GLOBAL CCS INSTITUTE

CO_2 CAPTURE TECHNOLOGIES

OXY COMBUSTION WITH CO_2 CAPTURE

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CONTENTS

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OXY COMBUSTION WITH CO_2 CAPTURE

Oxy-combustion methods/ technologies

The nitrogen that is approximately 80% of the air commonly used for combustion serves to dilute flue gas CO_2 content to less than about 15% for boilers and other thermal heat recovery systems. Post-combustion capture processes are designed to separate the relatively dilute CO_2 from the bulk flue gas nitrogen. In oxy-combustion processes, the bulk nitrogen is removed from the air before combustion. The resulting combustion products will have CO_2 content up to about 90% (dry basis). If regulations and geochemistry permit, the raw, dehydrated flue gas may be stored directly without further purification. Otherwise, the flue gas impurities (predominantly O_2, N_2, and Ar) may be removed by reducing the flue gas (at moderate pressure) to a temperature at which the CO_2 condenses and the impurities do not.

Oxy-combustion plants will include the following major component systems.

- Air Separation Unit (ASU) – This system separates oxygen from air and supplies the oxygen for combustion.
- Combustion / Heat Transfer / Gas Quality Control system (GQCS) – The components of this system are nearly the same as components for a corresponding air-fired plant. The fuel is burned with a mixture of oxygen (from the ASU) and recycled flue gas. The combustion products are cooled to usefully recover heat and, at a minimum, cleaned of fly ash.
- CO_2 Purification Unit (CPU) – At a minimum, the CPU will include a flue gas drying sub-system and compressors to deliver the product CO_2 to a receiving pipeline or geological storage site. If required, it will also include a partial condensation process to purify the product CO_2 and remove impurities to specified levels.

In addition, there will be material handling systems and thermal power utilization systems, and other balance of plant systems, but these are unlikely to differ significantly from their air-fired counterparts.

Oxy-combustion may be employed with solid fuels such as coal, petroleum coke, and biomass, as well as liquid and gaseous fuels.

Oxy applications

Oxy process for power generation

In order to exploit the extensive engineering experience designing and operating air-fired combustion/heat transfer equipment, a ‘synthetic air’ approach is generally used for oxy-combustion processes being proposed for steam-electric power plants. In the synthetic air approach, flue gas is recycled and introduced to the combustor with oxygen in proportions that mimic the combustion and heat transfer properties of air.

The alternative approach is to employ reduced flue gas recycle (compared to the synthetic air approach) which results in higher flame temperatures. While the high flame temperature approach has been deployed with fluid fuels in selected industrial applications, there is little or no relevant commercial-scale experience with this approach in large combustion / heat transfer systems. An objective of the reduced recycle/high flame temperature approach is a commensurate reduction in combustion/heat transfer/flue gas handling capital costs.

Figure 4-1 shows a block diagram of the major component systems for an oxy-fuel steam-electric power plant.

