# Higher Efficiency Power Generation Reduces Emissions

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Coal is the primary fuel for generation of electricity in the United States and many other countries. In the U.S., roughly half of all kWh produced come from the more than 350,000 MW of coal-fueled power plants. Further, considerations of energy independence and balance of payments, the greater price stability and lower cost of coal compared to natural gas make coal today's preferred choice for new base load power generation.

Coal use ,however, represent a challenge of reducing emissions of air pollutants and CO2. In response to this challenge a number of technologies capable of significantly reducing emissions of criteria pollutants: SOx, NOx, PM, Hg, and CO2 have been developed and are in commercial use, with further prospective developments towards "Near Zero Emission'(NZE) coal plants.

Potential reductions in greenhouse gas emissions, particularly $CO_2$, are gaining significant attention. 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 MWh generated.
Carbon capture and geological sequestration (CCS) is the key enabling technology for the reduction of CO2 emissions from coal based power generation. It is expected that CCS will become commercial for base load power generation around 2020-2025 following the construction and operation of several demonstration plants during the present and next decade.
Before the advent of commercial CCS technology options are available for high efficiency power generation with significantly reduced emissions of both CO2 and criteria pollutants. Prevalent among these options are**:**
**Pulverized coal combustion in ultra-supercritical steam cycle, and**
**Integrated Coal gasification Combined gas turbine-steam Cycle (IGCC)**
**.**

## Pulverized Coal in Ultra Supercritical Steam Plants( PC/USC)

The thermodynamic efficiency of a Rankine steam cycle increases with increasing temperature and pressure of the superheated steam entering the turbine It is possible to increase further the mean temperature of heat addition by taking back partially expanded and reduced temperature steam from the turbine to the boiler, reheating it, and reintroducing it to the turbine. In the usual designation of steam parameters the second and third temperature refers to single and double reheat, e.g. 309bar/594°/**594°/594°***C*, respectively.
As steam pressure and superheat temperature are increased above 221 bar (3208 psi) and 374.5ºC (706ºF) the steam becomes **supercritical (SC);** it does not produce a two phase mixture of water and steam as in subcritical steam, but instead undergoes a gradual transition from water to vapor with corresponding changes in physical properties.
**Ultra- supercritical (USC)** steam generally refers to supercritical steam at more than (1100ºF) temperature. EPRI's terminology for 1300ºF and 1400ºF plants is **Advanced Ultra Supercritical (AUSC).**

The average annual efficiency of the existing US coal-fueled electricity generating fleet is 32%, based on the higher heating value (HHV) of the coal.
Pulverized coal plants with USC parameters of 300 bar and 600/600 °C (4350 psi, 1112/1112°F) can be realized today, resulting in efficiencies of 44% (HHV) and higher, for pulverized coal fired power plants. These plants are 35% more efficient than today's US fleet of coal fired plants; i.e. they would use 35% less coal for the same power generation and emit 35% less $CO_2$. There is several years of experience with these 600°C (1112F) plants in service, with excellent availability.
Further improvement in efficiency achievable by higher ultra supercritical steam parameters is dependent on the availability of new, nickel alloys for boilers and steam turbines. Two major development programs in progress, the Thermie Project of the European Commission and a US program managed by EPRI for the USDOE's NETL and the Ohio Coal Development Office (OCDO), aim at steam parameters of 375 bar, 700°C/720°C (5439 psi,1292°F/1328°F), and 379 bar,730°C/760°C (5500 psi, 1346°F/1400°F ), respectively. The plant efficiency increases by about one percentage point for every 20°C rise in superheat and reheat temperature. An advanced 700 ºC (1293°F) USC plant will likely be constructed during the next seven to ten years constituting a benchmark for a 4**6**% efficiency (HHV) coal fired power plant.
It is estimated that before 2020 ,the time when CCS technologies may begin to become commercially available, about 45 gigawatts (GW) new coal based capacity will be constructed in the US. If more efficient presently available (1112F) USC technology is utilized instead of subcritical steam plants, $CO_2$ emissions would be about 700 MMt 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 CO2 emissions by using (CCS ), as it mitigates the significant energy cost of CCS application. 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 Ni alloys can minimize the cost of USPC technology.
Reductions in CO2 emissions as a function of plant efficiency are illustrated by **Figure 1** Coal consumption and $CO_2$ emission comparisons for presently available 500 MW PC/SubC, PC/SC and PC/USC plants are presented in **Table 1.**

