Technical Paper

BR-1850

Oxy-Coal Combustion for Low Carbon Electric Power Generation

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Presented to:
Fifth International Conference on Clean Coal Technologies

Date:
May 8-12, 2011

Location:
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B&W babcock & wilcox power generation group

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Abstract

Low carbon electricity production is the logical progression for the future use of coal as a primary power generation technology in an inclusive energy portfolio. Carbon capture systems development has matured to the point that projects are now focused on commercial-scale validations. The impact of increased energy production from renewables and nuclear power will create the need for additional degrees of freedom in carbon capture systems to provide flexibility and surety of operation. The current best technology for new build coal-fired power is ultra-supercritical pulverized coal with oxy-coal combustion for carbon capture and near-zero emissions.

The commercial development of carbon capture systems must now take on the added requirements of flexibility to meet changing power demand profiles and generation technologies in the growing market. These considerations are also manifest in the design of the systems and construction planning, such that both capital and operating costs are minimized, thereby reducing project risk and providing operating flexibility. Oxy-coal combustion technology is ready to provide solutions to meet these challenges.

In collaboration with EPRI and URS Corp., Babcock & Wilcox Power Generation Group, Inc. (B&W PGG) is completing a new build reference plant design study, detailing the engineering and economics. Utilizing current ultra-supercritical boilers and advanced oxygen production, this design incorporates the scale-up required for any central power station. Steam generator technology has demonstrated its flexibility and cycling capabilities, and recent demonstrations have proven oxy-coal combustion operations. Oxygen production using multiple compressors, multiple air separation unit (ASU) trains and liquid oxygen storage systems, provides a unique opportunity for capture flexibility. Results of this study will be discussed.

B&W PGG has completed pilot-scale evaluation of oxy-coal combustion at 30 MWth. Ongoing work continues in material evaluations, determining the effects of using additional coal-types, and overall system modeling and simulation. The United States (U.S.) has recently announced the award of the FutureGen 2.0 oxy-combustion coal power project to Ameren Energy with B&W PGG and Air Liquide. The repowering project will be 200 MWe for full-scale capture and storage and validate the technology for commercial readiness. Details of the project development in Phase 1 will be discussed.

Introduction

Oxy-coal combustion for low carbon electric power generation

Historically, ever-tightening emission constraints on coal-firing across different regions of the world have driven new technology developments. Globally, two forces seem to be pushing forward – use of coal for steadily growing world-wide electric power needs, and world politics increasingly singling out coal-fired power plants as a major point-source contributor to global climate change due to carbon dioxide (CO_2) emissions (Figure 1). With CO_2 becoming a regulated emission in the U.S. and Europe, new technologies to capture CO_2 are under development. For coal to continue to drive power generation and economic expansion across the globe in the most environmentally friendly manner, technologies must continue to be developed to reduce coal plant emissions to near zero. Current regulations to control emissions of sulfur oxides (SO_X), nitrogen oxides (NO_X), particulate matter (PM) and, more recently, mercury (Hg) continue driving higher levels of removal efficiency.

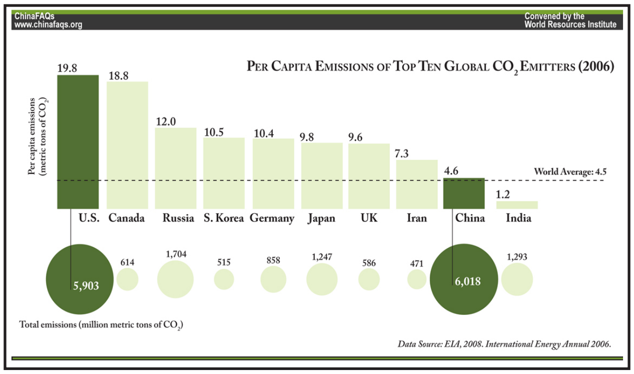

Fig. 1 Emissions of CO_2, select countries (WRI).

The next steps to take, on parallel tracks, are to develop the advanced ultra-supercritical (A-USC) steam cycle (700C steam temperature) plant, which will have energy efficiency near 53% LHV, and to incorporate carbon capture technology. The latter can be accomplished with either oxy-combustion or post-combustion scrubbers.

This paper describes the oxy-combustion clean coal technology B&W PGG is developing to enable near-zero coal plant emissions, including CO_2. To capture CO_2, there are two combustion-based technology paths: oxy-combustion and CO_2 scrubbing. Oxy-combustion is applied to the entire plant process, inherently providing near-zero emissions, and is ready for large-scale validation. CO_2 scrubbing can be applied to all or part of the plant emissions, with advancements in solvents and process design underway to enable effective processes with coal-fired flue gas.

The oxy-combustion technology has matured from the pilot stage to a viable commercial technology for CO_2 capture. Given the technical and financial risks associated with these first-of-a-kind carbon capture and storage (CCS) projects, commercial-scale technology validations that move beyond paper studies and computer models must be successfully performed if electric utilities are to accept and deploy CCS technologies on a wide scale.

