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# The answer of CFB technology to the greenhouse gas problem: $CO_2$ postcombustion capture and oxycombustion in supercritical CFB boilers

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# THE ANSWER OF CFB TECHNOLOGY TO THE GREENHOUSE GAS PROBLEM: $CO_2$ POSTCOMBUSTION CAPTURE AND OXYCOMBUSTION IN SUPERCRITICAL CFB BOILERS


## Abstract

CFB (Circulating Fluidized Bed) boiler technology is a modern way to burn coals with different characteristics, specifically developed to address today's needs for fuel flexibility and low emissions.

The main aim of this paper is to show how this modern technology can achieve a significant reduction of $CO_2$ discharged to the atmosphere, thus decreasing the greenhouse gas emissions. Two alternative technologies are compared:

- the first one can be considered commercially available today and consists in the $CO_2$ postcombustion capture by means of an amine scrubbing of flue gas discharged by the boiler;
- the second one is under development by FW and consists in adopting a combustion with near pure oxygen and recycled flue gas or $CO_2$, to produce a flue gas composed essentially by $CO_2$ and water.

In both alternatives the $CO_2$ stream is dried and compressed for use in EOR (Enhanced Oil Recovery) applications or disposed into geological reservoirs.

The paper analyses the advantages/disadvantages of the adoption of a CFB boiler with respect to a conventional PC (Pulverized Coal) boiler.
For the amine option a traditional plant is directly compared to that integrated with $CO_2$ capture in order to evaluate the power performances and the costs of the two alternatives. This comparison allows defining the level of carbon tax which brings the two COE (Cost of Electricity) values with/without $CO_2$ capture to be identical. A sensitivity analysis of COE versus the price of coal and the discount cash flow is also provided.


## Introduction

The increasing interest in electric power generation from coal brings up a matter about advantages and disadvantages of the relevant technologies.
The acknowledged advantages refer to strategic and technical issues; among the first ones:

- large reserves worldwide distributed;
- price fluctuation independent from crude oil in a free competition market;
- need to ensure a safe energy supply in a floating and unstable scenario of natural gas and oil prices.

From the technical point of view, the new coal power plants demonstrate the availability of clean technologies suitable to meet high efficiency and very low emission targets for $SO_x$, $NO_x$ and particulate.
However the gap between the $CO_2$ emissions of the most efficient coal power plant with respect to a natural gas combined cycle remains very high, even if a life cycle assessment is made. The future of coal is therefore connected to the $CO_2$ capture pathway.

FW is more and more involved in investigations and studies on $CO_2$ capture from different points of view:

- the techno-economical comparison of different $CO_2$ capture technologies like precombustion capture in IGCC plants, postcombustion capture and oxycombustion.
- the research and development of an oxycombustion CFB boiler.

In the following sections the two options related to the CFB technology are investigated: the postcombustion $CO_2$ capture by means of an amine scrubbing of flue gas, and the adoption of a combustion with near pure oxygen (oxycombustion). The fuel characteristics refer to a bituminous coal.
In parallel FW is developing for IEA GHG R&D Programme an interesting study on Power Plants capture fed by low rank coals (lignite) with $CO_2$ precombustion and postcombustion capture, as well as oxycombustion, whose results, when available, will be compared to the conclusions of this evalution.

## The Supercritical Circulating Fluidized Bed (CFB) Boiler

The circulating fluidized bed (CFB) boiler technology is a relatively young technology compared to pulverized coal boilers or other types of conventional coal fired boilers. It has developed from small-scale industrial boilers using a variety of fuels to utility size. Today CFB boiler in the size up to 300 MWe are in operation but larger sizes have been designed. Sizes up to 600 MWe are available and offered on commercial basis.
The first units in commercial operation developed 25 years ago were small industrial units that burnt easily combustable fuels such as bark and peat. But gradually the sizes grew and a variety of fuels were utilized for the energy production. The capability to burn fuels with characteristics not or hardly acceptable by the conventional boilers (i.e. high sulphur content, high moisture, high ash content) is becoming a key issue for CFB technology selection. Today the most frequently fuels used in CFBs are coal, brown coal or waste coal, and petroleum coke. Also renewables like biomass, industrial wastes, RDF (refuse derived fuel) are very suitable, both alone and in cofiring with fossil fuels.
There are several factors contributing to the success of the technology, which has and is conquering ground from conventional technology. Such factors are e.g. meeting regulatory emissions without extensive flue gas cleaning equipment, fuel flexibility, multi-fuel capability, high plant efficiency, high plant reliability, competitive investment cost.
In order to further increase the power plant efficiency, thus reducing the specific $CO_2$ emission, Foster Wheeler has designed a once through CFB boiler with supercritical steam parameters. These units (OTU), available on a commercial basis up to a size of 600 MWe, make use of the Benson technology licensed from Siemens. The efficiency gain obtained with supercritical parameters is in excess of 10% (more than 4 percentage points).

The technology with its “natural circulation”, positive thermodynamic flow characteristics, is ideally suited for CFB boiler application as the pressure drop is lower due to the low mass flux as well as the lower heat flux, which in its turn, ensures that overheating of the boiler tubes will not occur.

The key points above described demonstrate to be particularly useful when CFB technology is coupled with a postcombustion $CO_2$ capture.

