Advanced Coal Technologies: Greater Efficiency and Lower CO_2 Emissions

Higher Efficiency Power Generation Results in Lower Emissions

Coal is the primary fuel for generation of electricity in the U.S. and many other countries. In the U.S., over 50% of all the electricity is generated from the more than 300,000 megawatts (MW) of coal-fueled power plants. Considerations of energy independence, balance of payments, and greater price stability and lower cost of coal compared to natural gas make coal a preferred choice for new base load power generation.

Using coal under a carbon management regulatory scheme requires reductions in emissions of air pollutants and carbon dioxide (CO_2). A number of technologies that significantly reduce emissions of SO_2, NOx, Particulate Matter (PM), mercury (Hg), and CO_2 have been developed and are in wide commercial use, with further prospective developments toward “Near Zero Emission” power plants. A cost-effective and readily available option to reduce CO_2 emissions per unit of electricity generated is to increase the generating plant’s efficiency, so that less coal is burned per unit of electricity generated.

CO_2 capture and geological storage (CCS) is the key enabling technology for the reduction of CO_2 emissions from coal-based power generation. CCS will likely become commercially available for base load power generation around 2025-2030, following the construction and operation of several demonstration plants during the next ten years.

Until these CCS technologies are commercially available, options for efficient coal-based generation include:

- PC combustion in ultra-supercritical (USCPC) steam cycles, and
- Integrated gasification combined cycle (IGCC) technology.

USCPC Technology

The thermodynamic efficiency of coal-based power plants increases with increasing temperature and pressure of the superheated steam entering the steam turbine. As steam pressure and temperature are increased above 3,208 psi and 706ºF, the steam becomes supercritical; the water and steam form a single phase mixture. Supercritical PC (SCPC) technology generally refers to plants with steam superheat and reheat temperatures up to 1,112ºF; above that, the technology is referred to as Ultra-supercritical PC (USCPC). Advanced USCPC plants will use steam temperatures in the 1,200-1,400ºF range.

The average annual efficiency of the existing U.S. coal-fueled electricity generating fleet is 32%, based on the higher heating value (HHV) of the coal. Most of these plants operated at subcritical steam conditions.

USCPC power plants with steam conditions of 4,350 psia, 1,112°F superheat/1,112°F reheat are being installed worldwide today, with efficiencies as high as 44%. Simply put, these plants are 35% more efficient than today’s U.S. fleet of coal-fired power plants; this means that they would use 35% less coal for the same power generation, and emit 35% less CO_2. There are several years of operating experience with these USCPC plant, with excellent performance and availability.

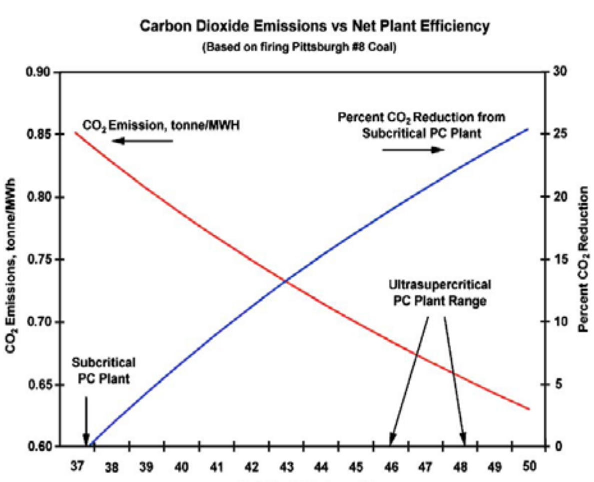
Further improvements in efficiency are dependent on the availability of new nickel-based alloys for these high temperatures and pressures in USCPC boilers and steam turbines. Two major development programs in progress, the Thermie Project of the European Commission and a U.S. program managed by the Electric Power Research Institute (EPRI) for the U.S. DOE and the Ohio Coal Development Office, are aiming at steam parameters of 5,439 psi and 1,292°F/1,328°F, and 5,500 psi and 1,346°F/1,400°F, respectively. Power plant efficiency increases by about one percentage point for every 36°F rise in superheat and reheat temperature. An advanced USCPC plant will likely be constructed during the next seven to ten years, constituting a benchmark for a 46% efficient coal-fired power plant. This high efficiency would result in a 25% reduction in CO_2, and all other emissions, compared to that generated by a new equivalent-sized subcritical PC unit.

