootblowers may be required to address this problem (Wall and others, 2012).

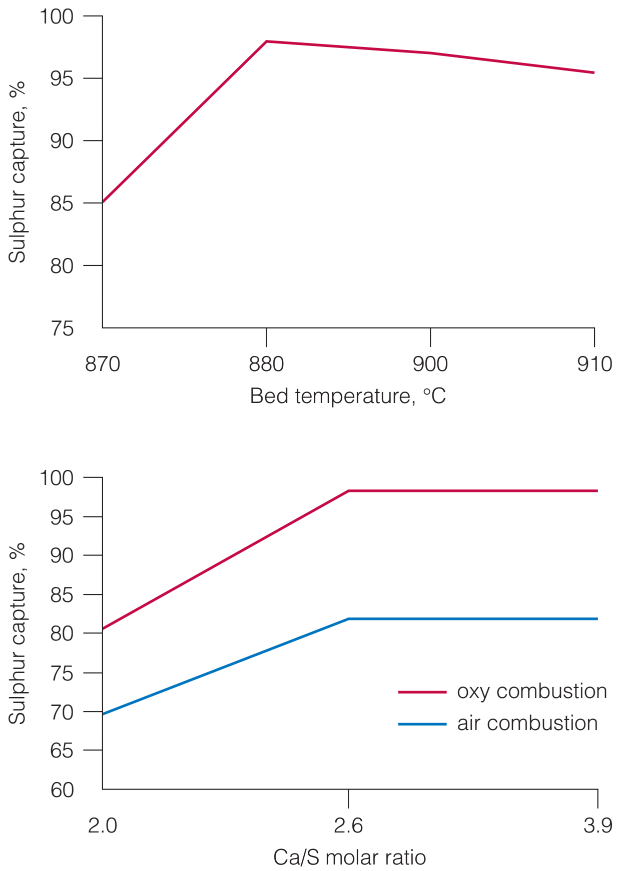

Figure 21 The effect of temperature and Ca/S ratio on SO_2 emissions at CIUDEN (Gomez and others, 2013)

5 Economic comparison of PCC and CFBC

As CFBC has emerged as a viable utility power generation technology, a number of power plant costing studies have attempted to compare the economics of plants using CFB and PC boilers. Accurately estimating power plant construction and operational costs has become increasingly challenging in recent years as more liberalised energy markets have reduced access to data and increased the volatility of costs. The investment required for a power plant can vary dramatically with region, with construction costs in OECD countries in particular having risen sharply in the past few years, partly mitigated by the global financial crisis. For a technology undergoing relatively rapid development such as large-scale and supercritical CFBC, there are also very few examples on which to base estimates. Lastly, cost estimates can be highly sensitive to the methodology and assumptions applied. For these reasons, figures obtained by separate studies should be compared with caution, but it is nevertheless informative to look at cost estimates for PCC and CFBC plant within individual studies and how these relative values have varied with time and region. This chapter will review cost comparison studies of the two technologies that have been performed in the last five years, as well as attempting to identify and quantify the principal economic differences present in the construction and running of each type of plant.

5.1 Power plant costing

Power plant costs are generally divided into capital costs associated with the construction of the plant and yearly operating and maintenance (O&M) costs, of which the cost of fuel, as the principal operational expenditure, is usually given separately. O&M costs are often divided into fixed costs, such as workers' salaries and maintenance and variable costs linked to plant capacity factor, such as sorbent purchase and waste disposal. Estimation of O&M costs can be based on assembled data from existing power plants or simulations of plants using modelling software such as Aspen Plus. This kind of software predicts the process behaviour of proposed plant designs based on physical relationships such as mass and energy balances. O&M costs excluding fuel are the smallest contributor to total plant cost, generally in the range 10–20% (IEA and others, 2010).

Fuel costs are easily estimated based on the coal prices at the time of the study, although it is obviously more difficult to take future variation into account, and none of the studies described in this chapter have attempted to do so. Coal prices can vary by a factor of ten, and depend strongly on region, coal quality, and whether the coal is imported or local (IEA and others, 2010). As a proportion of total plant expenditure, fuel usually represents 30–40% for new coal plants.

Capital costs are usually based on data from equipment vendors, contractors and utility companies, potentially in conjunction with plant specifications first obtained from modelling software. There is an inherently large degree of variability in construction costs, as a contractor's price will reflect the relative desirability of securing a contract as well as the current competition. Plant specifications specific to the customer, such as levels of reliability and environmental impact, will also have a significant effect. Construction costs are the largest expense incurred in coal plants and can amount to 50% or more of total costs over the plant lifetime.

There are a number of ways to express capital costs, potentially creating difficulties in the comparison of separate economic assessments. The total cost is typically divided into all expenditure associated with plant construction, known as engineering, procurement, and construction (EPC), contingency costs related to the relative risk or novelty of a project, and financing costs incurred over the construction period. NETL also uses a bare erected cost (BEC) which comprises the EPC without the cost of services provided by the contractor. The summed total plant cost is frequently expressed as a total overnight cost (TOC) in the currency at the start of the construction period, but this does not take into account escalation or financing of expenditure during the construction period. This value is probably the most widely used and useful measure for comparing plant capital costs, although its scope, such as whether it includes associated plant infrastructure, can vary and may not always be clear (NETL, 2011b).