## PART 1

## CFB Boiler with postcombustion amine scrubbing

### Process Description

The target assumed for this investigation is a reduction of nearly 85% of the $CO_2$ emissions to the atmosphere from a CFB power plant with a nominal 600 MWe gross power output. A South African bituminous coal (LHV: 25100 kJ/kg, sulphur: 0.55 %wt, moisture: 8 %wt, ash: 10% wt) is assumed.

Among the several technologies available for the capture of $CO_2$ a MEA scrubbing is adopted. This seems to be the most likely route to capture $CO_2$ from both PC and CFB boilers, due to the large gas flows coming from the boiler, the low pressure of the flue gas (ambient pressure) and the low $CO_2$ concentration (13.8% vol). The process scheme to be adopted is well known in the industry. It is mainly used today to purify syngas used in the chemical industry (ammonia, hydrogen), to remove $CO_2$ from natural gas, to supply $CO_2$ to the merchant market (beverage, dry-ice, etc.) and for use in enhanced oil recovery (EOR). There is as yet no commercial market for its use in the power industry for the post combustion capture of $CO_2$, and no commercial application with a similar size. In any case the same schemes, with minor modifications and scale up can be conveniently used in power industry for acid gas sweetening. Some concerns about the possible large degradation of amine due to impurities contained in the flue gas ask for further experimental investigations.

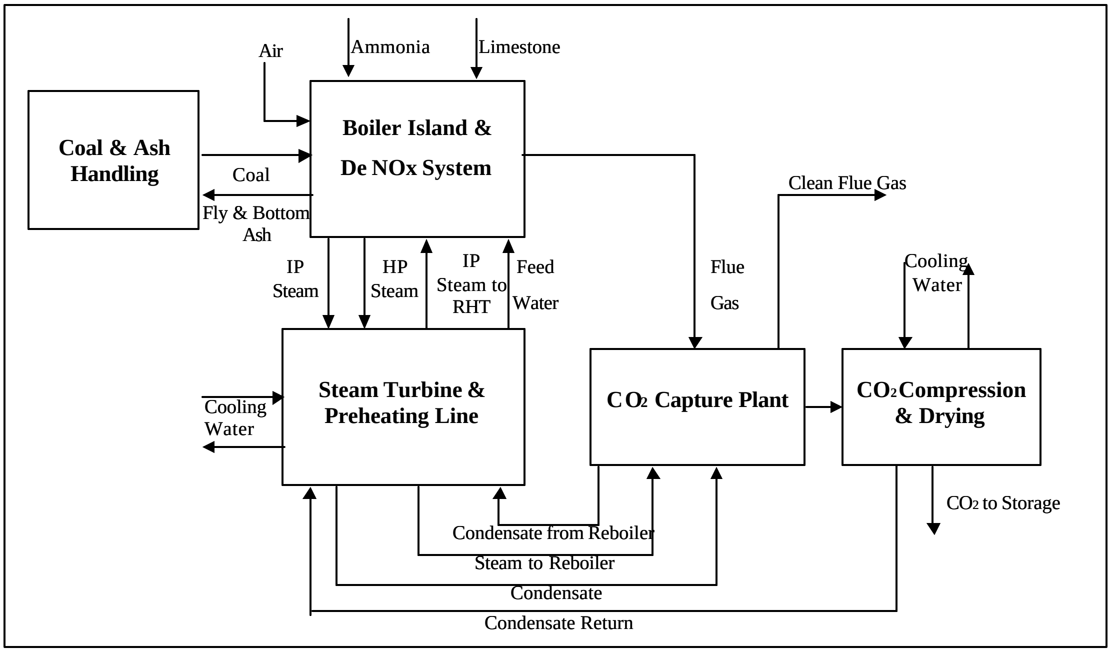
The energy consumption of the amine $CO_2$ recovery is very high. The energy is, first of all consumed by flue gas blowers to overcome the additional system pressure drop. However the main energy loss is related to the use of low pressure steam for amine regeneration by extraction from the steam turbine. Another indirect cost involved by the amine $CO_2$ removal is the additional expenditure in the upstream De-$NO_x$ and desulphurisation to meet the extremely low levels of residual $NO_x$ and $SO_x$ required before entering the amine scrubbing in order to limit the amine degradation.

In general a traditional CFB boiler has low emissions in terms of $NO_x$ and $SO_x$ due to the low furnace temperature and to the limestone injection. The $NO_x$ emission limits, established by international regulations, can be usually met without any additional device, due to the low combustion temperature (850-900 °C) which is typical of CFB technology. If necessary the $NO_x$ emissions may be further reduced by adopting an SNCR (Selection Non Catalytic Reduction) system. However an SCR (Selection Catalytic Reduction) system has to be considered in the case of the plant integrated with the $CO_2$ capture process, in order to reduce the $NO_x$ level to about 20 ppmv. The downstream amine based $CO_2$ absorption system, again requires a very low level of $SO_2$ in the flue gas (much lower than the emission limits required by regulations). This calls for a high $SO_2$ capture efficiency to reach the limit of 15 ppmv of $SO_2$ at the exit of the boiler.

One of the advantages of the CFB technology with respect to the traditional PC-USC boilers is the possibility to completely avoid the installation of the expensive and operationally complex FGD (Flue Gas Desulphurisation) unit.

