

# OXYFUEL COMBUSTION FOR COAL-FIRED POWER GENERATION WITH CO<sub>2</sub> CAPTURE – OPPORTUNITIES AND CHALLENGES

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## Abstract

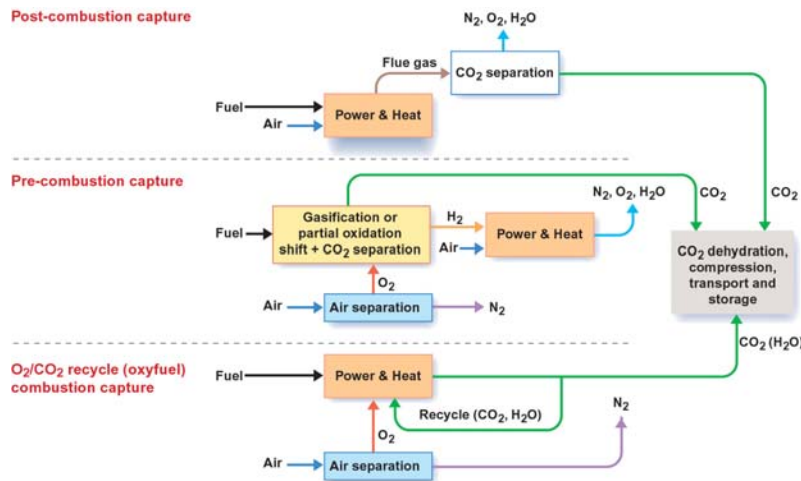
Oxyfuel or O<sub>2</sub>/CO<sub>2</sub> recycle combustion is a highly interesting option for lignite-based power generation with CO<sub>2</sub> capture, due to the possibility to use advanced steam technology, reduce the boiler size and cost and to design a zero-emission power plant. This technology, however, also poses engineering challenges in the areas of combustion and heat transfer, boiler design, boiler materials, energy-efficient oxygen production and flue gas processing. The overall challenge is to design a robust plant that has a sufficiently low total cost of electricity so that it is interesting to build, but it must also have a sufficiently low variable cost of electricity so that it will be put in operation as a base load plant once it is built.

## Introduction

Global warming is one of the largest environmental challenges of our time. Increased carbon dioxide level in the atmosphere is the dominating contributor to increased global warming. Carbon dioxide is emitted to the atmosphere through combustion of fossil fuels in power plants, automotive engines, for industrial use and for heating purposes. The world is currently depending on the use of fossil fuels for its energy supply, and will continue to be so for a long time yet to come, due to the abundant sources of in particular bituminous coal and lignite. Small-scale renewable electricity production is available on the market today, but the cost of avoiding CO<sub>2</sub> emissions through renewables (e.g. wind power) is at present very high. In addition, instabilities (with an increased risk of power outages) are usually induced in a power grid when a significant proportion of the power production comes from a large number of small generators. In the very long term, large-scale heat and power production technologies based on sustainable energy sources will have to be developed. These technologies are not commercially available, and the opportunity to find time for their commercialization will be given through near-term development of technology for emission-free fossil-fuel utilization.

The three main options for reducing CO<sub>2</sub> emissions from fossil-fuel based energy conversion are 1) increasing the fuel conversion efficiency 2) switching to a fuel with a lower fossil carbon content and 3) capturing and storing the CO<sub>2</sub> emitted from the fossil fuel. Vattenfall is actively investigating all three options and is prepared to apply any of them whenever found to be technically and economically possible. In order to make alternative 3 feasible, Vattenfall has taken the strategic decision to play a leading role in the development of emission-free fossil-fuel based power generation and has started the project “Carbon-Dioxide Free Power Plant”. The project deals with CO<sub>2</sub> capture, transport and storage, with main focus on lignite-fired power plants with CO<sub>2</sub> capture. The aim is to develop a commercially viable concept until 2015. Furthermore, Vattenfall is taking part in the development of CO<sub>2</sub> capture technologies as the coordinator of the EU Framework 6 project ENCAP (ENhanced CAPture of CO<sub>2</sub>). Vattenfall is also a partner in the EU-projects CO2STORE and CASTOR.

The concepts for power generation with CO<sub>2</sub> capture are usually divided into three different groups, post combustion capture, pre-combustion capture and oxyfuel combustion capture, as shown in Figure 1 and as widely explained in the literature. Vattenfall has chosen to focus its main efforts within CO<sub>2</sub> capture on the oxyfuel area, in particular on the O<sub>2</sub>/CO<sub>2</sub> recycle combustion of lignite. This does not necessarily mean, however, that the O<sub>2</sub>/CO<sub>2</sub> recycle combustion will be Vattenfall’s preferred technology when it is time to build power plants with CO<sub>2</sub> capture. As a producer of electric power rather than of power plants, however, Vattenfall has identified both the opportunities with O<sub>2</sub>/CO<sub>2</sub> recycle combustion capture, and the challenges that must be faced, in order to make this technology a viable alternative the day a decision will be made on what capture technology to actually build. The present paper gives a structured overview of both opportunities and challenges with the O<sub>2</sub>/CO<sub>2</sub> recycle combustion, mainly from a technology point of view, but also economic aspects are treated. In particular, attention has been given to describe problems connected to the flue gas cleaning that must be resolved, a topic that has often been omitted in earlier power plant studies.