The cost of electricity (COE), or busbar cost, is an estimation of the cost of generating a unit of energy, taking into account operating costs as well as payment of capital and financing costs distributed over the lifetime of the plant. Converting capital costs into a yearly expense of the form of an operating cost can be complex and relies on a number of estimates or assumptions on interest rates, return on equity for investors, taxation, and depreciation. These factors are incorporated into a discount rate, which determines the present value of future income and costs. The discount rate can be extremely influential on the estimated COE, and estimates at various rates are sometimes given to allow for error in the predicted rate. As a first approximation, the discount rate is used to calculate a single capital charge rate, which determines the proportion of the capital cost to be repaid each year. For a more accurate estimate, a complete discounted cash flow analysis can be carried out using a financial model. These models can be used to calculate either a COE, representing the cost of electricity in the first year of operation in currency of that year, and thereafter increasing with inflation, or a levelised cost of electricity (LCOE) which is constant for each year of the plant's operation and usually expressed in the nominal currency of that year (NETL, 2011b; IEA and others, 2010). LCOE is widely used to compare the costs of generating electricity with different technologies.

Both the variable operating costs and the yearly energy output of a plant need to be weighted by the plant capacity factor, or the percentage of the year for which the plant is operational. As base load plants, this can be up to 80% for both PCC and CFBC.

5.2 Review of economic studies

5.2.1 Subcritical CFBC

In 2007, a financial comparison of subcritical PCC, subcritical CFBC, and IGCC technologies was carried out by Basin Electric Power Cooperative for the construction of a new 368 MW plant at Dry Fork, using PRB subbituminous coal (Jenkins and Brown, 2007). The proposed CFBC plant includes SNCR for NOx abatement and, as is common for large CFB boilers in the USA, specifies for spray dryer FGD in addition to in situ desulphurisation to achieve acceptable levels of SO_2 emissions. The PCC plant employs both spray dryer FGD and SCR technology. Storage for the, assumed unsaleable, CFBC ash produced by in situ FGD is also accounted for. The financial analysis was based on a 42-year operating lifetime for both plants, and a 6% interest rate. The overnight capital cost of the CFBC plant is estimated to be 4% greater than that of the PCC plant, whilst first-year operating costs are ~20% greater. The lack of need for the expensive wet FGD installations typically used in PCC plants is generally seen as a principal cost saving advantage for CFBC, so it is unsurprising that this analysis favours PCC technology, despite the greater operating cost incurred in using lime sorbent for the PCC plant. The relatively high costs per kW obtained for both plants are difficult to compare with those of the larger installations in other studies, which benefit greatly from economies of scale (*see* Table 8).

Florida Power and Light also commissioned an economic comparison of subcritical CFBC and both sub- and supercritical PCC in 2007 (Black and Veatch, 2007). Based on achieving a total plant output of 2000 MW, a configuration of eight 250 MW CFB boilers was considered, as opposed to four subcritical or two supercritical PCC units. A fuel mix of local and imported bituminous coal and 20% petcoke was used for each plant, with wet FGD and SCR for PCC plants and in situ FGD and SNCR for the CFBC units. Figures were based on accumulated data from industrial sources. The study

Table 8 Cost comparison studies for subcritical CFB and PCC (Black and Veatch, 2007; Jenkins and Brown, 2007; IEA and others, 2010; Loyd and Craigie, 2011; Zhao, 2008)

	Dry Fork, 2006, $	Black and Veatch, 2007, 2012$	Harvard, 2008, Yuan	IEA, 2010 $	Parsons Brinckerhoff, 2011, €
CFBC capital cost, per kW	1404	2925	4566	3485	1128
PCC capital cost, per kW	1350	3055	3762	3485	1616
CFBC variable O&M, per MWh	4.0	4.44	–	8.86	–
PCC variable O&M, per MWh	2.6	2.94	–	8.53	–

indicates a 5% increase in CFBC capital cost per kW over subcritical PCC and a 17% increase with respect to the supercritical plant. The operating and maintenance costs for CFBC, fixed and variable combined, were also 15% higher.

A 2008 study by Harvard University compared the costs of a variety of coal plant technologies in China (Zhao, 2008). The CFB boiler considered is a 600 MW subcritical unit, with a considerably lower efficiency (37.6%) than all other technologies considered. A 16% higher capital cost is quoted for CFBC over supercritical PCC, or 21% higher than subcritical PCC, and a correspondingly high COE is also estimated.

The Projected Costs of Generating Electricity produced by the IEA and NEA in 2010 estimates location specific costs of power plants of all types expected to be commissioned before 2015 (IEA and NEA, 2010). Of 48 coal plants looked at in this study, only four are CFBC, three of which are 300 MW subcritical lignite-burning units in the Czech Republic, with and without biomass cofiring or carbon capture. It is informative to compare the costing of the base case CFBC unit with a lignite-burning PCC unit in the same region which has a capacity of 600 MW. Interestingly, the overnight capital costs for these two units are identical at 3485 $/kW, although fuel and O&M costs for the CFBC plant are slightly higher, presumably owing in part to the slightly lower efficiency ascribed to it. One 300 MW supercritical CFBC unit is considered by this report, for which the capital cost is considerably lower than the subcritical units, but as the only plant listed for the Slovak Republic it is difficult to meaningfully compare this figure.

An EU-based study by Parsons Brinckerhoff in 2011 aimed to identify the most economic way of continuing operation at the large number of coal plants that would otherwise be forced to close in 2015 under the IED (Loyd and Craigie, 2011). A number of options were considered, including simply upgrading the scrubbing system, but the installation of new subcritical CFB or PC boilers, whilst keeping the existing steam turbines are the most relevant options to this report. As the most polluting of the plants to be closed are generally lignite-fired, four 500 MW units burning this fuel were considered. Curiously, this study discounts the possibility of supercritical CFBC based on the technology not yet having attained 500 MW size, despite subcritical CFB boilers being considerably further from this target. Nevertheless, the CFBC units are estimated to be cheaper (over 4%) than the PCC equivalent in this case. The study concludes that new CFB boilers are the best upgrade solution for plants currently ‘opted-out’ of the IED, also taking into account the extended lifetime granted with respect to merely installing a new scrubbing system on existing boilers.