As shown in the Block Flow Diagram, the plant is composed by some traditional sections, i.e. the Coal and Ash Handling, the Boiler Island including SCR and fabric filter, the Steam Cycle, and by additional sections like the $CO_2$ Capture Plant and the $CO_2$ Compression & Drying.

## CFB with $CO_2$ Capture Block Flow Diagram



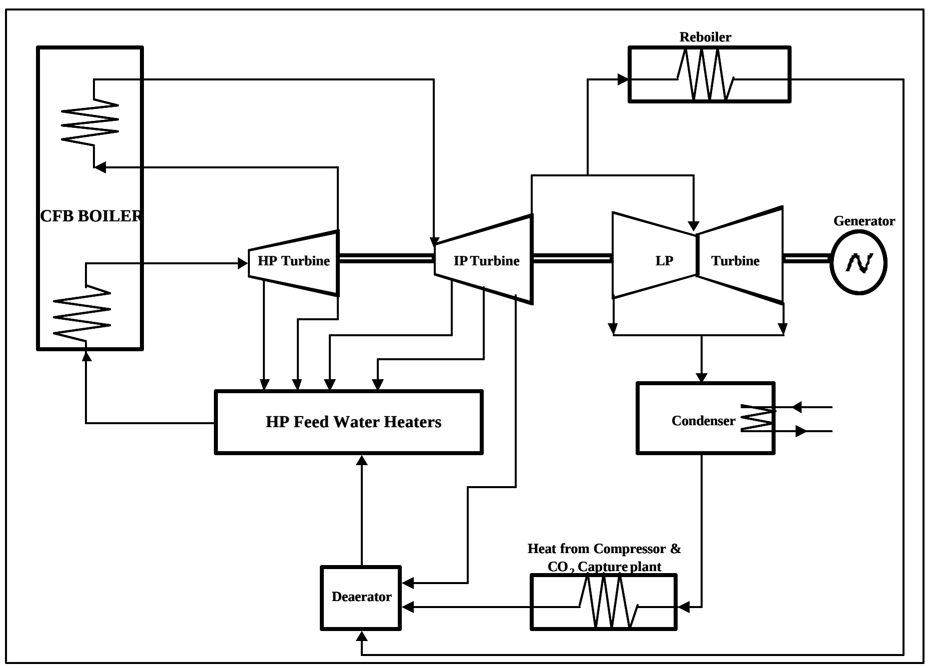

The flue gas at the outlet of the boiler is routed, after cooling, to the $CO_2$ capture plant. The cooling of the gas from 85°C (temperature at boiler outlet), to 30-35 °C is an operating requirement for the downstream $CO_2$ capture process. This cooling is performed by an adiabatic quench of the flue gas in a direct contact cooler, before entering the absorption columns. For the 600 MWe CFB boiler flue gas flowrate, two large absorption columns (approx 10 m diameter) and one regenerator are necessary.

After passing in the direct contact cooler the flue gas enters the absorption columns where it is contacted with lean MEA. The $CO_2$ is captured by the solvent and the sweet gas leaves the column at 55°C and goes to the stack. The rich amine from the bottom of the absorber is pumped to the regeneration section. The estimated demand of low pressure steam for regeneration, assuming a $CO_2$ recovery equal to 85%, is approx 500 t/h. After the regeneration MEA is recirculated back to the top of the absorption column and the $CO_2$ rich stream leaving the top of the stripper column is routed to the $CO_2$ compression and drying unit.

$CO_2$ has to be compressed up to a pressure well above 74 bar (critical parameters are 74 bar and 31 °C) in order to be exported and stored in supercritical conditions for a long term sequestration. The pressure at B.L. is assumed equal to 110 bar. This section is composed by proven technology equipment, commercially available for the capacity required by this application. Compression interstage cooling and water separation are provided in order to reduce the power consumption of the unit and limit the risk of corrosion of the materials of construction. The intercooling is achieved by preheating the cold condensate coming from the power island, in order to meet a high integration level with the power plant. Part of the heat for condensate preheating is also recovered on the overhead condenser of the amine regenerator in the $CO_2$ capture unit. This integration permits to completely avoid the use of the low pressure feed water heater of the Steam Cycle.

The power island consists in a steam turbine with HP, IP, LP sections all connected to the generator. The main steam parameters are 285bar/585°C for HP superheated steam, 600°C/48 bar for reheated steam with a condensing pressure of 0.033bar/26°C. The LP steam to the regenerator reboiler is extracted downstream the IP section at 3.6 bar, condensate is routed back directly to the dearator. As described above the difference from a traditional power plant is the LP feedwater heater elimination, compensated by the heat recovered in the $CO_2$ capture and compression units.

**Steam Turbine & Preheating Line**




## Technical Comparison with a PC Boiler with postcombustion amine scrubbing

The alternative with a PC Boiler shows a process configuration which is very similar to what described above for the CFB boiler, with the following differences:

- coal milling designed to achieve the pulverized coal size;
- installation of a Flue Gas Desulphurisation unit.

The supercritical parameters of a state-of-the-art Ultra Supercritical (USC) PC boiler are higher than those adopted for the CFB boiler, i.e. 300bar/600°C for HP superheated steam, 60 bar/620°C for reheated steam.