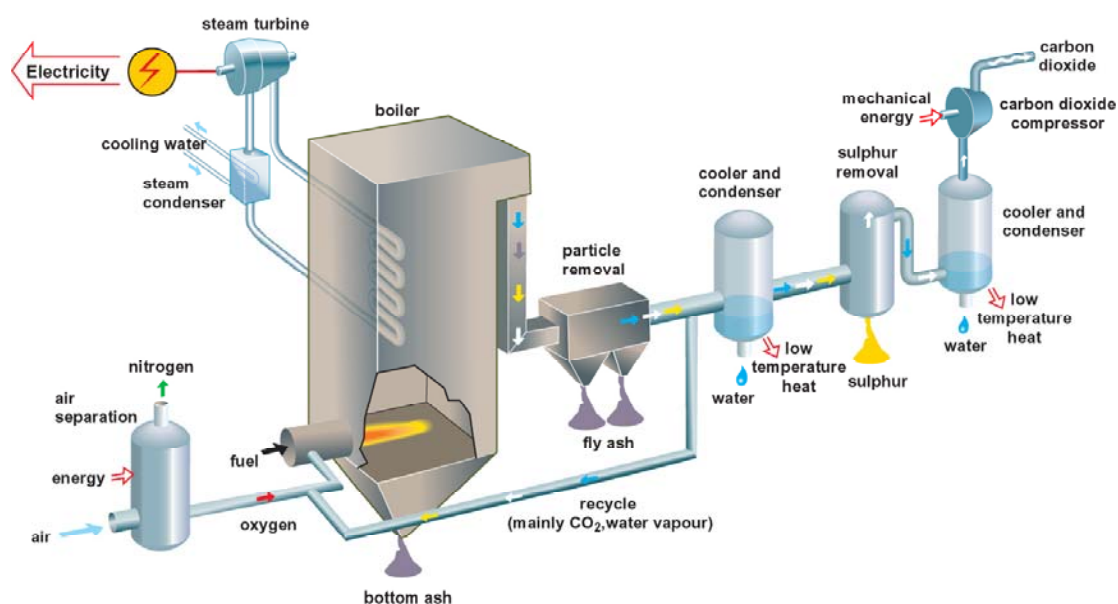
**Figure 1:** The three basic concepts for power generation with CO<sub>2</sub> capture

### O<sub>2</sub>/CO<sub>2</sub> recycle combustion of lignite

The principle of O<sub>2</sub>/CO<sub>2</sub> recycle combustion of e.g. lignite in a pulverised fuel (PF) boiler can be seen in Figure 2. This kind of concept is related to the investigations that Vattenfall have been performing together with university partners so far and is described by Andersson et al. [1]. Instead of air, oxygen (95% purity or higher) is fed to the boiler, and a major part (70-80%) of the CO<sub>2</sub>-rich exhaust gas is recycled back to the boiler to control the combustion temperature. The remaining part of the flue gas, (consisting mainly of CO<sub>2</sub> and water vapour and small quantities of Ar, N<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> and other constituents from air leakage and fuel) is cleaned, compressed and transported to storage or another suitable application, such as enhanced oil recovery (EOR). Provided that the gas is dry, it might be possible to sequester the sulphur with the CO<sub>2</sub>, although this needs further investigation. The steam power cycle is of the standard type that can be found in conventional coal-fired steam power plants.

Other studies of the power plant cycle with O<sub>2</sub>/CO<sub>2</sub> recycle combustion can be found in [2-8]. The concept has attracted much interest for retrofit studies, both for coal [3-8] and for refinery fuel gas and heavy fuel oil [9,10], often in a context where the CO<sub>2</sub> is intended for EOR [4,8-10]. Since power plants grow old and must be replaced, and with the advent of CO<sub>2</sub> emission penalties, Vattenfall has its focus on O<sub>2</sub>/CO<sub>2</sub> recycle combustion applied in new built power plants with advanced steam data where, unlike in the retrofit cases, an optimized process design based on best available technology can be made.