Deployment of CCS technologies is imperative to address global climate concerns and government participation is a necessity. The present high cost of building these first-of-a-kind CCS technologies is generally beyond the financial capacity of private industry. In the absence of regulations to establish a competitive value for CO_2 emissions, there are limited means available to recover the costs associated with building and operating CCS plants. At this stage in the technology development, funding assistance is needed from federal, state and local governments to share this expense. Assistance from government to obtain power purchase agreements that will support the long-term operation of these CCS plants is also necessary.

Validation of safe transport and permanent storage of CO_2 is also imperative. CO_2 capture is only half of the equation. Successful validation of the storage of large volumes of CO_2 in permanent geologic formations is crucial to gaining industry and public acceptance of CCS technologies. While there are several CO_2 storage projects in progress around the world, none are presently combined with a commercial-scale electric generating plant. An integrated test of CO_2 capture and storage will bring an essential body of scientific knowledge and operating experience that will play an important role in the successful deployment of CCS technologies.

Steam generation and environmental controls

Today, regardless of cost premiums, high efficiency is mandatory in developed countries for power plants to be permitted and demonstrate the lowest emissions. As power plant emissions have continually decreased since the 1970s, emission control systems have significantly improved performance and reduced cost [Alexander, 2008]. Today's state-of-the-art power plant has extremely low emissions and is driving towards near-zero.

Higher efficiency benefits all emissions and the progression of steam cycle improvements in Europe and the U.S. are examples of the world embracing this effort. Higher efficiency is the lowest cost option to achieve CO_2 emission reduction (compared to capture/storage).

The historic drivers to achieve higher steam temperatures were the economics of increased fuel efficiency and lower power cost, especially for those countries that import much of their fuel. Units built in the late 1950s in the U.S. at the Philo (1150F, 621C) and Eddystone (1200F, 649C) plants operated at supercritical pressure and high steam temperature [ASME 2003]. Materials at that time were not adequate and fireside corrosion and steam line cracking prevented continued operation at design temperatures. Today, the new driver is to reduce emissions, not only of criteria pollutants but also CO_2. Table 1 shows the effect of plant efficiency on reducing carbon emissions. During the last several years, a resurgent research and development (R&D) effort on high temperature steam plants has pushed towards 1300F (700C) steam temperature and beyond, referred to as advanced ultra-supercritical.

Table 1
Coal Power Steam Cycle Efficiency and Carbon Intensity

	Temperature SH / RH (F,C)	Carbon Intensity (metric tons of CO_2 per MWh)	Average Net Plant Efficiency (HHV)
Old Units (Brownfield) • Biomass retrofits • Potential future sites for new coal + CCS, nuclear	1000 / 1000 (540 / 540)	0.95	33%
Current technology	1115 / 1125 (600 / 605)	0.79	40%
Next generation	1395 / 1410 (760 / 765)	0.67	45 - 48%
Next generation w/CCS	1395 / 1410	0.07	39 - 42%

To be successful at these conditions, focus has been on materials R&D, for both the boiler and steam turbine, with programs in the U.S., Europe, Japan and China. B&W PGG has participated in the U.S. Department of Energy (DOE) consortium since 2003, and is internally conducting extensive materials R&D. New, high nickel alloys have been developed and are being Code-approved to ready the path forward. Some of the most promising materials are Super 304H, Inconel 740, and Alloy 617 [Sarver 2003]. Key technical challenges are: preventing fireside corrosion, limiting steam-side oxidation, developing new welding and manufacturing processes, and designing stainless steel headers with acceptable creep life. New units will need to be designed for variable pressure operation to provide load following capability while still meeting efficiency targets. The ability to load-follow adds to the operating flexibility of these units, and reinforces the need for CCS systems to be flexible to match the variable electric output of wind and solar generation.

Environmental control systems continue to improve while benefitting from higher boiler and steam cycle efficiencies. SO_2 removal systems using wet flue gas desulfurization (FGD) scrubbers have improved capture efficiencies from 70% in the 1970s to the 98 to 99% range available today. Additional SO_2 removal technologies include spray dryer absorbers and circulating dry scrubbers. Each technology has specific benefits based on fuel quality, byproduct reuse and water requirements. NO_X emission reduction starts with the combustion process utilizing the latest burner technology and furnace operation. By adding selective catalytic reduction (SCR) systems, up to 90% removal of all NO_X emissions are now achievable. In the U.S., multi-emissions control systems are now focused on mercury capture. Depending on fuel and equipment configurations, the latest sorbent injection technologies can achieve 90% capture of oxidized mercury.

Carbon capture and use or storage (CCUS)

There are many carbon capture technologies under development, however, none are yet operating at the scale needed to move to commercial operation. CO_2 scrubbing and oxy-combustion are the two leading combustion-based technologies being developed. Both can be applied to new units or retrofit to existing units. Both technologies are ready to move to near commercial-scale of over 100 MWe, much larger than the pilot-scale units of a few megawatts. It will take several years to fund, build and successfully operate these integrated plants before they are ready to deploy at commercial plants. At the same time, concepts for operating flexibility are being developed to further improve availability and net power.