### Comparison of the Overall Plant Performances

The following table shows the comparison between the plant performances for CFB and PC alternatives with and without the $CO_2$ capture. For the case without $CO_2$ capture, the performances of PC alternatives are superior due to the more pushed supercritical parameters which result in a higher efficiency (+1.4 percentage points equivalent to +3.1%). The same trend is shown by the comparison of the efficiency values for the case with $CO_2$ capture: the absolute difference is 1.3 percentage points in favour of the PC boiler, equivalent to +3.7%.

| PLANT PERFORMANCES | | | | | |
|---|---|---|---|---|---|
| | | CFB | CFB+$CO_2$ | PC-USC | PC-USC+$CO_2$ |
| **Coal Flow rate** | **t/h** | 182 | 182 | 182 | 182 |
| **Coal LHV** | **kJ/kg** | 25100 | 25100 | 25100 | 25100 |
| **Thermal Input** | **MWth** | 1266 | 1266 | 1266 | 1266 |
| **Gross power output** | **MWe** | 600 | 536 | 612 | 547 |
| **Total Auxiliary Consumption** | **MWe** | 32 | 88 | 28 | 83 |
| **Net Power output** | **MWe** | **566** | **448** | **584** | **464** |
| **Gross electrical efficiency** | **%** | 47.4% | 42.3% | 48.4% | 43.2% |
| **Net Efficiency** | **%** | **44.7%** | **35.4%** | **46.1%** | **36.7%** |

The comparison, under the same thermal power input, between cases with and without $CO_2$ capture for each combustion technology demonstrates the strong penalization of the net power output and consequently of net plant efficiency, due to the $CO_2$ capture and compression. The trend for the two alternatives is very similar.

### Environmental Impact

For both the combustion technologies the power plants integrated with the $CO_2$ capture process meet very stringent emission standards. No significant difference of pollutant concentration between CFB and PC alternatives may be appreciated, even if the same targets are reached with a different impact on the plant performances and operability, and investment cost.

The $NO_x$ and $SO_x$ levels need to be respectively reduced to 20 ppmv and 15 ppm at 6% $O_2$ vol. dry before entering the absorption columns in order to limit the amine degradation. The particulate is reduced by adopting conventional fabric filters and further decreased, for cases with $CO_2$ capture, by the flue gas washing in the direct contact cooler and the subsequent amine scrubbing. Both $NO_x$ and $SO_x$ are further reduced due to the undesired formation of Heat Stable Salts (HSS) by reacting with MEA, then eliminated by the MEA reclaiming system.

The $CO_2$ capture rate of 85% assumed as a basis of design ensures a significant reduction of the greenhouse gas emissions.

The table below offers a comparison of the gaseous emissions of the two technologies:

| | CFB | $CFB+CO_2$ Capture | PC-USC | $PC\text{-}USC+CO_2$ Capture |
|---|---|---|---|---|
| **Emissions** | **$mg/Nm^{3\,(1)}$** | **$mg/Nm^{3\,(1)}$** | **$mg/Nm^{3\,(1)}$** | **$mg/Nm^{3\,(1)}$** |
| **NOx** | 150 | 40 | 150 | 40 |
| **SOx** | 100 | 43 $^{(2)}$ | 100 | 43 $^{(2)}$ |
| **CO**<br>**Particulate** | Less than 150<br>30 | Less than 150<br>Less than 30$^{(2)}$ | Less than 150<br>Less than 30$^{(2)}$ | Less than 150<br>Less than 30$^{(2)}$ |
| | | | | |
| **Specific Emissions** | **kg/MWh** | **kg/MWh** | **kg/MWh** | **kg/MWh** |
| **NOx** | 0,416 | 0,120 | 0,387 | 0,111 |
| **SOx** | 0,278 | 0,129 | 0,258 | 0,120 |
| **CO** | 0,416 | 0,448 | 0,387 | 0,416 |
| **Particulate** | 0,083 | Nil | 0,078 | Nil |
| **$CO_2$** | 756 | 143 | 727 | 138 |
| **$CO_2$ to Storage** | - | 364 t/h | - | 360 t/h |

(1) Dry gas, $O_2$ Content 6% vol

(2) $NO_x$ and $SO_x$ and particulate emissions upstream AGR unit; after solvent washing, emissions are expected close to zero

### Investment Costs and Economical Evaluation

The following Table summarizes the investment costs of the two technology alternatives, each one for the two configurations with/without $CO_2$ capture. For cases w/o $CO_2$ the CFB alternative shows a more attractive specific investment cost (Euro/kW) due to the less complexity (adoption of an SNCR instead of an SCR for $NO_x$ reduction, no FGD required). The same trend is maintained for cases with $CO_2$ capture, deriving again mainly from avoiding the FGD, while SCR is necessary to reach the extremely stringent $NO_x$ concentration required by the amine washing.

| | CFB | $CFB+CO_2$ Capture | PC-USC | $PC\text{-}USC+CO_2$ Capture |
|---|---|---|---|---|
| **Total Investment Cost 10^6 €** | 622 | 728 | 671 | 791 |
| **Net Power Output MWe** | 566 | 448 | 584 | 464 |
| **Specific Investment Cost €/kW** | 1099 | 1625 | 1150 | 1705 |

Based on the plant performances, the investment and the operating costs related to each case a simplified economical analysis is performed to evaluate the Cost of Electricity (COE).