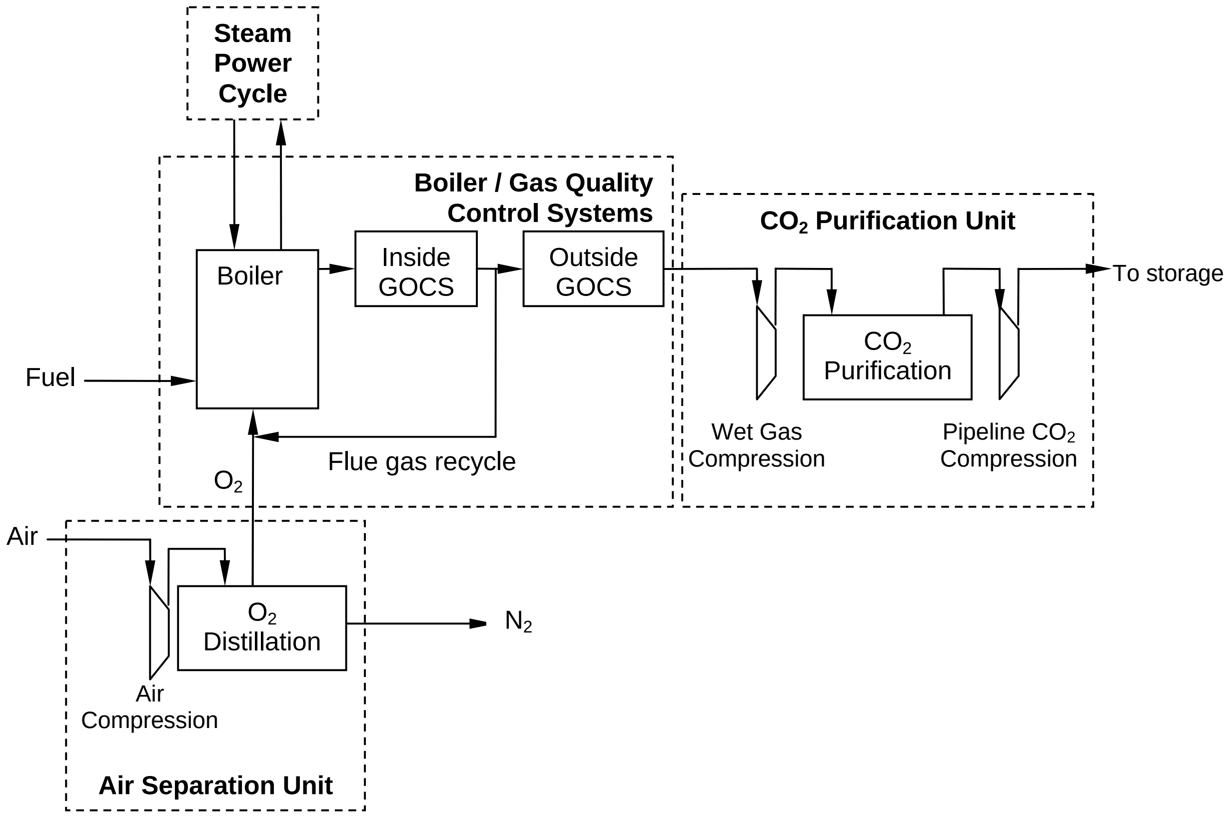

Figure 0-1: Oxy-Combustion Power Plant Simplified Block Diagram

Air separation unit

The incumbent technology for separating oxygen from air is distilling liquid oxygen at cryogenic temperatures. The technology is widely practiced on an industrial scale and is capable of producing a 99.5% pure oxygen product. It is the general industry consensus that the capital and operating cost (auxiliary power in the ASU air compressors) of producing the very high purity O_2 for oxy-combustion is not justified by the corresponding reduction in impurities in the flue gas. Thus, the O_2 produced for oxy-combustion is, typically, 95% - 97% pure, the balance being predominantly argon (Ar) and nitrogen (N_2). The primary energy cost in cryogenic air separation is auxiliary power for inlet air compression.

Combustion/heat transfer/flue gas handling systems

Boilers optimized for synthetic air oxy-combustion will be very similar to those optimized for air-combustion. Steam side temperatures and pressure capabilities developed for air-fired operation are also suitable for oxy-fired operation.

For solid fuels, either pulverized fuel or fluidized bed combustion systems may be employed. If specified, the equipment might be designed and operated to supply 100% capacity under both air- and oxy-fired conditions. Seamless transitions between air-firing and oxy-firing have been demonstrated at pilot scale.

Care must be exercised in design and construction of boiler / flue gas handling system components to minimize air in-leakage and minimize oxygen-to-flue gas leakage in recycle heaters. These leaks will serve to increase net flue gas flow rate and dilute flue gas CO_2 concentration.

Flue gas recycle

Up to 80% of the flue gas leaving the furnace is recycled to control temperatures. Net flue gas (not recycled) from oxy-combustion systems is approximately 20% - 25% that of an air-fired system due to the separation of nitrogen prior to combustion. Employing flue gas recycle will tend to increase the concentrations of minor flue gas components such as moisture, SOx, HCl, HF, and fly ash, unless means are employed to remove these materials inside the recycle loop. The same is generally true of NOx, but NOx in the recycle flow may also be destroyed in the furnace by reburning.

Flue gas quality control system costs are generally minimized by treating the net flue gas after the recycle loop rather than flue gas inside the recycle loop, due to the lower net flue gas flow. System designers are generally able to accommodate the higher flue gas moisture content without removing moisture inside the recycle loop. Fly ash is generally removed from the flue gas inside the recycle loop. The inherently lower NOx production (see below) from oxy-combustion generally does not require other active NOx removal systems.

SO_2 control

As in air-fired combustion, fuel sulphur is converted largely to SO_2 during oxy-combustion with traces of SO_3. SO_2 will accumulate in the flue gas recycle loop and, in boiler applications, must be controlled to maintain the SO_2 concentrations in the furnace below those at which excessive gas-side tube corrosion occurs. The accumulation of SO_2 in the recycle loop is illustrated in Figure 4-2 for a low-sulphur Powder River Basin (US) sub bituminous coal and a higher sulphur eastern (US) bituminous coal. The furnace SO_2 concentrations realized for the low sulphur fuel are sufficiently low under all conditions to not require SO_2 removal inside the recycle loop for boiler applications. This is not the case with the higher sulphur fuel. SO_2 removal from the recycle loop would be required to keep furnace concentrations below the 2,000 ppmv – 3,000 ppmv range above which gas-side tube metal corrosion would be excessive.

The SO_2 controls employed for air-fired flue gas are all suitable for oxy-fired flue gas. These include direct limestone injection in a circulating fluidized bed (CFB), wet flue gas desulphurization, and dry flue gas desulphurization. When forced oxidation is employed to support wet flue gas desulphurization, the oxidation vessel (where air is used to convert SO_3^{2-} to SO_4^{2-}) must be isolated from the scrubber vessel to preclude diluting the flue gas with air.