#### O<sub>2</sub>/CO<sub>2</sub> recycle (oxyfuel) combustion capture



**Figure 2:** The principle of O<sub>2</sub>/CO<sub>2</sub> recycle combustion in a PF boiler.

## Opportunities with O<sub>2</sub>/CO<sub>2</sub> recycle combustion of coal

*The advantage of ongoing technology development for enhanced steam cycle efficiency*

One of the main opportunities with O<sub>2</sub>/CO<sub>2</sub> recycle combustion of coal in new plants is that the steam cycle is able to take advantage of the ongoing development to increase steam cycle efficiency through the use of advanced steam technology and lignite drying. This advantage is shared with coal-fired post-combustion capture power plants. The development of advanced steam technology is not specifically linked to the CO<sub>2</sub> capture field but more in general to the development of materials for extremely high pressures and temperatures, in combination with new boiler and turbine designs. During the 1990's, power plants were built with very advanced steam data, such as Vattenfall's lignite-fired units in Germany. Also several hard-coal fired and natural-gas fired plants have been built. Data for some plants are shown in Table 1. All data in Table 1 except for the Lippendorf and Niederaussem are from [11].

TABLE 1: DATA FOR SOME ADVANCED STEAM POWER PLANTS WITHOUT CO<sub>2</sub> CAPTURE

Power Station	Capacity (MW)	Steam parameters	Fuel	Efficiency (% LHV)	Commissioning year
Lippendorf	2*920	260 bar/554°C/583°C	Lignite	42.6	1999
Niederaussem K	950	275 bar/580°C/600°C	Lignite	45.2	2002
Haramachi 2	1000	259 bar/604°C/602°C	Bituminous		1998
Nordjylland 3	400	290 bar/580°C/580°C/580°C	Bituminous	47	1998
Skærbæk 3	400	290 bar/580°C/580°C/580°C	NG	49	1997
Avedøre 2	400	300 bar/580°C/600°C	NG	49.7	2001

For the ferritic materials used in the power plants in Table 1, the limit for the materials lies just above 600°C. Therefore, to go further in the development of steam data, the project AD700 has been initiated within the VGB organization. The project is in its second phase (2002-2005) and 50% financed by the EU and the Swiss government. Vattenfall is one of the 35 companies taking part. The technical objective of the project is development and demonstration of an economically viable, pulverised coal-fired power plant technology with a net efficiency of more than 50% (without CO<sub>2</sub> capture) to be available shortly after 2010. The long-term target after year 2020 is net efficiency above 55% (without CO<sub>2</sub> capture) based on steam temperatures above 800°C.

AD700 covers new materials (Ni-based superalloys, austenitic steels), new materials manufacturing methods and new welding methods. Also boiler, turbine and other plant design issues will be addressed using these of these new and expensive materials. The project has recently decided on a large-scale test facility in the German Scholwen power plant.

Raw lignite contains roughly 50% of moisture, meaning that a non-negligible amount of the heat released during combustion is employed to evaporate water. Future lignite-fired plants will probably include lignite drying by using low-temperature heat from the steam power cycle or the flue gas. This will boost the efficiency to levels comparable with bituminous coal. The additional investment cost for lignite drying is likely to be balanced by the increase in plant efficiency so that the specific investment cost in EUR/MWh<sub>e</sub> is unaffected.

### *Reduced boiler heat losses and compact boiler design*

In the air-fired boiler, large quantities of inert nitrogen is heated as a consequence of the combustion process, and although this nitrogen is cooled down again, it has a temperature above the ambient as the exhaust gas is released. The heat loss with the flue gas in a conventional air-fired boiler amounts to up to 10%. A significant part of this loss is the heat energy that leaves with the nitrogen in the flue gas. In the O<sub>2</sub>/CO<sub>2</sub> recycle combustion boiler, there is no bulk nitrogen in the gas path, which in turn means that the heat losses with the flue gas can be significantly reduced. With the development of lignite drying through the use of low-temperature process heat, the inert flow through the boiler and thus the heat loss from the boiler will be further reduced.

Many studies, both theoretical and experimental, that are related to the combustion of coal in an O<sub>2</sub>/CO<sub>2</sub> atmosphere have been focusing on retrofit of existing PF boilers [3-8], where the boiler geometry is determined by the air-firing case, and where it has been a target for the O<sub>2</sub>/CO<sub>2</sub> recycle case to obtain combustion conditions (flame temperature, heat transfer) as similar as possible to those of the air firing case. Therefore, the recirculation of CO<sub>2</sub> from the boiler exhaust has been rather significant (typically around two thirds of the flue gas), in order to imitate the conditions during air firing, when nitrogen is present as an inert. Most likely, a first

generation of new oxyfuel boilers will also adapt this boiler design philosophy. With increasing knowledge and refined tools for modelling of combustion of lignite in an  $O_2/CO_2$  atmosphere, it will be possible to refine the boiler design for the second and third generations of boilers. A major target will be to reduce the rate of, or even entirely avoid externally recycled flue gas. To maintain the flame temperature within acceptable limits, internal recycling of flue gas inside the boiler can be used. This will reduce the size of the boiler significantly, which means that the efficiency loss due to thermal radiation to the environment will be reduced (this loss is already today quite small though, around 1% of the fuel thermal energy), and also reduce the electric power requirement for the flue gas recirculation fans. A significant reduction of the boiler size will also lead to a reduction in boiler investment cost, since the cost of the boiler is more or less proportional to the weight of the boiler parts.