5.2.2 Supercritical CFBC

Supercritical (SC) CFBC is still quite new to the market, and with only one plant currently operating commercially, there is little economic data accessible on this technology. It is therefore unsurprising that most of the economic studies considering SC CFBC to date have been performed by Foster Wheeler, the manufacturers of the supercritical unit at Lagisza. As early as 2006, shortly before construction commenced at Lagisza, a conceptual study was carried out by Foster Wheeler on the economics of USC CFBC, with steam conditions of 31 MPa and 593°C (Fan and others, 2006). Using the company's own SOAPP plant evaluation software and Aspen simulations they estimated the cost of 400 and 800 MW units and the associated cost of electricity, based on a plant lifetime of 20 years. For the purposes of comparing the two technologies, plant specifications were chosen to match those of a DOE economic evaluation of a 400 MW USC PCC unit in 1999. The total plant costs for the 400 MW CFBC unit were calculated at 1551 $/kW compared to 1170 $/kW for the earlier PCC study, or 1350 $/kW for a 2006 update of a similar, 550 MW PCC unit. The simulated 800 MW CFBC unit is more competitive with the PCC unit, at a capital cost of 1244 $/kW.

Despite this early study predicting a slight economic and efficiency advantage to be retained by PCC at supercritical conditions, both technologies were offered by Foster Wheeler to the Polish utility Poludniowy Koncern Energetycyny for the Lagisza project. According to the boiler manufacturer, CFBC was chosen by the utility on the basis of lower overall cost derived from lack of FGD and SCR systems, slightly higher efficiency (0.3 percentage points), and fuel flexibility which permits use of biomass and other opportunity fuels (Venäläinen and Psik, 2004). The details of the economic analyses by either company demonstrating the economic advantage gained by CFBC are not available.

This advantageous position of CFBC is further reinforced by Foster Wheeler in a more recent comparison of the two boiler types at supercritical conditions, incorporating experience gained from the operation of the Lagisza plant, and with a view to marketing their supercritical CFBC in Asia and other markets (Utt and Giglio, 2012b). This report assumes basically equivalent capital costs for each boiler type at 660 MW size, with the PCC unit ending up 7% more expensive per kW simply due to the wet FGD system it requires.

An extensive comparison of 550 MW SC CFBC, SC PCC and USC PCC units was published in 2011 by the NETL as part of its assessment of low-rank coal firing technologies (NETL, 2011a). Aspen Plus was used to simulate each unit, with the resulting indications of boiler and associated equipment size incorporated in the capital cost estimations based on industry data and scaled estimates from existing projects. Costing for both lignite and subbituminous coal, with and without carbon capture, was performed. This model predicts a slight gain in thermal efficiency for SC CFBC over SC PCC, associated with the lower flue gas exit temperatures achievable when acidic gases have been scrubbed in situ and corrosion from condensation of acidic species is therefore not a concern. The estimations of capital costs for supercritical PCC and CFBC are in broad agreement with Foster Wheeler's studies. Although the cost of the CFB boiler itself represents a considerable additional expense (~$100,000) over a PC boiler, it is more than compensated for by the saving on flue gas clean-up equipment (~$135,000), resulting in a lower bare erected cost for CFBC. This effect is more pronounced for the lignite-fuelled cases, for which greater scale-up is necessary for a PC boiler than a CFB boiler, reducing the extra cost of CFBC, and the cost of flue gas clean-up is also raised. However, this study also adds a 15% process contingency expense to CFBC on the grounds that a 550 MW SC CFB boiler would be first of a kind and an untested technology. This factor is largely responsible for a greater final capital cost for CFBC, and a corresponding ~5% higher LCOE for the newer technology. O&M costs are slightly higher for CFBC for the case using subbituminous coal, and slightly lower when fuelled with lignite (*see* Table 9).

The CFBC-favouring effect of using lower quality fuels is also highlighted by a Russian study comparing the costs of 330 MW SC CFBC and PCC units for retrofit and new power plants (Ryabov, 2010). Based on data from suppliers and the two SC CFBC units under construction in Russia, capital costs for the CFBC unit were estimated to be greater for three Russian coal types, although only marginally (~3%) for the low heating value Ekibastuzskiy coal. Further estimates were made to take into account the potential increase in flue gas cleaning costs if Russian emission standards become

Table 9 Breakdown of NETL baseline costs for CFBC and PCC plants (NETL, 2011a)				
Costs	CFBC		PCC	
	Subbituminous	Lignite	Subbituminous	Lignite
Boiler, $/kW	678	733	507	594
FGD, $/kW	0	0	247	261
Total Bare erected cost, $/kW	1480	1563	1530	1663
Process contingencies, $/kW	210	221	204	220
Project contingencies, $/kW	102	110	0	0
Total plant cost, $/kW	1932	2042	1879	2041
Total overnight cost, $/kW	2357	2490	2293	2489
Variable O&M, $/MWh	5.3	6.1	5.1	6.1
Fixed O&M, $/MWh	9.1	9.5	9.0	9.7
LCOE, $/MWh	78.0	81.9	73.3	78.8

more stringent. In this case, CFBC becomes more economical for two of the coals considered, with an 11% saving for Ekibastuzskiy coal.

It is clear that the move to supercritical conditions has allowed CFBC to gain considerable economic ground on PCC, having enabled larger units with efficiencies equivalent to those of PCC, and therefore the benefits of economies of scale and lower fuel costs. As the boiler price per kW has fallen, the effect of the saving on flue gas scrubbing equipment has become more significant, and some studies suggest that the construction cost of a CFBC unit may now even be less than that of a PCC unit. On the other hand, the relative maturity of PC boiler technology and FGD technology makes it more difficult for significant economies to be made in their construction.