As with the initial deployment of conventional emission control technology, it is plausible that carbon capture and storage technology will be launched first in North America and Europe followed by developing nations as costs and performance are improved. Storage technology programs underway in North America and Europe have shown promising geologic potential, but larger-scale and longer-term injections are still needed to satisfy regulators and the general public [GCCSI 2010]. Results thus far from the U.S. regional carbon sequestration program led by the DOE have shown sufficient reservoir capacity to last well into the next century, primarily in deep underground saline formations. The DOE's program goal is to open the door for large-scale storage before the middle of the next decade [U.S. Interagency Report 2010].

Research and development

Oxy-coal combustion pilot plant experience

Since 1991, with the support of the DOE, B&W PGG and Air Liquide (AL) have worked to bring an advanced carbon capture and storage technology to the market for coal-fired electric power generation plants. The oxy-coal combustion technology is now ready for near commercial-scale validation which will lead directly to full-scale commercialization and deployment into the power generation marketplace [McDonald 2010, McCauley 2009].

This oxy-fuel combustion technology has been through small lab pilot testing, large pilot testing, and a rigorous bottom-up integration and optimization analysis [McCauley 2008]. This product offering incorporates the best technological thinking for the integration of a modern pulverized coal (PC)-fired boiler and environmental control equipment, with an air separation unit (ASU) and compression purification unit (CPU). The oxy-coal technology is further integrated into an overall coal-fired power plant with CO_2 storage in a geologic formation.

The unique benefits of oxy-coal combustion allow for near-zero emissions of coal combustion products. Emissions of particulate matter, SO_2, NO_X, mercury and other hazardous air pollutants will all be well below current levels. This advanced technology will demonstrate these reduced levels and lead to commercially available near-zero emissions power (NZEP) plants for electricity generation.

To understand how these low emission levels are achievable, consider the process schematic in Figure 2 depicting the oxy-coal boiler concept. Combustion air is replaced with oxygen from an advanced ASU. Nitrogen that would normally be conveyed with the air through conventional air-fuel firing is excluded. Instead, a portion of the CO_2-rich flue gas is returned back to a conventional pulverizer/burner system, substituting CO_2 for the nitrogen in the furnace. The CO_2 in oxy-combustion impacts furnace operation and heat transfer in ways similar to the nitrogen in an air-fired system. These features allow the technology to be used in retrofit and repowering applications. Oxy-combustion creates a flue gas that is primarily CO_2, rather than nitrogen, and includes other products of combustion (although greatly reduced NO_X). The fraction of the flue gas that is not recirculated to the burners is sent to the CPU.

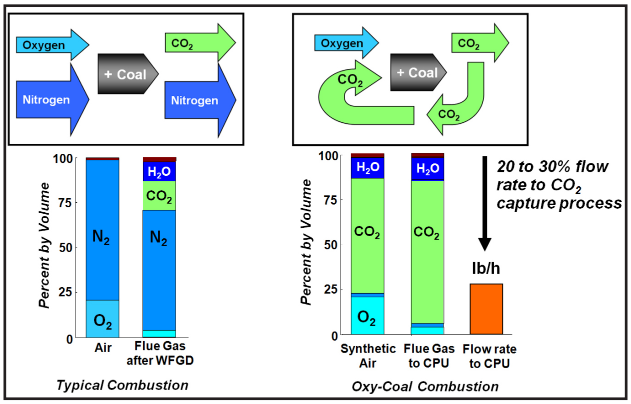

Fig. 2 Oxy-coal combustion process.

The flue gas leaving the boiler is cleaned using conventional particulate and sulfur removal systems as shown in Figure 3. Remaining particulate is further filtered in the CPU to protect the compressor systems. Primary and polishing scrubbers reduce sulfur prior to the CPU to low levels. The trace amount of SO_2 remaining is removed in the CPU. A NO_X removal system is not required as the remaining combustion-generated NO_X is almost completely removed as a condensable in the CPU. Mercury is removed in the primary scrubber and CPU. To provide pipeline quality CO_2 at the exit of the CPU, a small amount of inert constituents must be removed in the CPU. Small quantities of oxygen, nitrogen and argon present in the oxygen from the ASU (typically 95% pure oxygen) and from air in-leakage are vented to the atmosphere, along with some combustion products.

ASU advancements, including efficiency improvements, have been developed to reduce the auxiliary power requirement of the ASU. These improvements were evaluated during integration studies recently completed and it was determined that a slight increase in capital cost is easily justified by reduced power demand [Kraft 2009]. The main characteristics of the ASU for oxy-fuel combustion are low oxygen purity, low pressure (between 1.3 and 1.7 bar abs), and large size (typical oxygen requirement >8000 TPD for commercial-scale plants).