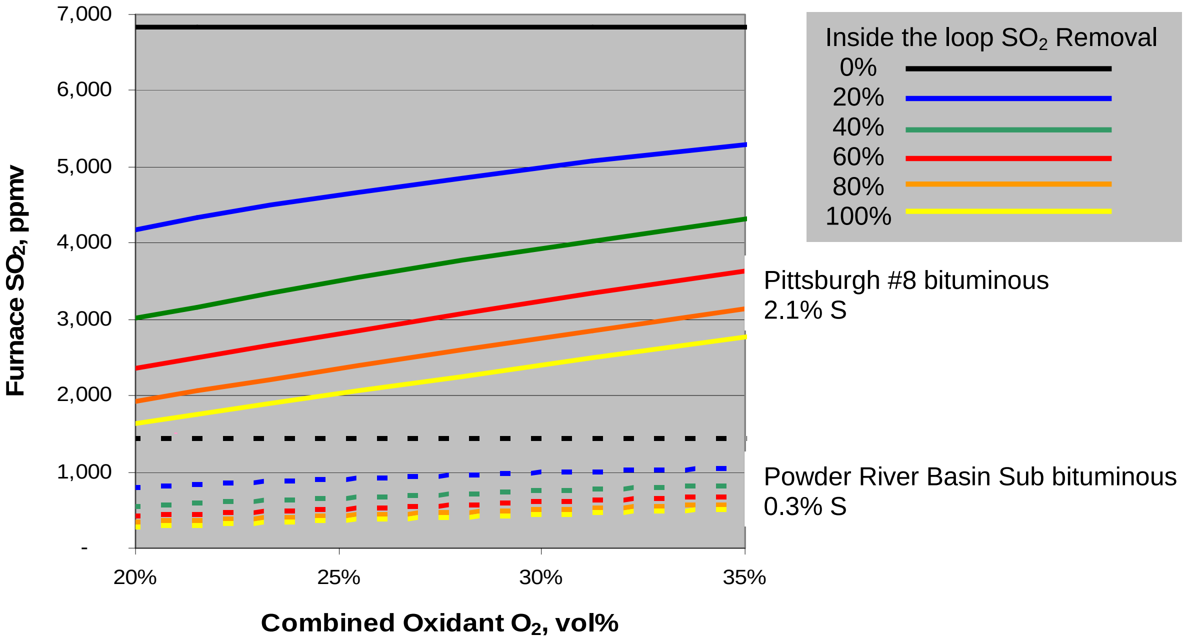

Figure 4-2: Oxy-Coal Furnace SO_2 content. Typical Oxy-coal process design is 25% - 30% O_2 in the

combined oxidant feed. Air-fired furnace SO_2 content is approximately the value at 21% O_2 and 100% Inside the Loop SO_2 Removal.

NOx control

Due to the low nitrogen concentrations at oxy-fired burners, thermal NOx production is minimized; NOx produced in the furnace comes primarily from fuel nitrogen. NOx production can be minimized by staging combustion and use of over-fire oxidant. In addition, as noted above, NOx entering the furnace with the recycle flue gas will be destroyed to a greater or lesser extent by the reburning mechanism. The aggregate effect is that, unless the facility is also specified for extended air-fired operation, the selective catalytic and selective non-catalytic NOx reduction technologies commonly employed for reducing NOx in air-fired flue gas are unlikely to be required for oxy-fired operations.

Particulate control

Removal of fly ash from oxy-fired flue gas is essentially the same as removing it from air-fired flue gas. Electrostatic precipitators or fabric filter bag houses are both suitable technologies. For designs where bag filters are cleaned by pulses of compressed gas, compressed CO_2 must be used (rather than compressed air) to preclude diluting the flue gas with air.

CO_2 purification/compression

The raw, wet flue gas entering the CPU will be cooled and compressed to intermediate pressure. CO_2 purification will always include deep drying. The dried, raw flue gas will contain 10%-30% diluents (Ar, O_2, and N_2) and trace contaminants (SO_2, SO_3, NO, NO_2, CO, etc.). If local regulations, geochemistry, and project parameters allow, the raw, dry flue gas may be compressed to pipeline or injection pressure with no further processing. Under these conditions, CO_2 capture will be 100% and there will be zero ambient air emissions.

If removal of diluents and trace contaminants is required to meet pipeline, geological or other CO_2 purity requirements, a partial condensation process is used to achieve product CO_2 purity specifications. In the partial condensation process, gases with a dew point lower than CO_2 are separated from the product CO_2 and vented. These include the diluents O_2, N_2, and Ar, the traces of CO produced in the furnace, and any residual NO not destroyed during wet compression (see below). The actual vent must be designed to effectively disperse the vent gas such that ground level concentrations of CO and CO_2 do not rise above local ambient standards. Gases with dew point higher than CO_2 (SO_2, NO_2) will condense with the product CO_2.

As indicated above, if the geochemistry, regulations, and other project parameters permit, it may be possible to compress and inject directly into storage the dried, raw flue gas. There is, however, uncertainty in the effect of the diluents and trace contaminants on the geochemistry of storing CO_2. Field experience transporting and storing dehydrated raw flue gas from oxy-natural gas combustion is being logged by Total as part of the Lacq project in southern France[1]. The CO_2 Capture Project® will be undertaking field tests for which oxy- flue gas will be stored underground[2]. Among other objectives, these activities are organized to evaluate the suitability of the impure CO_2 for geological storage.

While there are likely to be capital cost savings in not installing a CO_2 purification system, the greatest capital expense in the CPU is for compressors. There will be incrementally higher capital costs associated with larger compressors, larger pipelines, and larger storage volume to handle the diluents. Selection of pipeline materials may be affected by the diluents and trace contaminants. There may also be an incrementally higher power use associated with compressing the diluents. Various design efforts undertaken to date do not reach consistent conclusions on whether there are cost advantages to this strategy, presuming regulations and geochemistry permit[3,4,5].

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[1] Lacq *CCS Pilot Plant: Operational Feedback of the Surface Facilities One Year after Start-up.* IEAGHG 2nd Oxy-Fuel Combustion Conference. Yeppoon, Queensland, Australia. 12-16 September 2011.

[2] CO_2 Capture Project.

[3] *Energetic Evaluation of a CO_2 Purification and Compression Plant for the Oxyfuel Process*. R. Ritter, et al. IEA 1st Oxy-fuel Conference, Cottbus, Germany, September 7-10, 2009.

Cooling / Compression / Dehydration

During wet flue gas compression, much of the NOx entering with the flue gas will be oxidized to HNO_3 and captured by condensate in inter-coolers and/or final cooler/wash. The compression process may be designed to enhance NOx oxidation and capture. The compression process may also be designed to oxidize residual SO_2 to soluble SO_3 with subsequent capture along with HNO_3 in condensate.