5.3 Breakdown of costs for PCC and CFBC

5.3.1 Boiler cost

The principal additional cost of a CFBC unit over a PCC unit of equivalent capacity is that of the boiler itself. The more complex CFB boiler design incorporates large solid separators and fluidised bed heat exchangers which add to the quantity of construction material required. The study by Ryabov estimates that 550 to 660 tonnes of extra refractory are needed for a CFB boiler, as it is used for the cyclones and lower parts of the furnace, as well as 12% more metal associated with withstanding the higher pressures in a CFB boiler (Ryabov, 2010). A 14% higher boiler cost is estimated to result from these additional construction costs, decreasing for furnaces using lignite. The NETL baseline study calculates a 34% greater cost for a supercritical CFB boiler fuelled with subbituminous coal, and only 23% greater for lignite (bare erected costs). Although both boiler types require scaling up to accommodate the greater flue gas flow and fuel feed rate for lignite, the need to counter its increased tendency for slagging can result in much larger PC boilers than necessary for CFBC.

There is potential for reducing the cost of CFB boilers by simplifying the design and reducing the amount of steel and refractory required. In this respect, Foster Wheeler's compact design represents a significant advance, as by incorporating the cyclones and FBHE with the furnace the amount of refractory and metal used is reduced (Goidich and Hyppänen, 2001). Using flat waterwall panels to surround the cyclones is also cheaper than the curved membranes needed for conventional round cyclones. Chinese manufacturers are also developing a similar, square-shaped cyclone (Yang and others, 2012a). At supercritical conditions, the use of vertical once-through technology in CFBC also mitigates the additional cost over PCC, as expensive rifled tubing is not usually needed.

5.3.2 Fuel costs

The superior fuel flexibility of CFB boilers could allow savings on fuel costs for plants which are in a position to switch between alternative coal supplies. In particular, plants which employ a blend of imported coal and cheaper local coal should be able to maximise the proportion of cheaper coal used if import prices rise. Several Foster Wheeler studies have attempted to quantify this degree of economic flexibility in order to highlight the advantages of their 600 MW CFBC technology for power generation in Asia in particular. A potential annual saving of over $46 million is estimated to be associated with the capability of firing 100% Indian coal in CFBC, as opposed to a maximum of 70% in PCC where the remainder is imported South African coal. Similarly, for a plant using imported coal alone, the ability to switch between exclusive use of South African coal (100 $/t) and cheaper Indonesian coal (75 $/t) is estimated as representing a $14 million annual saving for the plant (Utt and Giglio, 2012a,b,c).

Coals with low volatile content such as anthracite can be more difficult to ignite in PC furnaces and can require larger quantities of auxiliary fuel such as natural gas or fuel oil to operate at low loadings. Longer residence times in CFBC make this less of a problem, and a saving on these expensive fuels may be possible. On the other hand, start-up from cold of a CFB boiler with any coal type can require more supplementary fuel than a PC boiler as the whole bed mass needs to be brought to temperature. This has been a particular concern in China, where some 300 MW CFB boilers have consumed up to 900 tonnes of oil per year from ignitions (Li and others, 2010b).

Coal for PC boilers has to be finely crushed in mills for it to burn quickly enough in the short furnace residence time. Dispensing with coal mills should represent a saving for CFBC, for which a much wider range of fuel particle size can be used. Surprisingly, the NETL cost study of the two technologies estimates almost equivalent costs for coal crushing and drying equipment (NETL, 2011a).

5.3.3 Emissions control costs

SO_2

The wet FGD units mostly commonly used on large PC boilers carry with them a high capital cost of 400–500 $/kW, or more than 10% of the total plant cost (Staudt and M J Bradley and Associates, 2011; Cichanowicz, 2010). Retrofitting a unit can lead to even greater expense, whilst application to larger units allows economies of scale to be made. On the other hand, operating costs of wet FGD are amongst the lowest of available scrubbers, and high SO_2 removal rates can be achieved. The relatively cheap limestone sorbent allows variable operating costs of around 1.8 $/MWh, depending on the sulphur content of the coal, and fixed costs of roughly 1 $/MWh (Sargent and Lundy, 2010a). Variable costs are highly dependent on whether a market can be found for gypsum by-product or whether it needs to be disposed of as waste. A plant may also be able to offset the operating cost of a wet FGD by using cheaper, high sulphur coal.

Semi-dry FGD systems require smaller-scale equipment and the capital cost is correspondingly around 60–80% that of a wet FGD unit (Sargent and Lundy, 2010a,b; Cichanowicz, 2010). However, the most commonly employed spray dryer absorbers use lime sorbent, which can be up to six times more expensive than limestone, and require a higher Ca/S ratio. Although this is partially offset by the much lower molecular weight of lime, variable operating costs are still roughly 1.5 times that of wet FGD, whilst fixed costs are similar. Consequently, semi-dry FGD becomes more favourable for smaller units and those using low sulphur coal.

Desulphurisation can be carried out in a CFB boiler by adding limestone directly to the furnace, dispensing with the need for wet FGD. However, the capture of SO_2 by this process is less efficient than wet FGD, and up to three times more limestone can be required to achieve the same rates of removal. Despite this, a comparative study at Shandong Huasheng power plant in China found that the operational cost of a PCC unit with FGD was 2.5 times more than a CFBC unit after the in situ desulphurisation was optimised with respect to limestone size and reactivity (Yue and others, 2010). The relatively low cost of limestone (15–20 $/t) means that the greater Ca/S ratio required for CFBC may not make a significant impact on O&M costs relative to the avoided fixed costs for labour and maintenance of a separate FGD unit. The NETL baseline comparison of low-rank coal power technologies includes the comparison of a spray dryer unit on a model 550 MW PC boiler with in situ desulphurisation in an equivalent CFBC unit (NETL, 2011a). Interestingly, even with the cost of lime more than three times that of limestone, the consumption of the more expensive sorbent is so much lower as to make it over 20% cheaper per MWh. The fixed costs of the process are not provided, but total fixed costs for CFBC and PCC units are equivalent.