CPU advancements by AL have been specifically designed to process the flue gas emissions to provide a high purity CO_2 product stream suitable for transportation and storage underground. While the CPU will be a first-of-its-kind, AL's extensive knowledge of similar processes and the fundamental science, as well as considerable understanding of oxy-fuel combustion and its flue gas products, have led to what is anticipated to be a robust and reliable design that is ready for commercial-scale validation.

To complete the final step to commercialization, a large-scale integrated test of the oxy-combustion technology is needed. (see Figure 4). Built on a foundation of engineering design and R&D testing during the last several years, the B&W PGG/AL team is ready for this step.

At the following large operational and near-term pilot plants, tests are undertaken to verify design hypotheses, evaluate different equipment and gather operating and maintenance knowledge. This is being done in several steps:

- CEDF Pilot (U.S.): B&W PGG's 30 MWth Clean Environment Development Facility (CEDF) in Alliance, Ohio. The CEDF tests piloted the complete combustion/environmental process, utilizing a full commercial-scale burner (100 MBtu/hr) direct-fired from a pulverizer. Oxygen was mixed with flue gas recycled from an electrostatic precipitator (ESP) and wet FGD system, simulating the commercial process and equipment. The CEDF test campaign was a success, characterizing different fuels and their emissions across a range of operating conditions.
- Lacq Pilot (France): This project, led by TOTAL, consists of oxy-combustion of natural gas in a 30 MWth boiler and subsequent CO_2 purification, transport and storage in a depleted oil field. AL's scope of supply (with the CPU) also included the CO_2 drying unit, which is one of the technological blocks in a CPU. AL will also participate in plant monitoring and operation. This pilot started in late 2009.
- Callide Pilot (Australia): This project, led by CS Energy, consists of oxy-combustion of lignite in a 100 MWth boiler and subsequent CO_2 purification, transport and storage in a geologic formation. AL's scope of supply is a CO_2 CPU, which has been specifically designed to test key technologies and be representative of a large-scale CPU. For example, this plant uses a centrifugal CO_2 compressor (instead of a screw compressor which is the adopted solution for this size) to monitor the behavior of the remaining particulates as well as of the acidic gases. This pilot has no equivalent worldwide and will fully confirm the performance of the CPU technology when started up in early 2011.

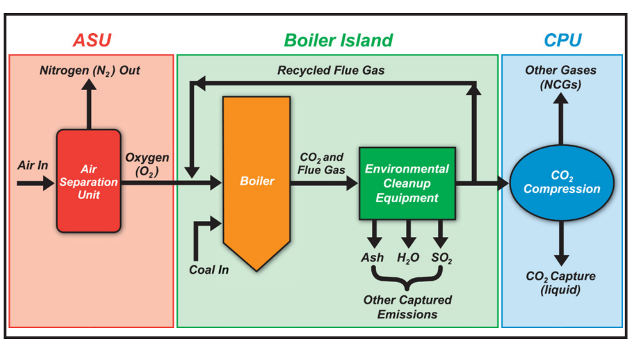

Fig. 3 Oxy-coal combustion process.

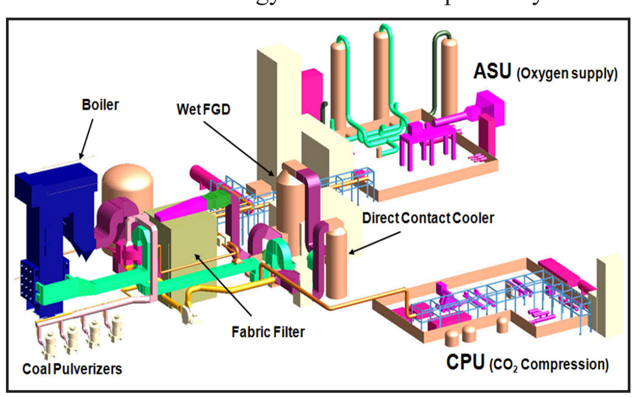

Fig. 4 Oxy-coal demonstration plant layout.

Oxy-coal combustion system simulation and modeling

Oxy-fuel coal combustion simulations using computational fluid dynamics (CFD) modeling techniques can provide a cost-effective way to support design. Since 1980, B&W PGG has invested considerable resources developing the proprietary COMO™ CFD modeling technology. COMO technology can model multiple fuels including fossil fuels (coal, oil and natural gas) and biomass fuels. The physical processes modeled include three-dimensional turbulent gas flow, particle motion, heterogeneous and homogeneous chemical reactions, and radiative and convective heat transfer. COMO technology has become an important research and development tool for B&W PGG to develop burner, furnace and boiler retrofits to reduce emissions and increase efficiency. B&W PGG has a range of state-of-the-art oxy-coal test facilities, from the Entrained-Flow Reactor (EFR) capable of feeding single coal particles, to the 1.5 MWth Small Boiler Simulator (SBS), and the 30 MWth CEDF.