The compressed flue gas is dried and, if a partial condensation purification process is employed, cleaned of residual mercury in the flue gas with activated carbon to preclude mercury-induced corrosion in the brazed aluminum components of the partial condensation process equipment.

The product CO_2 is finally compressed to the receiving pipeline pressure or well injection pressure. The primary energy use in the CPU is auxiliary power to perform the wet and dry compression.

Partial Condensation

Pressurized CO_2 is cooled to near -50°C (-58°F), at intermediate pressure, to condense the product CO_2. The liquid CO_2 is physically separated from the bulk impurities which are vented. Residual impurities in the liquid CO_2 may be separated by distillation to achieve a specified CO_2 purity. The liquid CO_2 is then used as a refrigerant and flashed to gaseous CO_2 to provide the refrigeration necessary for the process. The pressure drop associated with flashing the CO_2 to provide refrigeration must be made up during compression to pipeline / injection pressure.

Vent Gas CO_2 Recovery

Vent gas from a partial condensation process will largely contain the bulk impurities (O_2, N_2, and Ar) but will also contain CO_2 at a concentration up to 35%. This amounts to about 10% of the flue gas CO_2. Absorption processes and membrane processes have been proposed to recover CO_2 from the relatively modest vent gas stream at an incremental cost to capture well below the overall cost to capture CO_2. By this means, up to approximately 98% of the CO_2 in the flue gas might be captured.

Oxy-Fired Power Plant Performance

The gross power production (turbo-generator output) from an oxy-fired power plant will be essentially the same as a comparable air-fired power plant and is largely dependent on the efficiency of the steam cycle and not whether air or oxygen is used to burn the fuel. The oxy-fired plant will have increased auxiliary power use as indicated in Table 4-1. The increased auxiliary power use will serve to reduce the oxy-fired plant net power production and decrease oxy-fired plant net efficiency compared to an air-fired plant with comparable gross output. The data in Table 4-1 is ‘typical’ for plants employing an ultra-supercritical steam cycle with cryogenic air separation and partial condensation CO_2 purification.

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[4] *Economic Assessment of Carbon Capture and Storage Technologies*. Global CCS Institute. 2009.
[5] *Engineering and Economic Evaluation of Oxy-Fired 1100°F Ultra-Supercritical Pulverized Coal Power Plant with CO_2 Capture: Final Report*. EPRI, Palo Alto, CA: 2011. 1021782.

Table 0-1: Oxy-Coal power plant performance.

Note: An ultra-supercritical steam cycle is used. The 100% basis is the net power produced by the air-fired plant (before CO_2 capture).[6]

		Air-fired	Oxy-Fired
Gross Generation	MWe	106%	(*) 107%
ASU Power Use	MWe	-	14%
CPU Power Use	MWe	-	(**) 9%
Other Power Use	MWe	6%	7%
Net Power	MWe	**100%**	77%

(*) Increased gross generation includes thermal recovery from ASU and CPU

(**) CO_2 delivered at 150 bar, 99.99+% purity

Oxy Process for Cement Manufacture[7]

Portland cement is manufactured by calcining mixtures of limestone and silicates at temperatures in excess of 1400°C (2550°F). Fuel is burned in the calcining kilns to achieve the required temperatures. Extensive gas-solid heat recovery is practiced to minimize fuel use consistent with maintaining high product quality. Selected cement plants have employed oxygen-enriched air combustion to achieve the high kiln temperatures. Use of oxygen-enriched air allows for increased product throughput.

CO_2 emissions from the kiln include CO_2 produce by combustion of the fuel (approximately 40% of the total) and CO_2 liberated from the limestone as a result of calcining reactions (approximately 60% of the total). Flue gas CO_2 content up to 25% is experienced under these conditions. Petroleum coke is used to fire approximately half of the worldwide cement production, coal approximately a quarter, and other solid and fluid fuels the remaining quarter. Over 70% of worldwide cement manufacture capacity is located in Asia.

The overall application of oxy-combustion with CO_2 capture to cement manufacture is shown in Figure 4-3. The ASU and CPU systems are essentially the same as those described above for an oxy-combustion power boiler. The cement production process itself must be adjusted for oxy-combustion for at least two reasons: 1) the elevated CO_2 concentrations in the high temperature calcining process raises the required calcining temperature by up to 80°C (140°F), and, 2) The gas-solid heat transfer scheme which minimizes fuel use must be specifically developed for the flows and composition associated with oxy-combustion. Suitable designs for new plants can be developed, but retrofitting existing plants while maintaining production capacity and quality will be challenging. Additionally, efforts must be undertaken to minimize air in-leakage which would dilute the flue gas CO_2 content.

Particulate control is required for the flue gas being recycled and entering the CPU. As with the power boiler application, NOx production is reduced; selective and non-selective catalytic reduction systems are not required. SO_2 and SO_3 resulting from fuel sulphur combustion are captured in the cement product and no added flue gas desulphurization system is required.

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[6] Data developed from *Engineering and Economic Evaluation of Oxy-Fired 1100°F Ultra-Supercritical Pulverized Coal Power Plant with CO_2 Capture: Final Report*. EPRI, Palo Alto, CA: 2011. 1021782.
[7] *CO_2 Capture in the Cement Industry: Phase II Report.* European Cement Research Academy. TR-ECRA-106/2009. 2009.