In some circumstances, CFB boilers may require further downstream FGD in addition to limestone in the furnace to meet emissions standards, in which cases a spray dryer or flash dryer absorber is usually employed. Although the presence of unreacted lime in the flue gases will permit some saving to be made on sorbent consumption, the extra capital cost incurred significantly impinges on the saving made by avoiding a wet FGD installation.

NOx

The cost of NOx reduction measures will depend to a great extent on site-specific factors such as unit size, availability, fuel type, and unabated NOx levels. Low NOx burners for PCC are estimated to cost in the range of 20–30 $/kW to install, with the addition of overfire air increasing this cost by roughly 50% (Nguyen and others, 2008).

In regions where limits to NOx emissions are set at 200 mg/m^3 or lower, SCR is usually required for large PC boilers in addition to primary measures, whilst SNCR has proven sufficient for utility-scale CFBC due to lower initial NOx levels and enhanced SNCR performance. The expensive catalyst material and separate reactor needed for SCR result in a capital cost in the range of 200–350 $/kW, or 7–10 times the cost of installing SNCR, and therefore represents a potentially considerable saving for a CFB boiler (Cichanowicz, 2010; Nguyen and others, 2008). Although SNCR makes less efficient use of the ammonia or urea reagent than SCR, NETL models of CFBC and PCC 550 MW boilers using the respective abatement technologies estimate that the low initial NOx levels in CFBC would result in equivalent reagent consumption by both (0.22 $/MWh) (NETL, 2011a). In addition to the operating cost associated with the reagent, SCR requires relatively small quantities of replacement catalyst material. Once the most significant of the two costs, the cost of catalyst has fallen over recent years but can still amount to 70% of the reagent cost, making the operation of an SCR unit generally more costly than SNCR (Cichanowicz, 2010). Fixed costs for both technologies contribute much less than the variable costs of reagent and catalyst.

However, as boiler sizes increase and stricter NOx limits are imposed, CFBC units may also be obliged to adopt SCR as SNCR reaches the limits of its capabilities. The 550 MW CFB boilers under construction at Samcheok in South Korea are to be fitted with SCR in order to meet NOx limits of 100 mg/m^3 (Jäntti and others, 2012). Recently introduced similar limits in China may also result in application of the technology to CFBC there. On the other hand, SNCR technology is steadily improving with increased understanding of reagent mixing with flue gases and optimum use of the temperature window, and is beginning to be used on PCC units larger than 200 MW.

5.3.4 Solid waste recycle value and disposal costs

Disposal of fly ash and bottom ash from coal boilers can either represent a substantial cost or a source of revenue if they can be sold as useful materials. As discussed in the previous chapter, it can be difficult for CFBC ash to break into established markets for PCC ash, particularly when material specifications have been set, as in the construction industry. Recycling fly ash for use in concrete is the most profitable means of disposing of the material, representing a value of 45–65 $/t for the plant (Goss, 2013) (*see* Table 10). Although by far the major application for recycled PCC fly ash, only 20% of the total output in the USA in 2011 was used for this purpose (ACAA, 2011). The high lime and sulphur content of CFBC ash puts it outside the specified limits for use in concrete, and it is unlikely to be able to capture a portion of the market in the near future, despite ongoing research efforts to prove its suitability.

The most profitable applications of coal ash currently open to CFBC ash are use as a self-cementing material for grouting in oil fields or mine reclamation, or for stabilising waste sludge. Both these recycle routes are estimated to have a value of 25–35 $/t (Goss, 2013). Self-cementitious properties also render CFBC ash useful for use in soil stabilisation, which carries a value of 20–30 $/t. Other lower grade construction applications include use as structural fill and road base (6–12 $/t). However, by far the most common use for CFBC ash is in reclamation of surface mines or coal waste piles which, whilst an effective and practical means of disposing of the material, represents no real value for the plant. The widespread use of CFBC ash for this purpose, particularly in the USA, may have impeded the development of other markets for the material.

A general excess of supply for these recycle applications in regions of high coal usage such as the USA and China means that the majority is still disposed of in landfills and settling ponds without reuse. Costs of disposal are highly variable and depend on a number of factors including the distance to the disposal site and means of transportation. If the ash can be mixed with water and piped, cost of disposal can be in the range 3–5 $/t, or as much as 20–40 $/t if large volumes and long distances are involved (ACAA, 2013). Permits for new disposal sites can also increase costs. A fundamental drawback with CFBC ash is that the limestone added to the furnace adds significantly to the quantity of ash produced, potentially comprising up to half the total weight. Conversely, in PCC, proportionally less limestone is added to the wet FGD unit and the by-product of the process is entirely separate from the coal ash. If forced oxidation wet FGD is used, relatively saleable gypsum is produced which is widely used in the production of dry wallboard and, to a lesser extent, agriculture and concrete production. FGD gypsum can be sold at up to 10 $/t in the USA, although in some areas the wallboard market has become saturated. The European market for this product, on the other hand, is considerably more limited (EPRI, 2008; Roskill, 2009).

The NETL 2011 study on low-rank coal plants puts the cost of ash disposal at 14.77 $/t and does not incorporate estimates for possible fly and bottom ash sales (no gypsum is produced as semi-dry FGD is used for the PCC case) (NETL, 2011a). The subbituminous fuelled CFB boiler is estimated to produce 75% more ash than the equivalent PC boiler, primarily as a result of the 503 tonnes of limestone added per day. Disposal of this additional ash results in a significant operating cost increase from 0.94 $/MWh to 1.43 $/MWh. It should be noted that in a PCC plant using wet desulphurisation, this differential would be slightly larger, as the PCC ash in this study will include the 114 tonnes of lime added to the flue gases in the FGD spray dryer.