Engineering analysis for a reference plant at 700 MWe

Oxy-combustion process

The similarity of the oxy-combustion process to air-firing supports its use for both new and retrofit (or repowering) applications. For new units, the plant configuration can be designed to optimize capital and operating costs. Recently, B&W PGG and AL have made improvements beyond other reported oxy-combustion system designs. In cooperation with EPRI and URS Corp., a detailed study to develop a 700 MWe oxy-combustion reference plant design was undertaken in 2010 [EPRI 2010].

The oxy-combustion process for a 700 MWe gross reference plant employs the B&W PGG-AL advanced warm recycle process firing a low sulfur sub-bituminous coal (see Figure 5). The entire system is integrated for overall optimization, and heat from the ASU, CPU and flue gas cooler are incorporated into the steam cycle. In the warm recycle process, which improves plant heat rate, hot gas leaves the boiler and passes through a patent pending advanced quad-sector secondary and primary recycle gas heater. This recycle heater is internally arranged to prevent any feed oxygen loss to the flue gas entering the CPU compression process. To control the gas temperature entering the fabric filter and improve plant heat rate, the gas is slightly cooled by a heat exchanger. It then flows through a pulse jet fabric filter (PJFF) to the secondary forced draft fan. Preheated oxygen is then mixed with the secondary recycle gas and the gas flows back through the recycle gas heater where the temperature is raised before entering the boiler windbox.

Since there is no SO_2 or moisture removal in the secondary recycle stream, the moisture and SO_2 levels in that path and in the boiler are higher than with air-firing. This results in SO_2 levels in the furnace from the sub-bituminous coal combustion that are similar to those experienced in an air-fired boiler burning a moderate sulfur eastern bituminous coal. Furnace and superheater corrosion is anticipated to be relatively similar to existing units due to the moderate SO_2 concentrations and the low chlorine content in the coal. In addition, a small amount of other acid gases are removed in the PJFF due to the alkaline ash.

The remainder of the gas leaving the recycle gas heater enters the spray dry absorber (SDA) followed by a PJFF. This combination reduces SO_2, removes most of the SO_3, and nearly all of the particulate. To protect the CPU, SO_2 is further reduced and the gas is dehumidified in the direct contact cooler-polishing scrubber (DCCPS). The gas then passes through a reheater that increases the gas temperature slightly to prevent condensation entering the CPU or primary fans.

The primary fans provide the recycle gas to the recycle gas heater which raises the temperature after which the preheated oxygen is added. Oxygen in the primary recycle is controlled to mitigate risk of combustion in the pulverizers and coal pipes. The primary recycle gas is supplied to the pulverizers for drying and conveying the coal to the burners.

When air firing, the secondary recycle stream is isolated by dampers and all of the gas leaving the recycle gas heater flows into the SDA, PJFF, ID fan, and to the stack as in a conventional air-fired design. The recycle control dampers are closed and, through their air intakes, the secondary forced draft fan and primary fan provide fresh air to the recycle gas heater. The DCCPS is not in service in this mode.

Oxy-combustion engineering analysis

As part of the detailed reference plant study [EPRI 2010], oxy-combustion offers an attractive heat rate which is currently lower than competing technologies (see Table 2). According to the Energy Information Agency [EIA 2010], the US fleet average heat rate for coal fired plants in 2009 was 10,414 Btu/kWh (all coals) or 32.8% HHV. The oxy-combustion pulverized coal plant reported here (firing sub-bituminous coal) is predicted to achieve 31.5% HHV with oxy-combustion, a penalty of only 1.3 percentage points for carbon capture compared to the current fleet average.

In addition to offering high efficiency, oxy-combustion is essentially the same as a modern conventional proven pulverized coal-fired plant with the addition and integra-

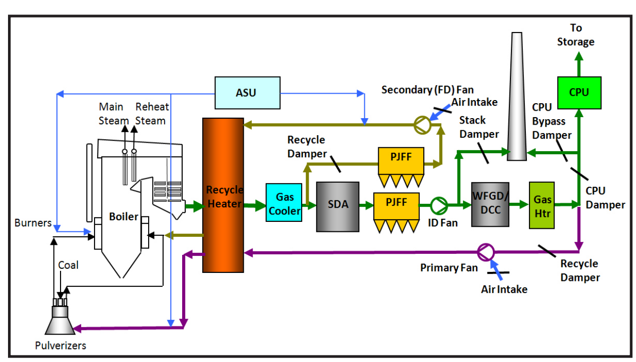

Fig. 5 700 MWe oxy-coal reference plant layout.

Table 2
Oxy-Coal Reference Plant Efficiency (EPRI)

Performance Parameter	Baseline Plant	Oxy-PC Plant
Gross Plant Output, kW	697,778	701,696
Power Block Auxiliary Power, kW	19,008	16,713
ASU Auxiliary Power, kW	N/A	89,100
CPU Auxiliary Power, kW	N/A	60,900
BOP Auxiliary Power & Transformer Losses, kW	21,792	26,361
Total Auxiliary Power, kW	40,801	193,075
Net Plant Output, kW	656,977	508,621
Plant Fuel Consumption, 1000 lb/hr	683.8	656.6
Plant Heat Input, MBtu/hr (HHV)	5744	5515
Net Plant Heat Rate, Btu/kWh (HHV)	8,743 Btu/kWh	10,842 Btu/kWh
Net Plant Efficiency, % (HHV)	39.0	31.5

tion of proven ASU and CPU systems. Another major attraction of oxy-combustion PC technology is near-zero air emissions. (see Table 3). The oxy-combustion PC plant will operate nearly the same as a conventional pulverized coal-fired plant. Comparison of the controls descriptions for the baseline and oxy-combustion plants shows that the transition from air to oxy-combustion is relatively simple. Load changing is essentially the same with the addition of oxygen control, and shutdown is simply the reverse of load increase and transitioning to air.