It is estimated that before 2025, when CCS technologies may begin to become commercially available, about 45,000 MW of new coal-based capacity will be constructed in the U.S. If more efficient USCPC technology is utilized instead of subcritical steam plants, CO_2 emissions would be about 700 million metric tons less during the lifetime of those plants, even without installing a CO_2 capture system. High efficiency coal-based power generation is also important to long-term solutions of reducing CO_2 emissions by using CCS, as it mitigates the significant energy costs of CCS.

Because of the reduced coal use for a given electricity output, the plant has a smaller footprint with respect to size of coal handling and emission control systems. These savings and the use of modern analytical techniques that enable optimal use of nickel alloys can help minimize the cost of USCPC technology.

The impacts of high efficiency on reductions in CO_2 emissions are illustrated in Figure 1.

FIGURE 1. CO_2 EMISSIONS VS. PLANT EFFICIENCY (HHV)



(Booras and Holt, 2004)

Using that data, for example, a 500 MW USCPC plant would emit 730,000 tons/year of CO_2 less than a subcritical PC plant, a reduction of 21%.

IGCC Technology

Gasification-based technologies convert coal to a synthesis gas (syngas) consisting mainly of CO and H_2.The syngas is cleaned to remove contaminants before it is used as a fuel in a gas turbine. The hot exhaust gas from the gas turbine is used to produce steam in a heat recovery steam generator for a steam turbine-electric generator. This combination of a gas turbine and steam turbine cycles is called combined cycle power generation. Integrating the coal gasification and combined cycle technologies, IGCC provides the benefits of using low-cost coal with the high efficiency of combined cycle power generation. Higher efficiency results in lower emissions per unit of electricity generated.

IGCC technology is being demonstrated in two plants in the U.S., two in Europe, and one in Japan. Industry standard designs are based on the use of eastern bituminous coal, although IGCC plants can be designed for a wide range of coals. The coal is pulverized and fed into the gasifier either in dry form or as coal-water slurry, along with either high-pressure air or oxygen. The temperature in the gasifier is in the range of 2,300-2,800°F, so that the coal ash can be removed as molten slag. The syngas undergoes rigorous cleanup of PM, mercury and sulfur, prior to entering the gas turbine.

The syngas can be cooled prior to cleanup, using heat exchangers, producing steam for generating additional power. Another element of efficient design is subsystems integration with the main generating plant. Air from the gas turbine's compressor can be used as the feed for the air separation unit, which produces oxygen for the gasifier. Nitrogen from that system is piped to the gas turbine combustor to be used as a diluent to reduce NOx formation.

While today's IGCC plant efficiency is comparable to subcritical PC units, experience with next-generation IGCC units is expected to lead to continued increases, eventually reaching USCPC efficiency levels. The IGCC unit in Puertollano, Spain, which uses a dry-feed gasifier, syngas coolers, and gas turbine-air separation unit integration, has a generating efficiency of almost 40%. Supercritical PC units operate in the 38-40% efficiency range, and USCPC units in Europe and Japan are achieving 42-46% generating efficiency.

CO_2 Capture and Compression

CO_2 capture from PC plants involves post-combustion cleanup; the separation and recovery of CO_2 that is at low concentration and low partial pressure in the exhaust gas. Chemical absorption with amines is presently the only commercially available technology. The CO_2 is first captured from the exhaust gas stream in an absorption tower. The absorbed CO_2 must then be stripped from the amine solution using large amounts of steam, regenerating the solution for recycle to the absorption tower. The recovered CO_2 is cooled, dried, and compressed to a supercritical fluid. It is then ready to be piped for use or to sequestration.

The use of steam for CO_2 removal reduces the steam available for power generation. To maintain constant net power generation, the coal input, boiler, steam turbine/generator, and emission control equipment must all be increased in size. The thermal energy required to recover CO_2 from the amine solution reduces the PC plant's efficiency by 5 percentage points. The energy required to compress the CO_2 to a supercritical fluid is the next largest factor, reducing the plant efficiency by another 3.5 percentage points.