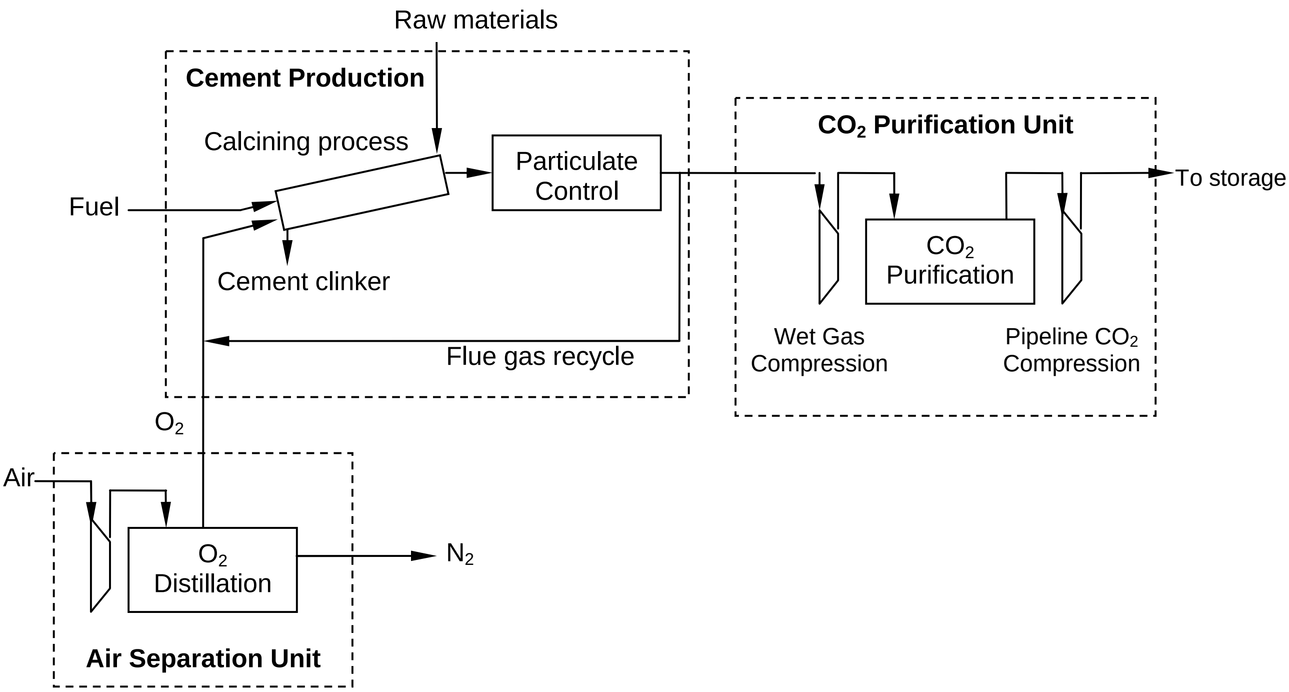

Figure 0-3: Oxy-Combustion Cement Manufacture Simplified Block Diagram

Oxy-Combustion: Current Status / Technology Providers

The component systems currently anticipated for full scale oxy-combustion applications (up to 3,200 MWth) have achieved commercial-scale readiness in other applications as follows:

- The largest single–train cryogenic ASU installed for industrial oxygen production is approximately 5,000 tonnes/day O_2. Three of trains of approximately this capacity would be required for a 2,000 MWth (~800 MWe) steam electric power plant. Cement plant oxygen demand will be substantially less, up to 2,000 tonnes/day. The primary design challenges for delivery of oxygen to large combustion appliances will be: 1) to optimize costs of delivering oxygen, 2) timely response to changes in oxygen demand from the host plant, and, 3) minimizing auxiliary power consistent with minimizing overall costs of delivering oxygen. Cryogenic air separation units are being offered by a number of industrial gas companies. Leading vendors include:
  - Air Products and Chemicals, Allentown, PA, USA
  - Air Liquide, Paris, France
  - Linde Engineering, Pulach, Germany
  - Praxair, Danbury, Connecticut, USA
- Under the ‘synthetic’ air approach, conventional, well-proven, atmospheric pressure combustion / heat transfer design tools may be used to design an oxy-fired boiler or other fired heating appliance at capacities up to 3,200 MWth heat input (~1,400 MWe). Extensive pilot-scale (<40 MWth) development of components such as burners, heat transfer surface, gas quality control systems, recycle fans, electrostatic precipitators, fabric filter bag houses, flue gas desulphurization, etc. have been undertaken by a number of vendors to validate their design tools. Leading steam-electric boiler vendors include:
  - Alstom, Levallois-Perret Cedex, France
  - Babcock and Wilcox, Barberton, Ohio, USA
  - Foster-Wheeler, Clinton, New Jersey, USA
  - Doosan Babcock, Crawley, West Sussex, United Kingdom

  - Babcock-Hitachi, Tokyo, Japan
  - Mitsubishi Heavy Industries, Tokyo, Japan
- Partial condensation CO_2 purification units are in service at industrial scale, removing a wide variety of contaminants depending on the source of the CO_2. None of these installations have all of the impurities commonly found in coal-fired flue gas. Neither do any of these facilities employ the auto-refrigeration process (using the liquid CO_2 produced as the refrigerant) envisioned for large oxy-combustion plants. The largest single-train partial condensation CO_2 purification process deployed commercially is approximately 4,000 tons CO_2 per day. Four trains of approximately this capacity would be required for a 2,000 MWth plant (~800 MWe) power plant.
  - Air Products and Chemicals, Allentown, PA, USA
  - Air Liquide, Paris, France
  - Linde Engineering, Pulach, Germany
  - Praxair, Danbury, Connecticut, USA

The greatest remaining technical challenge is integrating these systems into a complete steam-electric power plant.

It should be noted that the oxy-combustion/CO_2 capture power plant designs being developed and deployed for service in the next 4-5 years are based on individual component technologies and arrangements which have demonstrated sufficient maturity. These plant designs, however, may not be optimized. As experience is gained, it is likely that evolutionary changes in oxy-combustion plant flow sheets (with CO_2 capture) will serve to reduce capital and operating costs and improve plant performance.