Special design considerations for oxy-combustion

For flexible and reliable operation to meet local power demands, the oxy-combustion process has some unique properties that need to be addressed and understood. The experiences of B&W PGG and AL allow these to be anticipated and mitigated. Some of those design and operational matters are discussed below.

Air infiltration

Air infiltration can have a detrimental effect on the efficiency and cost of oxy-combustion. If allowed to become excessive, the impact of air infiltration on performance and cost can be significant. The introduction of nitrogen impacts NO_X and the additional mass flow must be handled by the ID fan and CPU compressor. Increased power consumption and capital cost generally result because both must be sized to accommodate air infiltration. Since air infiltration also introduces some oxygen, the ASU demand will slightly decrease if the boiler is operated at the same outlet oxygen level. This means that the ASU is sized for low air infiltration assuming a tight unit knowing that as air infiltration increases over time, the ASU output will reduce by the amount of additional oxygen gained from air infiltration and ASU power consumption will decrease slightly. To eliminate introduction of air in the oxy-combustion mode, liquid CO_2 from the CPU storage tank is vaporized and fed to a receiver tank for uses such as PJFF cleaning and pressure part openings sealing.

Use of nearly pure oxygen

High pressure, nearly pure oxygen requires careful handling. The combination of high pressure and high O_2 concentrations are conducive to rapid combustion in the presence of a fuel and an ignition source. While oxy-combustion operates at lower oxygen pressures, care must still be taken. To avoid combustible conditions, oxygen handling equipment and piping is specially cleaned prior to service or whenever it must be exposed for maintenance. In addition, the AL oxygen mixing devices are specially designed to avoid high oxygen concentrations near the walls of the flues and to quickly distribute the oxygen into the flue gas to avoid concentrations significantly above the concentration in air. Oxygen concentrations in the areas downstream of the oxygen mixing devices are continuously monitored and adjusted as necessary. Oxygen concentrations in the primary recycle stream to the pulverizers are kept low to minimize risk of combustion of pulverized coal in the pulverizers and burner piping.

Leakage of flue gas with high carbon dioxide concentration

Flue gas with oxy-combustion contains a high concentration of CO_2, over 80% by volume dry. The CO_2 in the flue gas is not toxic, but it is usually accompanied by a low oxygen concentration in much of the process, and if breathed would act as an asphyxiate. In addition, CO_2 is considerably heavier than air (about 1.5 times) and tends to sink into low areas within enclosed regions of the plant and collect (driving the air out), creating potentially dangerous conditions if entered into without proper safety equipment. To prevent these conditions, several measures are taken. First the process is designed to avoid high positive pressures and minimize the potential for leaks by assuring that all joints and equipment are gas tight. To prevent accumulation of flue gases, HVAC systems for the main building, as well as enclosures that house certain process equipment, must be designed to provide proper ventilation and sufficient air movement, especially in areas where leaking flue gas might become trapped. For the safety of plant personnel, CO_2 monitors with audible and visible alarms will be placed at strategic locations within buildings and monitored from the control room. When entering areas of potential danger, personnel will need to wear proper safety equipment.

Acid gases and corrosion

Sulfuric Acid: As in any coal-fired plant, acid gases are produced which can aggressively corrode components if not properly treated. It is believed by many that oxidation of SO_2 to SO_3 is slightly higher with oxy-combustion. However, since an SCR is also known to increase SO_2 to SO_3 oxidation, and since greenfield oxy-combustion plants are not expected to have an SCR in service during oxy-firing operation, the SO_3 formation with oxy-combustion is not expected to be greatly different than air-fired units operating with an SCR. The proposed strategy is to: 1) remove as much of the SO_3 as practical prior to recycling the flue gas to prevent an unacceptable concentration in the boiler, 2) operate above the sulfuric acid dew point and moisture dew point wherever practical to prevent formation of corrosive acids within the equipment, and 3) use acid-resistant materials where acid condensation is possible. Because dry scrubbers followed by the PJFFs are known to capture essentially all of the SO_3, components downstream of the PJFF have low risk of corrosion from sulfuric acid.

Hydrochloric and Hydrofluoric Acids: HCl and HF formed by coal combustion at the levels encountered with air firing are generally not considered of great concern for corrosion.