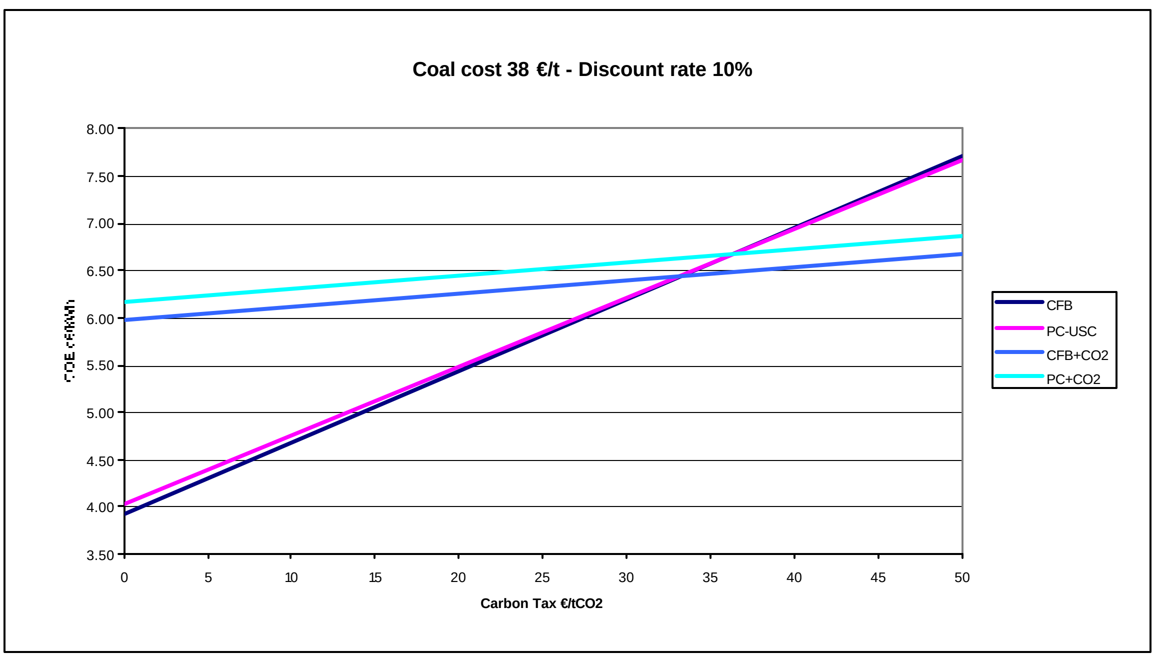
The following additional parameters are assumed:

- cost of coal: 38 Euro/t
- cost of limestone: 20 Euro/t
- cost of amine: 1300 Euro/t
- 7900 operating hours/year
- 10% discount cash flow
- plant life: 25 operating years
- maintenance cost equivalent to approx 3% of the total capital costs
- direct labour: 105 persons
- overhead costs: 30% of direct labour cost
- no selling price is applied to $CO_2$ potentially used for EOR.

For each technology the comparison of COE values for cases with and without $CO_2$ capture outlines the consistent penalty on the cost of electricity caused by the $CO_2$ capture (approx +50% for both the technologies).
The table shows a slight advantage of the CFB technology for cases without $CO_2$ Capture (3.0% on COE) demonstrating that the lower investment cost more than compensate the lower electrical efficiency. The trend is confirmed by the cases with $CO_2$ capture.

| | CFB | CFB+$CO_2$ Capture | PC-USC | PC-USC+$CO_2$ Capture |
|---|---|---|---|---|
| **COE c€/kWh** | 3.93 | 5.97 | 4.04 | 6.15 |

In order to make the comparison more interesting, the cost of energy is also calculated in presence of a carbon tax expressed in €/t of $CO_2$ emitted. This evaluation permits to establish what should be the taxation level necessary to make the two solutions economically equivalent.