Almost pure oxygen will be available for the combustion process in the boiler. This means that it will be possible to control and optimize the combustion process through the injection of oxygen in dedicated areas inside the boiler, which is not possible in air-fired boilers [6]. This means that the boiler design will have an additional degree of freedom compared to conventional air-fired boilers, which can be taken advantage of to control combustion conditions, emission formation and temperature distribution.

When oxyfuel combustion is applied to a CFB boiler, opportunities to significantly reduce the amount of flue gas recycle exist. In a CFB boiler, the combustion temperature can be controlled through the recirculation of bed material, meaning that  $CO_2$  recycle need not be very high, and that the boiler size and cost can be reduced in an easier manner than for the PF case. Alstom [12] have reported that pilot scale testing of oxyfuel CFB with  $O_2$  concentrations of up till 70% is being performed.

#### *Zero-emission power plant*

In pre-combustion and post-combustion capture, it is the  $CO_2$  that is removed from a mixture of gases. Typically, it is estimated in these cases that 85-90% of the  $CO_2$  from the power plant can be captured. In the oxyfuel case, on the other hand, it is water and non-condensable gases that are removed from the  $CO_2$ -rich stream. Fractions of  $CO_2$  may be dissolved in the water as it is condensed out from the  $CO_2$  rich exhaust, and some more  $CO_2$  may be lost during the process of removal of non-condensable gases. Nevertheless, almost all of the  $CO_2$  will be captured, and if deemed desirable, there may be a possibility for co-capture of other pollutants, mainly sulphur oxide. Should co-capture not be possible, the absence of bulk nitrogen in the flue gas means that the equipment for flue-gas desulphurization (FGD) and nitrogen oxide removal ( $deNO_x$ ) will have a smaller volume, and thus be cheaper, than the corresponding equipment for air-fired power plants. Furthermore, acid water-soluble pollutants will be dissolved in the water condensed from the process and not emitted to the atmosphere, which may very well be the case in atmospheric coal-fired boilers. The cleaning of the condensed water can be done with methods already commercially available. Also the particles that remain in the flue gas after the particle removal unit will to a large part be removed with the flue gas condensation. Altogether, with careful design, the  $O_2/CO_2$  recycle combustion power plant may offer a possibility for zero-emission or close-to-zero-emission not only of  $CO_2$  but also of other harmful substances.

### **Challenges with $O_2/CO_2$ recycle combustion of coal**

#### *Boiler design*

As described above, opportunities have been identified for boiler efficiency improvement and cost reduction for the  $O_2/CO_2$  combustion with or without recycle of flue gas. In order to be able to develop and take advantage of these opportunities, there are several challenges related to the boiler that must be faced.

*Fundamentals:* Combustion of coal in an  $O_2/CO_2$  atmosphere has been investigated experimentally on laboratory and pilot scale to increase the knowledge of combustion characteristics, and to support development of CFD modelling tools. A review of some studies can be found in [13] Many studies have a retrofit objective. There is a need for more experimental and modelling work enabling scale-up and optimization of the operating conditions of PF boilers with internal recycle, and reduced external recycle. Flame properties must be determined, as well as the combustion process, heat transfer, gas phase kinetics, behaviour of sulphur and nitrogen in an  $O_2/CO_2$  atmosphere, ash-behaviour, slagging and fouling, and composition of deposits. Evaluation of the resulting emissions has been made and a general conclusion appears to be that no major operational difficulties are encountered when recirculating a large amount of flue gas. Another frequently encountered conclusion is that  $NO_x$  formation is reduced compared to combustion in air, but it is not clear how the  $NO_x$  formation from fuel nitrogen is depending on the combustion process.

Unlike the  $N_2$  molecule, the  $CO_2$  and  $H_2O$  molecules are emitters of thermal radiation, meaning that when  $N_2$  is substituted with  $CO_2$  in the boiler, the heat transfer characteristics will change. There will be a need for verification and validation of reliable heat transfer models that include the changed thermal radiation characteristics. Concerning combustion and heat transfer, it is desirable that not only manufacturers' in-house codes but also commercial codes are developed and validated to fit the boiler performance in an  $O_2/CO_2$  atmosphere.