However, HCl can be corrosive in high temperature superheaters, especially with high concentration of SO_2. As with any other constituent in the flue gas, if not removed before recycling, the concentration will be higher than with air firing. With warm recycle, the SDA-PJFF combination captures essentially all of the HCl and HF in the primary stream and some is captured in the fabric filter in the secondary stream thereby maintaining the levels in the boiler similar to air firing.

Carbonic Acid: With the high concentrations of CO_2 in the flue gas, carbonic acid can form when liquid water is present. Although it is considered a mild acid, damage may result if not properly considered. Given that significantly increasing the CO_2 concentration in the flue gas is an objective of oxy-combustion and with the higher presence of moisture, there is potential for carbonic acid corrosion wherever water can condense. In general, the process is operated above the water dew point, but in areas where such operation is not possible, such as the exit of the DCCPS, appropriate materials are utilized.

FutureGen 2.0

Oxy-combustion large-scale validation project overview

Ameren Energy Resources (AER), B&W PGG, Air Liquide Process and Construction (ALPC), and the FutureGen Industrial Alliance (FGA), together with the DOE, have formed this key group of industry experts to perform a large-scale validation project of the oxy-combustion advanced clean coal power generation technology including geologic storage of over 90% of the CO_2 produced by the plant.

The Meredosia Power Plant, located on the Illinois River near the village of Meredosia in Morgan County, Illinois, will be the host. The purpose-built, oxy-combustion coal-fired plant will repower the 200 MWe steam turbine system for the existing Unit 4. The oxy-coal process will be designed around the use of an Illinois bituminous coal. The project will also evaluate blends of Illinois coal with other coals to determine the range of flexible operations. The oxy-coal

Table 3
Oxy-Coal Reference Plant Emissions (EPRI)

Constituent	Baseline Plant		Oxy-PC Plant	
	Design Basis	Predicted	Design Basis	Predicted
NO_X	0.03 lb/MBtu	0.02 lb/MBtu	<0.03 lb/MBtu	0.012 lb/MBtu
SO_2	0.03 lb/MBtu	0.03 lb/MBtu	Near Zero*	Near Zero*
PM_{10} (Filterable and Condensable)				
Boiler	0.018 lb/MBtu	0.0099 lb/MBtu	Near Zero*	Near Zero*
Cooling Tower Drift	Not Specified	0.00063 lb/MBtu	Not Specified	0.0010 lb/MBtu
Hg	90% reduction	6.694×10^{-7} lb/MBtu	Near Zero*	Near Zero*
CO	0.08 lb/MBtu	0.08 lb/MBtu	0.08 lb/MBtu	0.06 lb/MBtu
CO_2	No Capture	213.40 lb/MBtu 0.846 tonne/MWh_{net}	90% Capture	21.6 lb/MBtu (90% Capture) 0.106 tonne/MWh_{net}

* Below practical measurement

process design will also evaluate alternatives to minimize fresh water demand by incorporating economical use of water resources within the process, utilizing wet cooling, and water conservation techniques. Because the plant is in operation and an existing steam turbine is being repowered, sufficient access to electric transmission systems with available markets for the power are already in place.

The CO_2 captured will be provided at the fence to an off-taker to be designated by the DOE who will transport and store it in a deep saline formation. The unique characteristics of oxy-coal combustion allow for near zero emissions of criteria pollutants. In the oxy-combustion mode, the emissions of particulate matter, sulfur dioxide, nitrogen oxides and mercury will be essentially zero. This advanced technology will validate these extremely low emission levels and will lead to commercially available NZEP plants for electric generation.

The DOE will provide the largest portion of the total project cost with the remainder of the cost shared by AER, other project team members, and other government and private sources. Successful operation of this large-scale integrated test project will allow the world to continue to utilize the abundant coal reserves, reduce dependency on scarce energy sources, and prove the viability of deep geologic storage of captured CO_2. This is a key part of the DOE program to validate and prove CCS technologies (see Table 4).

This project will be the first-of-a-kind, commercial-scale, oxy-combustion coal plant in the world. It will successfully integrate an innovative ASU and CPU into a full-scale utility coal-fired electric generating plant by repowering an existing 200 megawatt plant with the oxy-combustion technology. The project will validate the technical and financial feasibility of the oxy-combustion technology for utility power plant applications. The plant will produce near zero emissions and capture and store over 90% of the CO_2 produced by the plant, equivalent to about 1.2 million tonnes of CO_2 per year. The project will meet the DOE carbon capture and storage program goal of having first generation CCS technologies in operation in the 2015 to 2016 timeframe. The project will support the State of Illinois' goal regarding the deployment of clean coal facilities, and support the regional CO_2 sequestration goals of Illinois and the DOE. Most importantly, the project will prove that coal can be an environmentally clean energy option for base-load electric generation.

The geology in Illinois is very favorable to safe storage of CO_2 (see Figure 6). The state sits on one of the largest geologic formations for CO_2 storage in the U.S. The Mt. Simon, St. Peter and Cypress sandstone formations extend across the lower two-thirds of Illinois and have the potential to store over 100 billion tons of CO_2. Sufficient pore space exists to store all of the CO_2 produced by Illinois coal-fired power plants for hundreds of years. The FutureGen Alliance has recently chosen a location in Morgan County as the CO_2 storage site, which is 32 miles from the power plant.