Table 10 Price ranges for coal ash recycle applications in the USA (Goss, 2013)

Application	Value, $/t
Portland cement substitute	45–65
Self-cementing ash for oilfield grouting and waste stabilisation	25–35
Self-cementing ash for soil stabilisation	20–30
Road base	6–12
Flowable fill	2+

5.4 Biomass cofiring costs

Some of the most significant costs associated with cofiring biomass are for auxiliary equipment required for storage and handling of the large volumes of fuel involved, which will be largely independent of the type of coal plant. Other costs will strongly depend on whether a retrofit or new build case is considered. A PC boiler can be retrofitted for low cofiring ratios with well-suited fuels such as wood pellets, without major changes to existing equipment, but firing over 15% biomass is likely to necessitate significant capital expenditure on specialised mills and burners. CFB boilers, on the other hand, are able to cofire biomass at relatively high ratios with minimal design alterations. This is reflected in an Austrian study on the cost of retrofitting 100 MW boilers of both types for biomass cofiring which estimates a three times greater capital expense per kW for PCC (Obernberger, 2003). However, new build PCC plants are likely to be more competitive, particularly as experience with cofiring in PC boilers increases and the necessary specialised equipment is developed.

5.5 Oxyfuel combustion costs

The principal additional capital costs of any oxyfuel combustion unit are that of the air separation unit (ASU) for production of oxygen, and the CPU unit for compression and purification of CO_2 in the flue gases, which are independent of the boiler technology used. A NETL study carried out in 2010 estimates the cost of an ASU at roughly 600 $/kW and CPU at 200 $/kW for 550 MW plants, whilst Alstom estimates from 2005 put the combined units at 37% of the total cost of a 200 MW unit (NETL, 2010; Jukkola and others, 2005). On the other hand, there is potential for the operating cost of both these units to be reduced in CFBC, assuming that both boiler technologies can achieve the same efficiency. Lower excess air required for CFBC equates to a lower oxygen demand per kW, and therefore less demand on the ASU, whilst higher boiler pressures should reduce air ingress and provide a purer gas stream for the CO_2 compression stage.

Savings on the cost of boilers and associated auxiliaries may be possible in oxyfuel combustion, as at oxygen concentrations higher than that of air a smaller boiler can be used to accommodate the

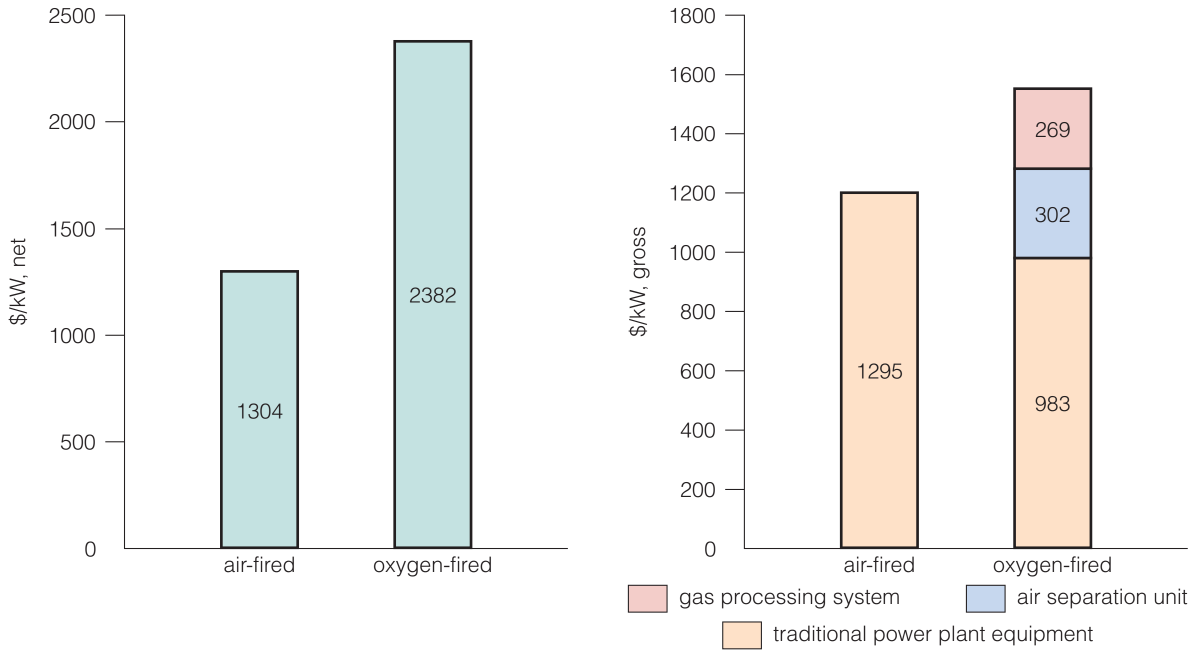

Figure 22 Comparison of estimated total plant investment costs for Alstom's 210 MW oxyfuel CFB boiler design and an air-fired CFB boiler of the same gross output (Jukkola and others, 2005)

reduced gas flow. As CFBC operates at lower temperatures and can make use of circulating solids rather than hot gases for heat transfer duty, there is a greater potential than PCC for using high oxygen concentrations and smaller boilers in oxyfuel firing. This is highlighted by a 2005 study from Alstom, which considers an oxyfuel CFB boiler using 70% oxygen and with a net output of 138 MW (210 MW gross) (Jukkola and others, 2005). The boiler required for this model is estimated to be half the size of an air-fired unit of the same gross output, and correspondingly 20% cheaper (see Figure 22).