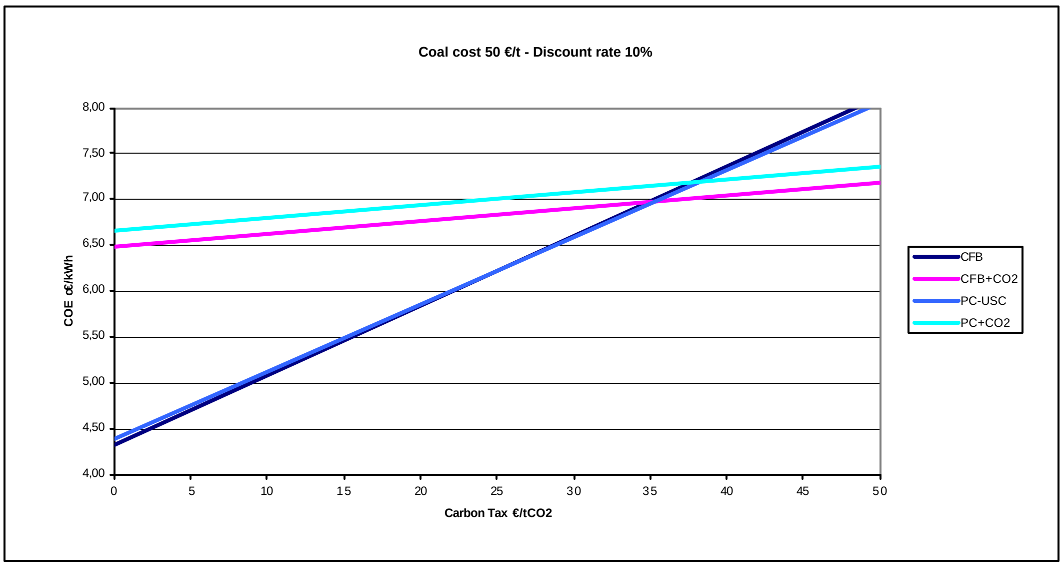


The diagram shows that up to a carbon tax in the range of 35-38 €/t, both conventional PC and CFB plants produce a COE lower than the corresponding plants with $CO_2$ capture.
Above 38 €/t the $CO_2$ capture becomes convenient for both the technologies.
It is interesting to explain the progressive change of COE for the conventional PC and CFB plants at increasing carbon tax values: over a certain value the better efficiency of PC technology completely offsets the advantage of the lower investment cost.

The comparison is also extended making a sensitivity analysis versus the cost of coal in the range of 34-50 €/t, and the discount rate in the range of 5-15%.

### COE vs Coal Price (10% DCF, no Carbon Tax)

| | CFB | CFB+$CO_2$ Capture | PC-USC | PC-USC+$CO_2$ Capture |
|---|---|---|---|---|
| **Coal Cost €/t** | **COE c€/kWh** | **COE c€/kWh** | **COE c€/kWh** | **COE c€/kWh** |
| **34** | 3.81 | 5.82 | 3.92 | 6.02 |
| **38** | 3.92 | 5.98 | 4.04 | 6.18 |
| **50** | 4.33 | 6.48 | 4.39 | 6.66 |



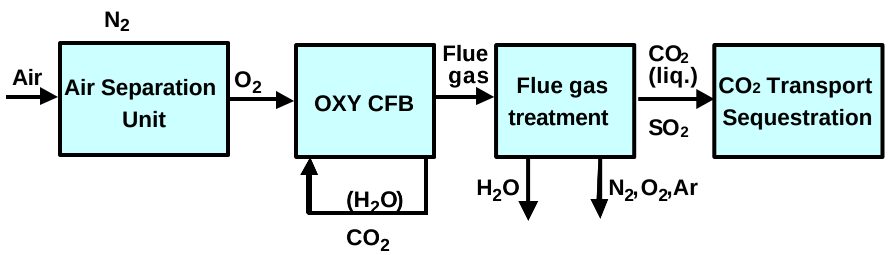

### COE vs DCF (38€/t Coal Price, no Carbon Tax)

| | CFB | CFB+$CO_2$ Capture | PC-USC | PC-USC+$CO_2$ Capture |
|---|---|---|---|---|
| **Discount rate %** | **COE c€/kWh** | **COE c€/kWh** | **COE c€/kWh** | **COE c€/kWh** |
| **5** | 3.23 | 4.94 | 3.27 | 5.09 |
| **10** | 3.92 | 5.98 | 4.04 | 6.18 |
| **15** | 4.61 | 7.02 | 4.81 | 7.27 |

## PART 2

## Oxycombustion in CFB boilers

In oxycombustion the aim is to change the combustion process to produce near nitrogen free flue gases. Thus, the main gas compounds are $CO_2$ and $H_2O$ with smaller amounts of other gases, such as $O_2$, $N_2$, $NO_x$, $SO_x$ and Argon. Water concentration can be reduced by a condensation equipment which leads into $CO_2$ rich flue gases. Such gases are much easier and cheaper to transform into supercritical $CO_2$ form by further compressing and liquefying.




The oxycombustion plant is equipped with Air Separation Unit (ASU), Oxy CFB power plant and $CO_2$ compression and liquefaction up to 110 bar. Oxygen is mixed with recirculated flue gases, which creates mainly a mixture of $O_2$ and $CO_2$. $O_2$ content may be e.g. 21 % like in air, or higher in which case furnace volume could be smaller. In case of 21 % the boiler concept is essentially the same as with air blown CFB boilers.

Many studies are currently under execution for PC boilers to evaluate the advantages of the oxycombustion with respect to the $CO_2$ post combustion capture downstream to a traditional air combustion. The following technical/economical key issues have been defined:

- Reduction of the boiler size and cost due to the lower volumes, if $O_2$ concentration is increased above 21%;
- Impact of ASU on performances and investment cost;
- Impact of $CO_2$ purity on performances and investment cost of the Flue Gas Treatment Section.

The first results of those evaluations are:

- a significant increase of the net electrical efficiency achievable with oxycombustion vs amine postcombustion scrubbing (approximately +10%).
- a higher specific investment cost (Euro/MW) which determines a higher cost of electricity (COE) with respect to the postcombustion amine scrubbing option.

However it is recognized that the expected technology developments for $O_2$ production and process optimizations will make this technology more competitive.

The following paragraphs provide a brief description of R&D activities performed by FW to develop an oxycombustion CFB boiler design.