*Design:* Combustion of coal in pure oxygen gives a high flame temperature, which will cause ash melting and enhance the formation of  $NO_x$ . The suggested solution to this in a PF boiler is usually an external recirculation of flue gas, as shown in Figure 2. Since it is desirable to reduce the external recirculation rate to reduce the boiler size and increase the efficiency, the challenge is to design a boiler with internal recirculation of cooled gases inside the boiler to cool down the flame. This is very much the same as the thousands of existing oxyfuel applications in industry. As long as there is an external recirculation, it must also be decided at which point in the flue gas stream this recycle should be extracted. Most likely the recirculated stream should be extracted after a primary particle removal, to avoid extensive build up of particulates. Usually it is assumed that the stream is extracted before the flue gas condenser, although this is not obvious. Furthermore, a strategy for adding the oxygen in the boiler must be developed, so that  $NO_x$  formation and CO-levels can be kept low. Another challenge is related to the air leakage into the boiler. It must be determined how the boiler should be sealed or even work with overpressure to minimize air leakage, or if leakage air should be dealt with in the downstream gas cleaning process.

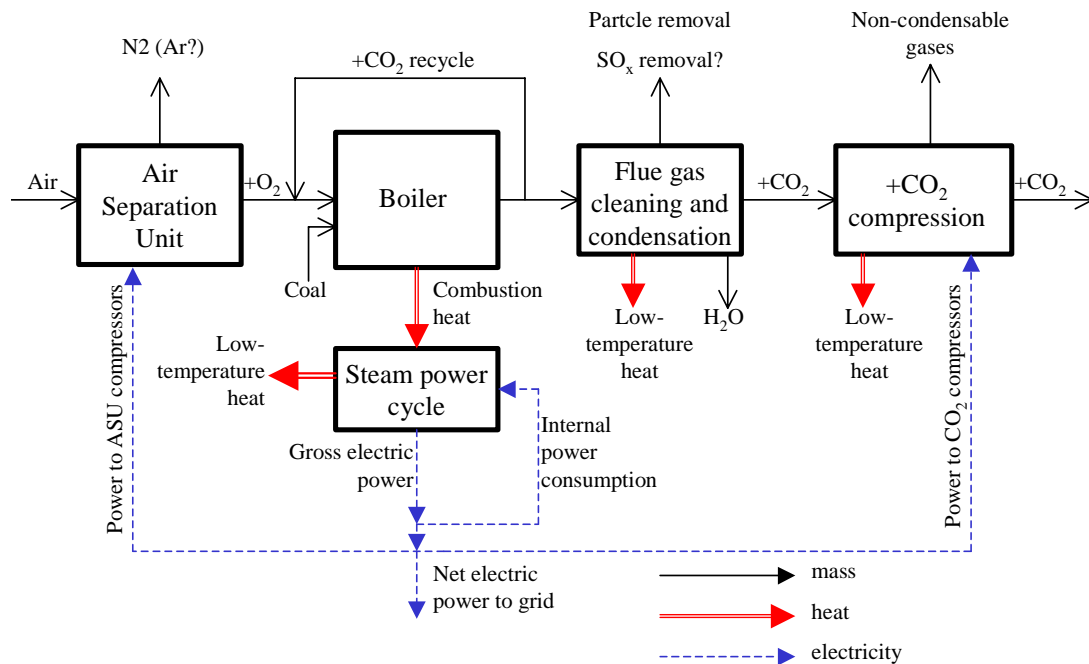
*Materials:* Higher  $CO_2$  contents in the flue gas means that the heat flux to the walls and superheaters will be higher and high-temperature corrosion is therefore likely to occur more rapidly in an  $O_2/CO_2$  combustion boiler than in an air-fired boiler. The reported increase of fouling and of  $SO_3$  in the deposits [5] will also increase the risk of corrosion. Corrosion testing is therefore necessary. Also, field-testing of an existing boiler before and after retrofit to  $O_2/CO_2$  combustion would be a useful way to investigate the increased corrosion risk. With increased knowledge of corrosion behaviour, requirements of boiler materials can be determined more accurately.

### *Oxygen production*

In general, studies of the oxyfuel technology for  $CO_2$  capture from coal assume that the oxygen is produced with a cryogenic air-separation unit (Cryo-ASU), although membranes and chemical looping are sometimes mentioned for future concepts [14], Cryo-ASU is the only available large-scale technology for oxygen separation from air at present. It will most likely be the technology employed in the first generation of  $O_2/CO_2$  recycle combustion capture of  $CO_2$ . The Cryo-ASU may be either of the low-purity kind, producing oxygen with 95% purity (the remaining 5% being mainly argon) or of the high-purity kind that produces oxygen of more than 99% purity. The high-purity Cryo-ASU is more expensive and more energy consuming than the low-purity Cryo-ASU. Roughly, the electric power consumption of a Cryo-ASU may amount to 20% of the plant gross power output for the  $O_2/CO_2$  recycle combustion power plant, which of course is very detrimental to plant efficiency.