In 2010, NETL produced a detailed cost analysis of oxyfuel firing of low rank coals in both PC and CFB boilers to complement the costing of air-fired units detailed above (NETL, 2010). As for the conventional combustion study, 550 MW supercritical (both PCC and CFBC) and ultra-supercritical (PCC only) units were modelled using Aspen Plus, for cases using both subbituminous and lignite fuel. As the operation of oxyfuel auxiliary equipment draws a significant load, the gross power output of each unit was correspondingly raised to give the required net power rating. Significantly, the oxyfuel CFBC units were considered with only downstream FGD in the form of a flash dryer absorber and no limestone injection to the furnace, probably due to doubts over the capability of in situ desulphurisation under oxyfuel conditions. As in the air-fired study, spray dryer absorbers were applied to the PCC units for reasons of water scarcity combined with the benefit of producing hotter flue gases for recycling to the boiler than wet FGD. No NOx control technologies were considered due to the inherently low levels produced by oxyfuel combustion.

In this study, total plant costs comprise over 70% of the LCOE in all cases and so are by far the most important point of comparison between the cases considered. The appearance of two separate figures for the capital cost of oxyfuel CFBC introduces some uncertainty, but for the purposes of this review the larger figure of 3491 $/kW will be considered, assuming the disparity accounts for the absence of CPU in the data presented for the oxyfuel CFBC case. With this figure, the total plant cost of oxyfuel CFBC is 13% greater than oxyfuel PCC, representing a widening of the price gap between the two technologies upon moving from air-firing to oxyfuel due to a greater increase in the cost of CFBC (*see* Table 11). The study links this added cost to the greater contingency costs associated with untried CFBC, although in the presented data the more significant factors are disproportionate increases in the costs of coal and sorbent preparation, and feedwater. These factors negate the savings made on boiler cost in the oxyfuel CFBC case, which shows less than half as much percentage increase over the air-fired case as the oxyfuel PC boiler.

Another study performed by Alstom, in conjuction with EDF and the University of Compiègne (Jaud, 2009), compared the cost of oxyfuel CFBC and PCC at the 600 MW scale. Using a 70% oxygen design for the CFBC, the cost of electricity was calculated to be 10% cheaper than a standard oxyfuel PCC.

Foster Wheeler's Flexiburn oxyfuel CFBC design was cost evaluated in 2009 in conjunction with

Table 11 NETL cost estimates for oxyfuel PCC and CFBC using low-rank coals (NETL, 2010)

	Oxyfuel PCC		Oxyfuel CFBC	
	Subbituminous	Lignite	Subbituminous	Lignite
Boiler, $/kW	1155	1177	1312	1480
Total BEC, $/kW	2439	2495	2678	2924
Contingencies, $/kW	422	431	416	475
Total plant cost, $/kW	3093	3163	3491	3821
LCOE, $/MWh	99.8	106.0	110.7	124.0

Vattenfall (Simonsson and others, 2009). A 500 MW gross output (381 MW net) oxyfuel unit based on the supercritical boiler at Lagisza was considered and calculated to require 2952 €/kW of capital investment. Despite using a more conventional oxygen concentration of less than 30%, the 82% cost increase over air-fired CFBC shows good agreement with the Alstom study for a 70% oxygen boiler, possibly due to additional economies of scaleos.

5.5.1 Oxyfuel emissions costs

Given that considerable cost savings in CFBC are derived from its different methods of flue gas treatment, any changes to these under oxyfuel conditions must be accounted for. Of some significance is the reduction in NOx emissions in oxyfuel firing, which obviates the need for the expensive SCR unit normally required in air-fired PCC and removes this element of saving for CFBC.

SO_2 emissions may be reduced in oxyfuel PCC but a wet FGD unit is still likely to be required in most cases. On the other hand, there is some uncertainty over the capabilities of in situ desulphurisation with limestone when used with oxyfuel CFBC, as it requires relatively high bed temperatures to achieve typical air-fired efficiencies. If downstream FGD is required in conjunction with or instead of furnace desulphurisation, a significant cost penalty would be incurred for oxyfuel CFBC which could restrict its use to low sulphur coals. However, recent results from the CIUDEN oxyfuel CFBC pilot suggests that high SO_2 removal rates are achievable in oxyfuel firing if the bed temperature is kept to at least 880°C (Gomez and others, 2013). Further research will be required before the feasibility of in situ desulphurisation under oxyfuel conditions can be conclusively assessed.

6 Conclusions

Developments in CFBC technology over the last decade have led to increases in boiler capacity, efficiency, and reliability which have allowed CFB boilers to benefit from economies of scale and provide a viable alternative to PCC for utility power generation. In particular, the adoption of supercritical steam conditions and high efficiency operation of a 460 MW CFBC unit in Poland has proved a crucial step in expanding the capabilities of CFBC well beyond its traditional role for small-scale generation from niche fuels. In China, utility CFBC even at subcritical conditions has managed to capture a significant share of the country's rapidly growing coal capacity, and the recent commissioning of the world's largest supercritical CFBC unit may mark the beginning of similar growth at this scale. Elsewhere, construction of a multiple unit 4400 MW CFBC plant in South Korea is further demonstration that this technology may be in the process of acquiring a more prominent share of global coal power. However, the suitability of CFBC for a utility project remains highly dependent on site-specific factors such as type and consistency of fuel supply, local emissions standards, potential for cofiring, and options for ash disposal. Furthermore, the potential advantages and drawbacks of CFBC have undergone some evolution in the last ten years as a result of developments in the technology and the changing political and economic landscape of coal power in general. The complexity of this situation is most clearly demonstrated by the wide variation in motivating factors behind recent CFBC projects. This report has investigated these factors and reviewed the available literature on the technical and economic distinctions between CFBC and PCC, with a view to clarifying the capabilities each technology is currently able to offer in the utility power sector.