Pilot Plant Projects Underway

Vattenfall has operated a dried lignite-fueled 30 MWth pilot plant at their Schwartze Pumpe power station in Germany since mid-2009[8]. Component systems installed include ASU, oxy-PC boiler, gas quality control systems, and externally-cooled, partial condensation CPU. Liquid CO_2 is trucked off-site to industrial markets.

The Schwarze Pumpe project has shown achievement of TRL-6 for oxy-combustion with CO_2 capture (for application to electric power production). The results of the project have given Vattenfall sufficient confidence in the technology to progress to design of a 250 MWe oxy-coal sub-scale commercial demonstration plant.

Total's Lacq project, located west of Lyon, France, has also shown achievement of TRL-6 for oxy-natural gas combustion and geological storage of raw, dried oxy-combustion flue gas. Component systems include an ASU, an oxy-natural gas 30 MWth boiler, flue gas cleaning/compression/drying and direct injection of the raw, dried flue gas into a depleted natural gas reservoir[9]. This plant has been in service since early 2010.

CIUDEN is completing construction of an oxy-coal test facility in Spain that includes a 20 MWth oxy-PC boiler and a 30 MWth oxy-CFB boiler. Liquid oxygen is trucked to the site. A slip stream CPU is employed. Oxy-coal operations will commence in 2011. Successful operations at CIUDEN will show achievement of TRL-6 for oxy-combustion with CO_2 capture as applied to electric power production

CS Energy has converted a retired 100 MWth (25 MWe) pulverized coal power plant to oxy-combustion at the Callide station in Queensland, Australia. The facility includes an ASU, oxy-PC boiler, steam turbo-generator, and a slip stream CPU capturing approximately 10% of the CO_2 produced. The liquid CO_2 will be trucked to storage site injection wells. Oxy-coal operations will commence in 2011. Successful operation of this plant will show achievement of TRL-7 for oxy-combustion with CO_2 capture as applied to electric power production.

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[8] *Oxy-Combustion Testing in 30 MWth Pilot Plant Schwartze Pumpe*. IEAGHG 2nd Oxy-Fuel Combustion Conference. Yeppoon, Queensland, Australia. 12-16 September 2011.
[9] Lacq *CCS Pilot Plant: Operational Feedback of the Surface Facilities One Year after Start-up.* IEAGHG 2nd Oxy-Fuel Combustion Conference. Yeppoon, Queensland, Australia. 12-16 September 2011.

Sub-Scale Commercial Demonstration Plants in Development

Four sub-scale commercial demonstration plants are in development world-wide. All of these are in the planning/engineering stages and the decision to proceed to construction has yet to be made. These projects will result in a commercially-dispatched, integrated, oxy-coal steam electric power plants. Successful operation of one or more of these plants would show achievement of TRL-8 for oxy-combustion with CO_2 capture as applied to electric power production.

Full Scale Commercial Projects in Development

There are currently no full scale (1,000 – 2,000 MWth) oxy-fired projects under development.

Technical Readiness of Oxy-Combustion for Cement Manufacture

The European Cement Research Academy (ECRA) has developed a research and development plan that would result in a demonstration plant (successful operation of which would achieve TRL-8 or TRL-9) project starting in the 2014-2015 time frame[10]. Preliminary studies undertaken by ECRA have achieved TRL-5[11]. Laboratory and Process Development unit activities are underway to achieve TRL-6 in 2011. The plan calls for construction and operation of an oxy-combustion cement manufacture pilot plant, successful operation of which would achieve TRL-7, in the 2011-2014 time frame.

Oxy Future Direction / Challenges

Retrofit / Repowering

Existing air-fired power plants might be retrofitted with an ASU, oxy-fired burners, flue gas recycle, and a CPU. The resulting plant would be derated by the auxiliary power these systems consume less any improvement in steam cycle capacity that might be available. Alternatively, the existing plant, typically a sub-critical steam cycle, might be repowered by adding an ultra-supercritical topping steam cycle and a new, ultra-supercritical, oxy-fired boiler. While such retrofit/repowering schemes have been proposed, it has yet to be shown that they can result in an oxy-fired plant that is lower in cost than an optimized, new-build plant. The large fleet of air-fired power plants in service, however, calls for more study of this option.

Lower-cost O_2 production

The cryogenic ASU is costly and the largest auxiliary power use in an oxy-fired power plant is for the air compressors in the ASU. Any oxygen separation process that reduces auxiliary power is likely to be an economic boon to the oxy-combustion option. Two of the leading technologies under investigation:

- Chemical Looping Combustion (CLC) – oxygen is separated from nitrogen by a reversible reaction with suitable solids which are then transferred to a ‘combustor’ where the solid-oxygen reaction is reversed, the fuel burned, and the resulting CO_2 produced in concentrated gas stream. Bench-scale activities are on-going to identify suitable solids (work to achieve TRL-5). Process development units are being constructed for developing solids handling schemes and to characterize performance of the candidate solids and the overall process[12] (work to achieve TRL-6). A successful CLC process would dramatically reduce auxiliary power use in air separation by replacing the air compressors in a cryogenic ASU with fluidizing blowers in the CLC process.
- Ion Transport Membrane (ITM) – Selected ceramic materials exclusively allow oxygen ions to migrate through the solid. The process takes place at very high temperatures (~1,000°C, ~1,800°F) and moderate pressure across the membrane is required. Operations are underway to achieve TRL-7 with the native ITM

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[10] *CO_2 Capture in the Cement Industry: Phase II Report.* European Cement Research Academy. TR-ECRA-106/2009. 2009.