In Figure 3, the main flows of mass, thermal energy and electric power are shown for the coal-fired  $O_2/CO_2$  recycle combustion power plant. The gross electric power output, which is produced by the electric generator, is partly consumed by the power plant internal consumption to drive e.g. feedwater pumps and flue gas recirculation fans. The two main consumers of energy in the plant are however the  $CO_2$  compression and the compression of air to the Cryo-ASU, which severely penalizes the plant net efficiency. Through optimisation of the  $CO_2$  compressors and introduction of intercooling between the compressor stages, the energy consumption for  $CO_2$  compression can be minimised. In many studies the compressors are assumed to use electric power from the grid or internal electric power. Since the motor drives are very large, almost two hundred MW in a 1000 MW plant, most likely they will be steam turbine drives. This means that a new optimization factor is introduced, namely the steam consumption in these drives. More efficient heat integration between the Cryo-ASU and the rest of the power plant will be a necessity. In [1] this was shown to be some 60 MW saving in a typical 1000 MW unit, including  $SO_x$  removal.

The replacement of the Cryo-ASU with some other means of less energy consuming oxygen separation from air has not been fully explored. As can be seen in Figure 3, there are three major sources of low-temperature heat in the plant. If any of this heat, in particular the low temperature heat that may otherwise be a loss, could be employed for oxygen production, this might reduce the efficiency penalty caused by the oxygen production.



**Figure 3:** Mass, heat and electricity streams in the  $O_2/CO_2$  recycle combustion plant. “+ $CO_2$ ” and “+ $O_2$ ” symbolizes that the streams may contain more than their main constituents

In the EU-project ENCAP, three non-cryogenic options for  $O_2$  separation from air are being investigated: 1) Membrane separation through ceramic oxygen-ion transfer membranes 2) Ceramic Auto-Thermal Recovery [14] and 3) Chemical looping combustion [15].

The application of any of these technologies to the  $O_2/CO_2$  recycle combustion of coal must lead to a closer integration of the oxygen production with the rest of the power plant process. It is too early to definitely judge these methods and determine which is the most suitable for  $O_2/CO_2$  combustion capture. It is at present not obvious that there is a benefit in terms of efficiency, investment cost and, in the end, the cost of electricity with these technologies compared to the Cryo-ASU.

#### *CO<sub>2</sub> purity requirements and flue gas cleaning*

Depending on the target for the  $CO_2$  (EOR or storage), the requirements on the purity of the  $CO_2$ -rich stream that leaves a power plant with  $CO_2$  capture will probably differ. This topic has not been much dealt with in process analyses of power plants with  $CO_2$  capture, and there are several question marks in this area that require attention. One major challenge is the technical and economical optimum specification. *Economically*, for the  $O_2/CO_2$  recycle combustion, it may be preferable if  $SO_x$ ,  $NO_x$ , non-condensable gases and the last fractions of water in the  $CO_2$  rich stream need not be removed, since this will reduce the plant investment required, and also most likely reduce the energy penalty caused by the  $CO_2$  capture. This might, however, require use of more expensive materials in e.g.  $CO_2$  compressors and pipelines. *Technically*, it is a question about how clean the  $CO_2$  must be for transport and further usage/storage, but also about how clean  $CO_2$  it is possible to obtain with different purification steps such as particle removal, water condensation, dehydration,  $SO_x$  removal and removal of non-condensable gases, and how to minimize the loss of  $CO_2$  to the atmosphere during the purification process.

*Particle removal* after the boiler is primarily a question of reducing deposits in the recirculation of the flue gas and what can continue with the flue gas stream from the process. This particle removal will probably be by cyclones in a primary step within the recirculation loop and with electro-static filters (ESP) or fabric filters thereafter in the reduced gas stream. The choice depends on system configuration, operating requirements, energy and economical analyses. Not all particles will be removed in an ESP though, but most of the remaining particles in the stream that is not recycled will end up in the flue gas condensate.

*Flue gas condensation* is a well-known method for heat recovery from moist flue gases to improve the overall efficiency in combined heat and power plants, and to remove pollutants in the case of waste incineration [16].

Usually, flue gas condensation technology is focused more on heat recovery than on efficient removal of moisture and pollutants. Also, there is an issue of scale-up. The fuel thermal input in a lignite-fired power plant boiler may very well be above 2000 MW<sub>th</sub>, whereas existing flue gas condensers are connected to boilers where the fuel thermal input is an order of magnitude smaller. It should be noted that with the introduction of lignite drying, the water contents of the flue gas will be reduced, but still significant residual moisture will be condensed and removed from the CO<sub>2</sub>-rich flue gas. In addition, the concentration of acid gases in the flue gas from oxyfuel combustion should be higher than in conventional flue gas. Corrosion-related issues must therefore be carefully handled for the flue gas path way and for the flue gas condenser.