Since its early development, CFBC has filled a role of offering superior fuel flexibility, both in terms of tolerance to variation and ability to burn a wide range of fuels, and reduced emissions of SOx and NOx. Of these two established benefits, fuel flexibility has come to the fore in recent years, as increasingly deregulated markets have encouraged utilities to seek cheaper fuel sources and the ability to easily change supply source has become increasingly attractive. In addition, development of coal power in India, China, and South Korea has necessitated the exploitation of poorer quality coal reserves such as high ash bituminous and anthracite which can create problems for standard PC boilers. In Poland, fuel flexibility has also been an important factor in adoption of CFBC as it provides a high level of boiler tolerance to variable coal sourced from several mines. In the USA, the option of cofiring petcoke, waste coal, or biomass has lent considerable economic incentive to recent utility CFBC projects. However, it remains to be seen if CFBC will retain the same level of tolerance to fuel feed as boilers are increased in size. At larger scales and higher steam conditions it has been observed that more careful control of bed material may be required to maintain high efficiencies and reduce boiler damage.

On the other hand, the low emissions status of CFBC is likely to diminish as new, stricter emissions standards are introduced which exceed the capabilities of desulphurisation through limestone fed directly to the furnace. In addition, the adoption of SCR by the 550 MW CFBC units at Samcheok may indicate that for new, larger boilers, cheaper SNCR could prove insufficient NOx control even with the relatively low emissions from CFBC. In China in particular, where CFBC is widely used to burn high sulphur anthracite, new SO_2 emissions limits of 100 mg/m^3 may have a profound influence on the competivity of CFBC, as installation of downstream scrubbers will add significantly to capital cost. On the other hand, the fact that all utility CFB boilers built in the USA in the last decade have already been obliged to incorporate downstream FGD is some evidence that the technology can remain viable. It is quite possible that, as emissions become increasingly regulated, the status of CFBC as a high-sulphur coal technology will shift to one that is better suited to lower levels of sulphur which can be sufficiently abated using limestone in the furnace. The development of new downstream scrubbers, such as activated carbon-based systems capable of removing SOx, NOx and mercury, may also compete with CFBC, particularly if mercury or nitrous oxide emissions limits are widely introduced.

Despite the well-established benefits of CFBC, the technology would nevertheless remain uncompetitive for utility boilers without offering the levels of efficiency, load following, and reliability that can match current PC boilers. The thermal efficiency of CFBC has progressively increased in recent years, primarily through raising steam conditions and reducing auxiliary power requirements, so that the Lagisza supercritical unit can claim to achieve 43.3% efficiency burning bituminous coal. Research in China has shown that the power drain from fans for fluidisation air – the main impediment to high CFBC efficiency – can be significantly reduced by adjusting the size distribution of bed material and thus the pressure drop through the furnace. Fewer data are available on the load following capabilities of large CFB boilers, but there are indications that the high thermal inertia of the inert bed material can result in slower ramp times than PCC and difficulties in ignition. On the other hand, CFB boilers are more able to operate at low outputs for low volatile coals. Although generally regarded as highly tolerant to high ash loadings, many early utility CFBC units have suffered severely reduced availability as a result of ash erosion and agglomeration. As experience with the technology at large scale has grown many of these problems appear to have been resolved by improved design and operational practice, although some fuel flexibility may be sacrificed.

Power plant costs are difficult to estimate and can be highly variable between region and individual projects, but there are several indications that the cost of CFBC plants has reduced over the last few years to approach that of PCC. Whilst manufacturers claim that the cost of the boiler alone is now competitive with a PC boiler, more conservative estimates allow for the significant saving possible on eliminating wet FGD to achieve comparable costs. This advantage could be lost if additional FGD equipment is required for a CFB boiler. The determining factor in CFBC competitivity for a given project may be whether significant operational cost savings can be made by moving to lower cost fuels when necessary. This is likely to be more important for plants with a choice between imported and locally sourced coal or other solid fuel. Ash disposal could also represent additional costs for a CFBC plant, as the addition of limestone to the furnace increases ash production and prevents its use for high value recycle applications such as cement substitute. CFBC ash is none the less widely used as a lower value construction material, where its self-cementitious properties are often desirable, and in agricultural and waste stabilisation, for which high lime content is also beneficial.

As international policy moves towards mitigating the CO_2 emissions from power generation, biomass cofiring and carbon capture technologies are two developments which will have an increasing impact on coal plants and in which CFBC could play an important role. In contrast to its role in coal-firing, CFBC is an established technology for biomass-firing, and many of the recent utility CFB boilers have incorporated the capability of burning up to 20% biomass with little design alteration required. On the other hand, as the practice of cofiring biomass in PCC rapidly grows and experience is gained, it appears that the more established boiler technology will become equally competitive for cofiring wood wastes for which relatively standard PCC equipment can be used. CFBC is nevertheless likely to retain an advantage for difficult high slagging biomass types such as agricultural wastes.

Oxyfuel combustion, in which elimination of nitrogen from the furnace produces a more easily captured stream of relatively pure CO_2, is emerging as one of the most viable carbon capture technologies. Both oxyfuel PCC and CFBC have been successfully tested at the pilot scale, but it is thought that CFBC has greater potential for combustion at higher oxygen concentrations, thus economising on boiler size. Research into the viability of this idea is in its early stages, and both boiler technologies await scaling up to the demonstration plant scale.

The next few years are likely to provide the true test of how well CFBC can compete with PCC for utility power generation, as the performance of a number of new supercritical units can be assessed and strict new emissions standards in China and the USA will begin to take effect. Of particular importance is whether the newly-built supercritical unit in China will lead to adoption of supercritical CFBC on a similar scale to subcritical units, and what role they may play in the country's energy mix. CFBC also has the potential to make inroads in India, where expansion of coal generating capacity has so far been focused on PCC, but widespread blending of high ash local coal with imported coal could favour the more flexible technology, as could the possible future introduction of SO_2 emissions limits. Other markets likely to see increased activity include South Africa, where CFBC would be aimed at exploiting substantial coal mining waste, and countries with significant lignite resources such as Turkey and Indonesia. Whilst CBFC is unlikely to become dominant in the coal power sector, it is clear that its recent rapid growth has yet to reach its peak.

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