## Coal gasification combined gas turbine-steam cycle (IGCC)

Gasification-based technologies use partial oxidation of coal with oxygen as the oxidant to produce a synthesis gas (syngas) consisting mainly of CO and $H_2$..The gas is cleaned to remove contaminants before it is used as fuel in a combustion turbine. The exhaust gas of the gas turbine raises steam in a heat recovery steam generator(HRSG) for a steam turbine-electric generator set. The combined cycle efficiency improves through the reduced effect of the steam condenser's heat loss. As with combustion technologies, higher efficiency results in lower emissions per MWh.
While the IGCC concept is being successfully demonstrated in two plants in the US and two plants in Europe, utility power generation demands introduce new challenges that will require further RD&D to overcome. The gasification process operates best under steady-state conditions. The load change conditions associated with utility electricity generation will burden the technology. The many chemical syngas cleanup processes

will have to respond to these changes on a real-time basis. In addition, the gasifier and associated gas cleanup systems will be exposed to a much larger range of fuel quality than experience has demonstrated. Again, this variation introduces conditions that require more RD&D to commercialize.

In the prevalent designs the gasifier operates at high pressure. Bituminous coal is pulverized and fed as coal-water slurry. The temperature in the gasifier is above 1300 C, so that the coal ash can be removed as liquid slag. The product syngas undergoes rigorous cleanup of particulates, sulfur and nitrogen oxides, and mercury, prior to entering the gas turbine (GT) combustor. Pre combustion cleanup of the syngas is economically favorable because of its low volume flow rate, undiluted by nitrogen, and the elevated pressure.

The syngas can be cooled prior to cleanup by radiant and convective heat exchangers which raise steam, and improve the plant efficiency. However, because of the additional cost and operational problems due to fouling of the convective heat exchanger, it is often omitted in recent designs at the detriment of the plant efficiency.

Another element of efficient design is subsystems integration with the main generating plant. For example, air can be fed to the Air Separation Unit that produces oxygen for the gasification process by the main compressor of the GT ,and the nitrogen can be returned to the gas turbine combustor to be used as a diluent to reduce NOx formation. The gain in improved efficiency, however, is weighed against operating a more complicated plant of reduced availability.

The electricity generating efficiencies demonstrated to date do not live up to earlier projections due to the many engineering design compromises that have been made to achieve acceptable operability and cost. The current IGCC units have, and next-generation IGCC units are expected to have electricity generating efficiencies that are less than or comparable to those of supercritical PC generating units. Current units typically gasify high-heating value, high-carbon fuels. Polk IGCC with a Texaco-GE water-slurry gasifier, radiant syngas cooling but no combustion turbine-air separation unit integration operates at 35.4% (HHV) generating efficiency. The Wabash River IGCC with a water-slurry fed E-Gas gasifier, radiant and convective syngas cooling and no integration operates at about 40% generating effi ciency. The IGCC in Puertollano Spain with a dry-feed Shell type gasifier, radiant and convective and combustion turbine-air separation unit integration has a generating efficiency of about 40.5% (HHV). Supercritical PC units operate in the 38 to 40% efficiency range, and ultra-supercritical PC units in Europe and Japan are achieving 42 to 46% (HHV) generating efficiency.

## PC and IGCC with CO2 Capture and Compression

$CO_2$ capture from pulverized coal combustion (PC) 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 amount 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 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 efficiency by 5 percentage points. The energy required to compress the $CO_2$ to a supercritical fluid is the next largest factor, reducing the efficiency by 3.5 percentage points. All other energy requirements amount to less than one percentage point.