[11] *ibid*.

[12] *Chemical Looping Combustion Prototype – Alstom*. National Energy Technology Center, US Department of Energy. Contract Number: DE-NT0005286. May 2011.

technology[13]. In addition to developing the native ITM technology, it will be a challenge to effectively integrate the native technology into an oxy-combustion power plant.

Low Recycle Operations

Reducing the flue gas recycle required for 'synthetic air' has the potential to reduce boiler size/cost. Low-recycle operations a have been conducted at PDU scale (~15 MWth) achieving TRL-6.

Pressurized Oxy-Coal Combustion

Conducting the oxy-combustion under gas pressure would marginally reduce auxiliary power, primarily in the flue gas recycle fan. A gas-pressurized boiler plant could also reduce latent heat loses in the flue gas (higher boiler efficiency) by recovering the heat of flue gas moisture condensation at a temperature usable to the power cycle. Pressurized oxy-combustion process development has been conducted at the 5 MWth level, achieving TRL-6. There are a number of developers proposing pressurized oxy-combustion pilot plant operations which would achieve TRL-7 but none of these have reached the deployment stage. There is relevant pressurized air-coal combustion experience up to 250 MWth which might be applicable.

A parallel challenge to pressurized oxy-combustion process development is development of the associated gas-pressurized boiler design. Capital costs for pressurized oxy-coal power plants with uncertainty comparable to atmospheric pressure oxy-coal power plants await more detailed component designs, particularly the gas-pressurized boiler.

Ultra-low Emissions

By its nature, an oxy-coal power plant is likely to be a 'near zero' emitter of all criteria pollutants excepting, possibly, carbon monoxide. This is a side effect of either: 1) compressing and storing the entire flue gas flow (zero emissions to the ambient air), or, 2) the nature of the partial condensation CO_2 purification process. Carbon monoxide production is comparable to air-firing, and, if a partial condensation purification process is employed, the CO will be vented along with the bulk flue gas impurities (including oxygen). Provisions for oxidizing the vent gas CO would reduce steady state emissions of all criteria pollutants to 'near zero'.

In addition, suitable start-up and shut-down sequences of operation which do not require air-firing (and resultant elevated NOx production) might be developed and for which near-zero emissions levels would be achieved for all operating states.

GQCS – CPU optimization

The unique chemistry of NOx and SO_2 during wet compression might be exploited to reduce or eliminate bulk flue gas desulphurization requirements in the flue gas quality control system, transferring bulk desulphurization to the CPU. This would potentially result in a significant overall plant capital cost reduction.

Prospective Oxy-Combustion Power Plant Efficiency Improvements

The state of the art (2011) in steam-electric power plant design employs a high efficiency, ultra-supercritical steam turbine cycle. Such a cycle would likely be selected for an oxy-fired power plant with CO_2 capture employing an atmospheric pressure boiler. An analysis has been conducted on the performance and cost of such a power plant in comparison to an air-fired power plant employing the same steam turbine-generator[14]. The air-fired plant has a net power generating efficiency of 39.0% (HHV). The comparable oxy-fired plant has a net efficiency of 31.5%, a 7.5 percentage point drop associated with power used in the ASU air compressors and CPU CO_2 compressors, and flue gas recycle fan.

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[13] *Development of Ion Transport Membrane (ITM) Oxygen Technology for Integration in IGCC and Other Advanced Power Generation System.* National Energy Technology Center, US Department of Energy. FT40343, June 2011.
[14] *Engineering and Economic Evaluation of Oxy-Fired 1100°F Ultra-Supercritical Pulverized Coal Power Plant with CO_2 Capture: Final Report*. EPRI, Palo Alto, CA: 2011. 1021782

The several future efficiency improvements to the oxy-combustion process for power generation include:

- employing an Advanced USC steam turbine cycle: 680C/700C/352 bar (1256F/1292F/5100psia), approximately 3.5 percentage point improvement;
- gas pressurised oxy-combustion – reduction of recycle fan auxiliary power use and improvement of boiler efficiency, approximately 1.4 percentage point improvement; and
- chemical looping combustion for O_2 separation – dramatic reduction of auxiliary power used in air separation, approximately 5 percentage point improvement.

These data are shown in Figure 4-4. The benefits of both gas pressurized oxy-combustion and chemical looping combustion may be difficult to achieve together. Nonetheless, chemical looping combustion combined with an advanced ultra-supercritical steam turbine cycle may well be more than adequate to make up for the added auxiliary power in the CO_2 purification unit and recycle fan resulting in an oxy-combustion plant with near zero emissions of conventional pollutants, up to 98% CO_2 capture, and efficiency comparable to the best power plants currently being built.