**CFB Oxycombustion process**

Effect of $O_2/CO_2$ combustion gas on combustion phenomena can be studied in a smaller scale test devices. Combustion tests in a pilot scale CFB test rig at Technical Research Center of Finland have lead into the following conclusions:

- no drastic changes in combustion is expected when nitrogen is replaced with $CO_2$ in combustion gas;
- increasing $O_2$ concentration will increase combustion rate of char and reduce unburned carbon in ash leading to higher combustion efficiency (fig. 1). Higher combustion rate leads also to higher local heat production rates in the furnace;
- no significant changes seem to occur in emission levels of $SO_2$, $NO_x$ and CO. $SO_2$ absorption with limestone addition will mainly take place through calcined CaO as is the case with air combustion. $NO_x$ levels may increase slightly due to varying temperature levels and higher oxygen concentrations, but, on the other hand, nitrogen free combustion gas will have a compensating effect by reducing thermal $NO_x$.

As a conclusion, combustion phenomena seem to be essentially similar to air combustion in CFB. In addition, $O_2/CO_2$ gases provide more potential to optimise and develop the combustion process to improve the overall performance of the process.

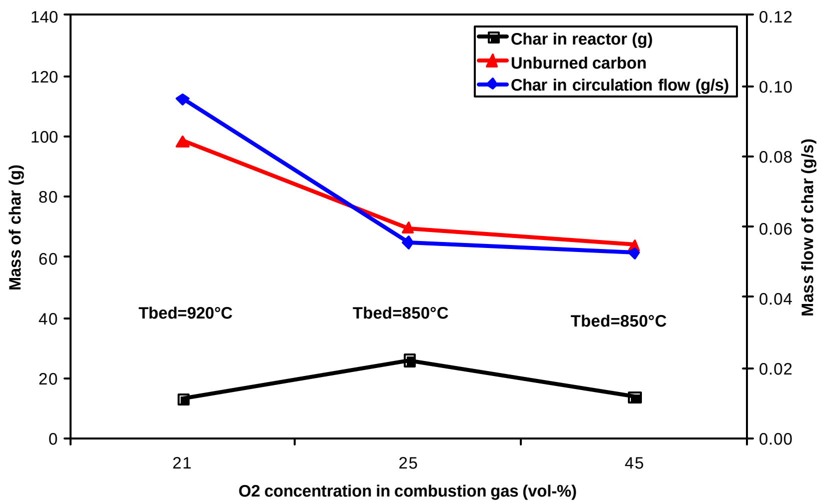



**Figure 1 Char content as a function of $O_2$ concentration in combustion gas**

With enriched $O_2$ concentrations the volume of fluidising gases is reduced and adiabatic combustion temperature is increased. Thus, furnace cross section and volume will be decreased while the heat transferred in the furnace will be increased. That will create a challenge to manage the furnace temperature levels and to locate and develop designs for heat exchangers in the hot loop of CFB furnace. This requires suitable modeling and design tools, which can predict the process performances in oxygen enriched conditions.

A preliminary model analysis was made for a 200 $MW_e$ CFB boiler in order to study the furnace process with enriched $O_2$ concentrations. $O_2/CO_2$ ratio was in the calculation 50%/50% whereas a reference case was a typical air blown CFB boiler. The results of $O_2$ and temperature profiles are shown in figures 2-3. As it might be expected, higher concentrations of oxygen tend to create larger temperature gradients in the furnace. However, the levels of temperatures are still within the range of normal CFB furnace operation and most probably temperature profiles will be more uniform with proper design configurations .

**Figure 2**
**Oxygen concentration in CFBs with air combustion and oxygen enriched combustion**

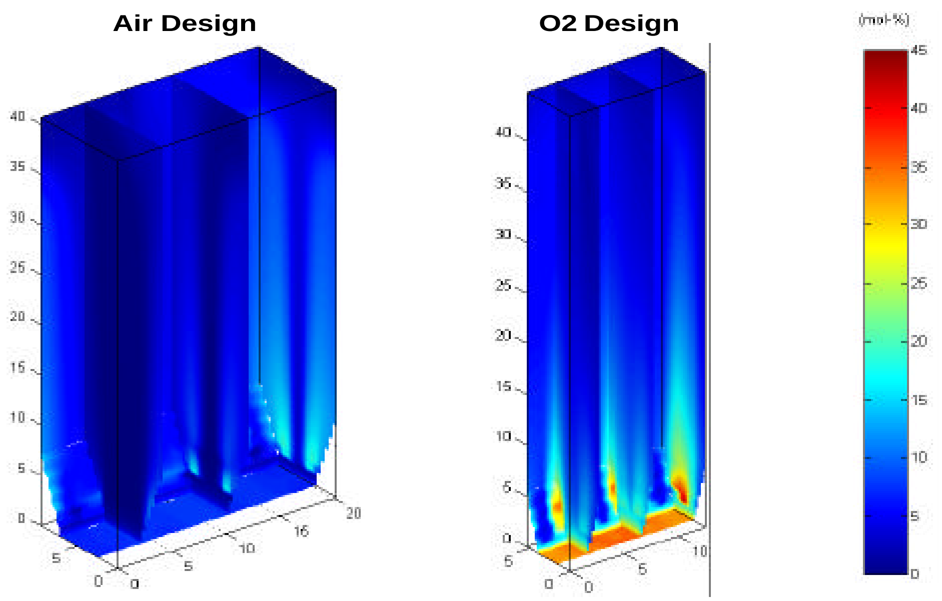
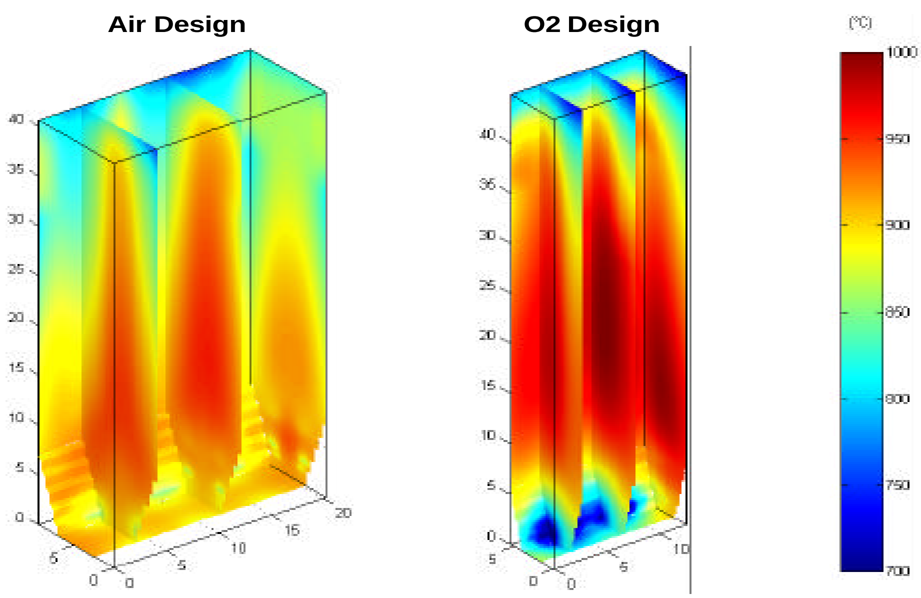