SO<sub>2</sub> removal from the flue gas is well-known technology for large lignite-fired power plants, but it is also rather costly. There are two main issues that need to be resolved in the O<sub>2</sub>/CO<sub>2</sub> recycle combustion case. The first issue is whether it is possible to co-capture SO<sub>2</sub> with CO<sub>2</sub> and if the resulting stream has a composition that is acceptable for transport and storage, and is compliant with legal demands. If the answer is yes, the expensive desulphurisation system could be omitted. Theoretically, the critical constants of SO<sub>2</sub> lie close to those of CO<sub>2</sub>, therefore SO<sub>2</sub> with the concentrations found in the flue gas should be easily mixed with CO<sub>2</sub> under most operating conditions of the CO<sub>2</sub> processing. The main obstacles for the co-capture of SO<sub>2</sub> with CO<sub>2</sub> will be related to corrosion problems in connection to transport and storage, the concerns of safety, environmental regulation and legal related issues. The second concern is if it is possible to remove SO<sub>2</sub> from the flue gas in a process that is integrated with other gas cleaning processes, for example flue gas condensation, in a way that is more compatible with the requirements on both SO<sub>2</sub> removal and CO<sub>2</sub> recovery. Presently, both issues are open questions.

Dehydration to remove the water still remaining in the flue gas after the flue gas condenser may very well be necessary to avoid corrosion and hydrate formation, in particular if the SO<sub>2</sub> is not removed from the CO<sub>2</sub>-rich stream. The dryer the CO<sub>2</sub> stream, the higher the allowance for the corrosive components in the CO<sub>2</sub> stream. The final dehydration of CO<sub>2</sub> should be integrated into an intermediate stage in the CO<sub>2</sub> compressor train, exactly where is depending on the water solubility in the CO<sub>2</sub> under various pressures. Based on physicochemical properties of the CO<sub>2</sub> stream, including the choice of the dehydration processes, it will be possible to make an optimisation of primary water removal and further dehydration.

Removal of non-condensable gases, including N<sub>2</sub>, Ar, excess O<sub>2</sub> and NO<sub>x</sub> will take place as an integrated part of the CO<sub>2</sub> compression train if necessary. A phase transfer of CO<sub>2</sub> to the liquid state may be performed and thereafter the non-condensable gases are flashed from the liquid CO<sub>2</sub>. A high selectivity of the non-condensable gases for the separation is required in order to achieve a high CO<sub>2</sub> recovery and avoid that CO<sub>2</sub> is emitted to the atmosphere. Connected to this is the lack of knowledge of physical properties for mixtures of high-pressure CO<sub>2</sub> and non-condensable gases. To avoid emission of NO when releasing the stream of removed non-condensable gases to the atmosphere, it is important to ensure either that the fuel nitrogen is mainly converted to N<sub>2</sub> in the combustion process or that the stream of non-condensable gases is treated to convert the NO to N<sub>2</sub> through for instance ammonia injection at an appropriate gas temperature.

Another issue related to the non-condensable gas content in the flue gas is how much effort should be made to avoid that these gases enter the power plant. N<sub>2</sub> and NO formation from the fuel-nitrogen during the combustion cannot be avoided. There may also be some air leakage into the boiler, in particular with the fuel feed. The excess O<sub>2</sub> in the combustion should from this point of view be kept as low as possible, but some excess O<sub>2</sub> will be necessary to ensure complete combustion. Depending on the oxygen separation method, the oxygen that enters the O<sub>2</sub>/CO<sub>2</sub> recycle boiler may also very well contain argon and minor fractions of nitrogen. An overall economic and technical analysis will be necessary combined with boiler and combustion designs in order to decide whether to avoid as much as possible of the non-condensable gases upstream of the CO<sub>2</sub> processing or to separate them during the CO<sub>2</sub> processing.

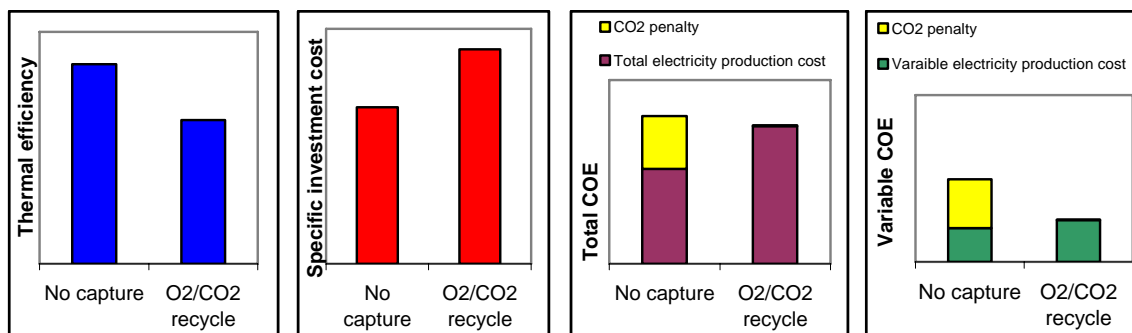
### **Process integration – the overall technical challenge**