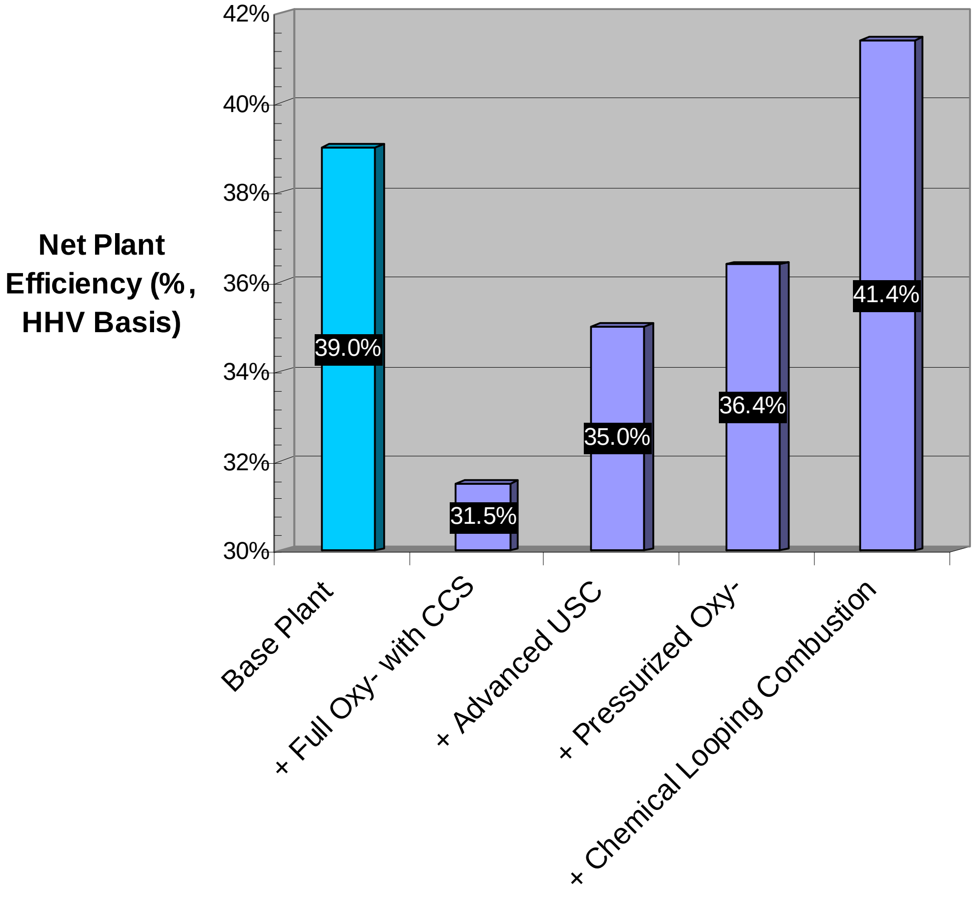

Figure 0-4: Oxy-Combustion Developments to recover Energy Losses from CO_2 Capture

ACRONYMS AND SYMBOLS

AFBC	Atmospheric Fluidized Bed Combustion
AGR	Acid gas removal
AQCS	Air Quality Control System
ASU	Air Separation Unit
B&W	Babcock & Wilcox
Bara	Bars absolute
Barg	Bars gauge
BFW	Boiler feedwater
BP	British Petroleum
Btu	British thermal unit
CC	Combined Cycle
CCGT	Combined Cycle Gas Turbine
CCPI	Clean Coal Power Initiative
CCS	CO_2 capture and Storage (or Sequestration)
CCT	Clean Coal Technology
CF	Capacity Factor
CFB	Circulating fluidized bed
CHP	Combined Heat and Power
CO_2	Carbon dioxide
COE	Cost of electricity
COP	ConocoPhillips
CT	Combustion Turbine
DOE	U. S. Department of Energy
DOE NETL	Department of Energy National Energy Technology Laboratory
ECUST	East China University of Science and Technology
EEPR	European Energy Programme for Recovery
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
FBC	Fluidized-bed combustion/combustor
FEED	Front End Engineering Design
FGD	Flue gas desulphurization
FOAK	First of a kind
F-T	Fischer Tropsch
ft^3	Cubic feet
FW	Foster Wheeler
FWI	Foster Wheeler Italiana
GHG	Greenhouse Gas
GI	Gasification Island
GJ	Gigajoule
gpm	Gallons per minute (US)
GT	Gas Turbine
H_2S	Hydrogen sulphide
HgA	Mercury absolute
HHV	Higher heating value
HRSG	Heat recovery steam generator
HP	High pressure
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IP	Intermediate pressure
IPP	Independent power producer
kJ	Kilojoules
KBR	Kellogg, Brown & Root
LCA	Life Cycle Analysis
LCOE	Levelised Cost of Electricity

LHV	Lower heating value
LP	Low pressure
LSTK	Lump Sum Turnkey
mt	Metric ton
MDEA	MethylDiethanolamine
MMBtu	Million Btu
MPa	Mega Pascal
MTG	Methanol to Gasoline
MTO	Methanol to Olefins
NCCC	National Carbon Capture Center
NDRC	National Development and Reform Commission (China)
NETL	National Energy Technology Laboratory
NGCC	Natural Gas Combined Cycle
NH_3	Ammonia
Nm^3	Normal cubic meters
NO_X	Nitrogen oxides
NSPS	New Source Performance Standards
OCGT	Open Cycle Gas turbine
O&M	Operation and maintenance
PC	Pulverized Coal
PCC	Post Combustion Capture
ppmv	parts per million by volume
PRB	Powder River Basin (Coal)
PSDF	Power System Development Facility
psia	Pounds per square inch absolute
psig	Pounds per square inch gage
R&D	Research & Development
RD&D	Research, Development and Demonstration
RQ	Radiant Quench (GE)
RTI	Research Triangle Institute
RWE	Rheinische Westphalien Electricidadeswerke
SCFD	Standard Cubic Feet per day
SNG	Substitute Natural Gas
SCPC	Supercritical Pulverized Coal
SCR	Selective catalytic reduction
SO_2	Sulphur dioxide
SRU	Sulphur Recovery Unit
st	Short ton (2000 pounds)
stpd	Short tons per day
TCR	Total Capital Requirement
TFC	Total Field Cost
TPC	Total Plant Cost
USC	Ultra Supercritical
US EPA	US Environmental Protection Agency
WGCU	Warm gas clean up