**Figure 3**

**Temperature profiles in CFBs with air combustion and oxygen enriched combustion**



As a summary, oxycombustion in a CFB boiler seems to provide typical benefits of CFB boilers. A large variety of fuels including hard-to-burn fuels can be combusted and a boiler can be designed for several fuels. Low combustion temperature is suitable condition for low $NO_x$ levels and absorption of sulphur with limestone enables a cost effective method for sulphur removal. In addition, higher $O_2/CO_2$ ratios lead into higher combustion efficiency and reduce the flow rates of flue gases. Smaller furnace volumes may lead into several percent cost reduction of boiler island. Reduction of flue gas heat losses will also increase the boiler efficiency.

## PC versus CFB in oxycombustion

Competition between PC and CFB is somewhat similar to air blown cases (fuel types, emissions w/wo flue gas equipment, ash characteristics). However, there may also be additional potential advantages in CFB due to flexibility of fluid bed process, e.g. in making temperatures more uniform with enriched $O_2$ feed and high local heat production rates. Enrichment of oxygen could reduce cost of boiler island up to 8 % depending on the design configurations, due to smaller furnace volume and flue gas flow. The characteristic $NO_x$ and $SO_x$ levels of CFB may provide additional cost benefits for CFB depending on the allowed emission standards for the plant and $CO_2$ purity.

## Future developments

In the future the target is to develop CFB oxycombustion up to a commercially available technology. The following studies and activities are planned:

- continue small pilot scale testing and study combustion related phenomena in oxycombustion conditions with varying $O_2/CO_2$ ratios.
- Adjust and extend the design and modeling tools based on the experimental results obtained.
- Design and develop oxycombustion boiler configurations and concepts for varying $O_2$ enrichment conditions.
- Continue technical and economical feasibility analysis of oxycombustion power plants.
- Look for and prepare small scale demonstration of oxycombustion in a CFB boiler in size range 10-35 MWe.
- Aim at the larger scale demonstration of oxycombustion.

A small scale demonstration unit is planned to be in operation in 2008-2009. The larger scale demonstration project will be authorized after the performances and experiences of the first demonstration unit have been consolidated and analyzed. Thus the demonstration for commercial operation of oxycombustion is planned during the first half of the next decade.

## Conclusions

The evaluations performed in this study demonstrate the possible application of CFB technology in power plants with $CO_2$ capture and the promising economical and technical issues of such plants. The competition between PC and CFB technologies is keeping on applying also to power plants with $CO_2$ capture.

The post combustion $CO_2$ capture applied to both CFB and PC boilers seems to be a viable solution for the near future power industry market, if a consistent reduction in greenhouse gas emissions shall be imposed. The CFB advantages in terms of fuel flexibility, emissions without extensive flue gas cleaning equipment, multi-fuel capability, competitive investment cost are confirmed.

The oxycombustion technology is certainly an interesting solution, but additional R&D efforts are necessary.

The penalization of plant performances and consequently the impact on $CO_2$ is significant for the current technologies, but in a future scenario where a carbon tax on greenhouse gas emissions will be applied, these plants might become viable, taking into account the acknoledged advantages referred to a strategic use of coal. Further technological improvements are expected in the next years, i.e.:

- increase of plant efficiency by pushing the supercritical temperature value up to 700°C and more;
- optimization of the integration between the power island and the $CO_2$ capture process;
- use of new solvent formulations for flue gas scrubbing requiring low energy consumptions and causing a lower solvent degradation;
- economy of scale;

will lead to an increase of the plant performances and to a consistent reduction in the cost of electricity production.

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