RD&D is in progress pursuing the use of alternative sorbents, such as ammonia and solid materials, to reduce the energy intensity of the CO_2 capture process. The stakes are high because a successful solution would be applicable to new and existing PC plants.

IGCC lends itself favorably for efficient CCS, because CO_2 can be separated from a relatively small volume of high pressure syngas. Without CCS, IGCC is more expensive, and has lower efficiency and availability than PC. However, the cost of electricity (COE) for a PC plant using bituminous coal with CCS is higher than for IGCC with CCS. For coals of lower heating value, such as subbituminous coals or lignite the COE gap is substantially narrowed or can even be reversed. Also, ultra-supercritical PC combined with low energy consuming CO_2 capture or oxy-combustion technology, when developed, could be competitive with IGCC on the COE.

It is noteworthy that significant cost and performance loss is attached to the capture and compression of CO_2 from both PC and IGCC plants in preparation for its sequestration or use.

Oxy-fired PC Technology

When oxygen, instead of air, is used for combustion in a PC boiler, the mass flow rate of combustion products is significantly reduced and the flue gas CO_2 concentration is greatly increased. In order to avoid unacceptably high temperatures in the boiler combustion products, exhaust gas is recirculated into the combustion chamber. This restores the furnace exit gas temperature to normal levels, with a CO_2 concentration in the exhaust gas of 90% or greater. After the removal of condensables, this concentrated CO_2 stream is ready for use or sequestration, without energy intensive gas separation. In this case, the flow rate of the five-fold reduced flue gas volume through the post-combustion mercury, PM, and SO_2 emissions control equipments leads to reduced capital and treatment costs.

The cryogenic air separation unit consumes a significant fraction of the oxy-fired PC plant's output and reduces its efficiency by 6.4 percentage points. There is an urgent need for the RD&D of membrane type oxygen processes, which will lead to significant reductions in energy consumption.

Concluding Comments

Coal will continue to play a large and indispensable role in electricity generation in a carbon-constrained world.

The key enabling technology for CO_2 emissions mitigation in coal combustion and gasification plants is CCS.

CCS still must be demonstrated at large scale, integrated with power generation technology. Further, the legal framework for long-term sequestration must be developed before CCS becomes commercially available in the 2025-2030 time period.

Until that CCS technology becomes available, about 45,000 MW of new coal-based electricity generating capacity will be constructed in the U.S. without CCS (about 1,000,000 MW worldwide). ***Increased efficiency of power generation is the most predictable and cost effective method for CO_2 emissions reduction. In an existing coal-based plant without CCS, increased efficiency is the only practical method for mitigating CO_2 emissions now, and it will be important for future plants equipped with CCS in order to reduce the energy impacts and costs of CO_2 capture.***

PC is the prevailing technology for power generation. Compared to average emissions from the existing coal-based fleet, up to 35% reductions in CO_2 and pollutant emissions can be achieved today by using SCPC or USCPC technology in new plants.

IGCC technology is being demonstrated in the U.S., Europe and Asia. Today, without CCS, IGCC is more expensive, and has lower availability than PC plants but, if CCS were available today, IGCC may in fact be less costly than PC with CCS when using lower rank coals. Large-scale demonstrations of both PC and IGCC, with CCS, will be important to make these technologies commercially available.

There are critical technology developments in progress that can enhance the performance and economics of advanced power generation technologies until CCS is commercially available. A broad portfolio of advanced clean coal technology RD&D should be aggressively pursued to meet the CCS challenge.

Demonstration of CO_2 sequestration at large scale, and integrated with power generation, will give the public more confidence that a practical CO_2 emission control option exists. It will also maintain opportunities for coal to provide a low-cost, widely available energy source to meet the world's pressing energy needs in an environmentally responsible manner.

As a public advisory committee to the Secretary of Energy initially chartered in 1984, The National Coal Council has compiled over 30 reports at the Secretary's request on numerous issues affecting coal and U.S. energy policy. The factual information in this paper, and the conclusions based thereon, are drawn from these studies and the documents used to compile them, all of which have been submitted to the Secretary of Energy.