Conclusion

To deliver the first commercial carbon capture units before 2020, large-scale integrated projects must be deployed immediately. Currently, the U.S. is actively pursuing projects for demonstrating CCS in the range of 100 to 250 MWe. This size allows commercial-scale testing of all processes and equipment and will also generate up to 1 million tons/year of CO_2, an amount many believe necessary to adequately validate geologic storage. For oxy-combustion, the U.S. has announced that the FutureGen 2.0 project will be the repowering of a 200 MWe plant using the B&W PGG/AL oxy-coal process with geologic storage of 1.1 million tonnes/

Table 4
DOE Carbon Capture and Storage Validation Program

Project	Location	Capture Rate (tonnes/yr)	Repository	Start Date
Oxy-Combustion				
FutureGen 2.0	Meredosia, IL	1,150,000	GS	2015
Pre-Combustion Capture (IGCC)				
Summit Texas Clean Energy	Odessa, TX	2,700,000	EOR	2014
Southern Company	Kemper County, MS	1,800,000	EOR	2014
Hydrogen Energy California	Kern County, CA	1,800,000	EOR/GS	2016
Post-Combustion Capture				
Basin Electric	Beulah, ND	450,000 – 1,360,000	EOR/GS	2014
NRG Energy	Thompsons, TX	400,000	EOR	2015
American Electric Power	New Haven, WV	1,500,000	GS	2015
Industrial CCS Solicitation				
Leucadia Energy	Lake Charles, LA	4,000,000	EOR	2014
Air Products	Port Arthur, TX	900,000	EOR	2013
Archer Daniels Midland	Decatur, IL	900,000	GS	2014

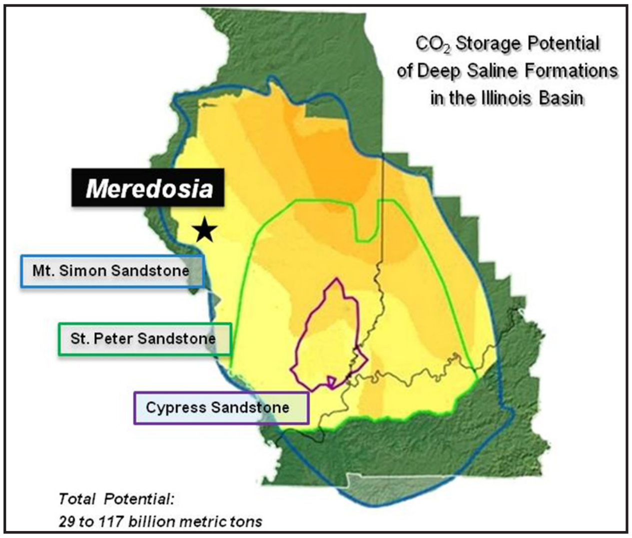

Fig. 6 FutureGen 2.0 carbon storage potential.

year of CO_2. This project will prove that coal can remain the key fossil fuel energy source for base-load power generation while meeting demand flexibility.

The obstacles for carbon capture, regardless of the technology utilized, all have a similar theme: 1) a worldwide commitment is needed, 2) carbon capture is an added cost to a power plant with no immediate economic benefit, and 3) countries with large coal fleets have a large capital investment that is long-term and cannot be easily displaced, while at the same time, growth demands must be met. It is for these reasons that joint demonstration projects will help accelerate the advancement (and cost reductions) of these new carbon capture technologies, lead to large-scale deployment, and begin to reduce the carbon intensity of energy production.

Oxy-coal combustion will operate similarly to an air-fired coal power plant, and the systems that comprise the technology are well known and proven (boiler, air quality control systems, ASU and CPU systems). The integrated operation with the CO_2 storage off-taker will be unique, and specific learning will be required in the first commercial plants. The ability to operate by utilizing air at partial loads, and the ability to store oxygen, adds flexibility that the owner needs to evaluate. Stored oxygen can be used during peak power demands, thereby increasing the net plant output.

In the meantime, deploying new advanced efficiency power generation technologies will allow the industry to get a head start on carbon intensity reductions and begin lowering the cost of future deployments. An added benefit to joint R&D and demonstrations is that the results can then be utilized in all countries without the need for duplicate efforts.

To assure the success of CCS technologies, continued government support is required to: 1) secure financial assistance in the form of grants, loans, loan guarantees and tax incentives, 2) facilitate the process for obtaining the permits needed to build and operate the power plant, CO_2 pipeline and CO_2 storage facility, 3) assist the industry in obtaining power purchase agreements that will allow these plants to recover their capital and operating expenses at a fair return, 4) develop a framework of laws and regulations that will define the risks associated with transport and long-term storage of the captured CO_2, and 5) help coal remain a low cost and secure worldwide domestic energy resource in a carbon constrained world.

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