The opportunities and challenges described above all sum up to the overall technical challenge, which is the overall power plant layout. Generally speaking, a power plant with CO<sub>2</sub> capture has a lower thermal efficiency than the equivalent plant without CO<sub>2</sub> capture. Energy-efficient integration of lignite drying, O<sub>2</sub> production, flue gas cleaning and recirculation in combination with boiler design and steam cycle layout will be necessary in order to minimize the negative impact of CO<sub>2</sub> capture. One issue that must be considered is that there are large quantities of low-temperature heat available, as indicated in Figure 3. Clever use of this heat so that the heat loss to the environment can be minimised will be a challenge. In the case where oxygen is produced with a Cryo-ASU, use of the cold waste N<sub>2</sub> for reduced temperature of the cooling water or for flue gas condensation could

also be an option to consider. An additional target during the design phase is that the power plant must be robust in operation and have a high reliability, availability and maintainability, which must be considered when evaluating process integration options.

### Cost of electricity – the driving force for power plant investment

From an investment decision point of view, plant economy is a major challenge for all concepts with CO<sub>2</sub> capture. A power plant will not be of interest to build unless it is economically viable, regardless of its technical performance. A power plant with CO<sub>2</sub> capture will not only have a lower thermal efficiency than the equivalent plant without CO<sub>2</sub> capture, it will also have a higher specific investment cost, as shown schematically in Figure 4. A power plant with CO<sub>2</sub> capture will first of all need to have a sufficiently low predicted total cost of electricity (COE) so that it is interesting to build, and also have a sufficiently low variable cost of electricity so that it will be operating as a base load plant once it is built. The gap in COE between plants with and without capture will have to be financed through sale of CO<sub>2</sub> for e.g. EOR and/or through the avoidance of CO<sub>2</sub> emission penalties.



**Figure 4:** Schematic illustration of differences between lignite fired plants with and without CO<sub>2</sub> capture through O<sub>2</sub>/CO<sub>2</sub> recycle combustion

Variable costs are the fuel cost, variable O&M costs and CO<sub>2</sub> emission penalties. Lignite is a very cheap fuel, and as mentioned above the O<sub>2</sub>/CO<sub>2</sub> recycle combustion power plant has the potential to be a zero-emission or close-to-zero-emission power plant, meaning that it will not be subject to any significant economic CO<sub>2</sub> penalty. The typical expected economic performance (excluding cost for transport and storage) of a lignite-fired O<sub>2</sub>/CO<sub>2</sub> recycle combustion power plant of around 900 MW<sub>e</sub> gross power production is shown in the two rightmost diagrams in Figure 4. In the case of a CO<sub>2</sub> emission penalty of, say, 20 EUR/ton CO<sub>2</sub>, the total COE will probably be slightly lower for the O<sub>2</sub>/CO<sub>2</sub> recycle combustion case than for a conventional power plant. The decision when to put the power plant into operation once it has been built, will be made based on the variable COE. Due to the reduced thermal efficiency, the power plant with O<sub>2</sub>/CO<sub>2</sub> recycle combustion capture will have a somewhat higher fuel consumption than the non-capture plant, but the cost for CO<sub>2</sub> emissions will be so significant for the non-capture plant, that its variable COE will be much higher than for the O<sub>2</sub>/CO<sub>2</sub> recycle combustion plant. This means that it is the O<sub>2</sub>/CO<sub>2</sub> recycle combustion plant that will have an advantage in the dispatch, be operated first and have the most operating hours of the two, and consequently it is this plant that is the most interesting to build of the two.

The comparison of total and variable COE for power plants with and without CO<sub>2</sub> capture is however not sufficient for a decision on to actually build one of several investigated concepts. COE for new power plants that are built must be compared with COE for other power plants on the same deregulated market. New power plants must be found to have a sufficiently low total COE to be profitable and a sufficiently low variable COE to be put in base-load operation.

### Concluding remarks

The development of lignite-fired power plants with O<sub>2</sub>/CO<sub>2</sub> recycle combustion for CO<sub>2</sub> capture is highly interesting, due to the possibility to use advanced steam technology, reduce the boiler size and cost and to design a zero-emission power plant. It may also have the economic performance that is required from a base-load plant operating on a deregulated electricity market with CO<sub>2</sub> emission penalties.

In order to realize this power plant concept, work is required on combustion and heat transfer to enable a good boiler design. A reduction of the required energy consumption for oxygen production and an integration of the CO<sub>2</sub> removal process are important to improve plant efficiency. Several topics connected to flue gas treatment

need to be given more attention as an integrated part of the power plant studies. There is also a lack of physical properties data for pressurized CO<sub>2</sub> with impurities.

A design with enhanced performance and reduced cost of a lignite-fired O<sub>2</sub>/CO<sub>2</sub> recycle combustion power plant is the overall target of one of the sub projects of the currently ongoing EU-project ENCAP, where Vattenfall acts as the coordinator.

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