R&D is in progress pursuing use of alternative sorbents,such as chilled ammonia to reduce the energy intensity of the $CO_2$ capture process.
The stakes are high because a successful solution would be applicable to both new plant and to retrofit of existing plant, with CCS.

**PC /Oxy/USC** When oxygen, instead of air is used as oxidant for combustion, 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 ,mainly $CO_2$ are recirculated from the end of the boiler to the combustion chamber.This restores the furnace gas temperature to air combustion levels resulting in an O2 volume concentration of about 30%, compared to 21% for air-fired combustion. This difference is due to the higher specific heat of $CO_2$ than that of the replaced nitrogen, and also, to $CO_2$'s high radiative emissivity.. Flue gas recirculation (FGR) increases the $CO_2$ concentration in the flue gas to beyond 90% (the complement being $N_2$, due to air leakage and about 3% $O_2$ required for complete burn out of coal), making the flue gas ready for sequestration after the removal of condensables but without energy intensive gas separation. If avoidance of corrosion in the compressor and pipeline requires further exhaust gas polishing, the five-fold reduced flue gas volume leads to strongly reduced capital and treatment costs relative to those for an air blown combustion plant.
The presently available Cryogenic Air Separation process consumes a significant fraction of the generating plant's output and reduces its efficiency by 6.4 percentage points. The development of membrane type oxygen processes with greatly reduced energy requirements are urgent R&D targets.

**IGCC** lends itself favorably for efficient $CO_2$ capture and sequestration because $CO_2$ can be separated from a relatively small volume of fuel gas (syngas) at high pressure. Without CCS, IGCC is more expensive, and has lower efficiency and availability than PC/ SC and PC/USC technology but, if CCS were available today, equipped with CCS IGCC would be cheaper. For coals of lower heating value such as subbituminous coals or lignite. the COE gap is substantially narrowed or is even reversed.
It is noteworthy that there is significant cost and performance loss attached to the capture and compression of $CO_2$ from both combustion and gasification plants in preparation of its sequestration. Results of studies presented in Table 2 provide information on estimates of total plant cost, cost of electricity and avoided cost of CO2 for different demonstrated IGCC and PC/ USC technologies without and with CO2 capture and compression., respectively..

## Concluding Remarks

Coal will continue to play large and indispensable role in electricity generation, in a carbon constrained world, under any scenario,

The key enabling technology for $CO_2$ emissions mitigation in coal combustion and gasification plants is $CO_2$ capture and sequestration (CCS).

CCS has to be demonstrated at scale , integrated with power generation,
and the legal framework of sequestration has to be developed before CCS becomes commercial, probably by the 2020-2025 period.

Before the advent of CCS there will be about 45 GW new coal based electricity generating capacity constructed in the US (about 1000GW world wide) and the question arises of what the technology options are for these new plants?

Increased efficiency of power generation is the most predictable and cost effective method for $CO_2$ emissions reduction. In coal plant without CCS it is also the only practical method for mitigating $CO_2$ emissions now, and it remains important for future plants equipped with CCS to reduce the energy cost of $CO_2$ capture.
Pulverized coal combustion in Rankine cycle steam plant is the prevailing utilization technology. Compared to average emissions from the existing coal based fleet, up to 35% reductions in $CO_2$ and pollutant emissions can be achieved today in commercial Supercritical or Ultra supercritical new plants, without increase of cost of electricity.
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Coal gasification combined cycle (IGCC) plants are successfully demonstrated
in the US and in Europe. Today, without CCS, IGCC is more expensive, and has lower availability than high efficiency PC/ SC and PC/USC plants but, if CCS were available today, equipped with CCS IGCC would be cheaper. Also, IGCC has the capability of more cheaply further lowering criteria pollutant emissions.

There are important technology developments in progress that can change the performance and economics of advanced technology options by the time CCS will be commercial. 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 scale and integrated with power generation will give the public more confidence that a practical carbon emission control option exists and maintain opportunities for the lowest cost, widely available energy source to be used to meet the world's pressing energy needs in an environmentally responsible manner.

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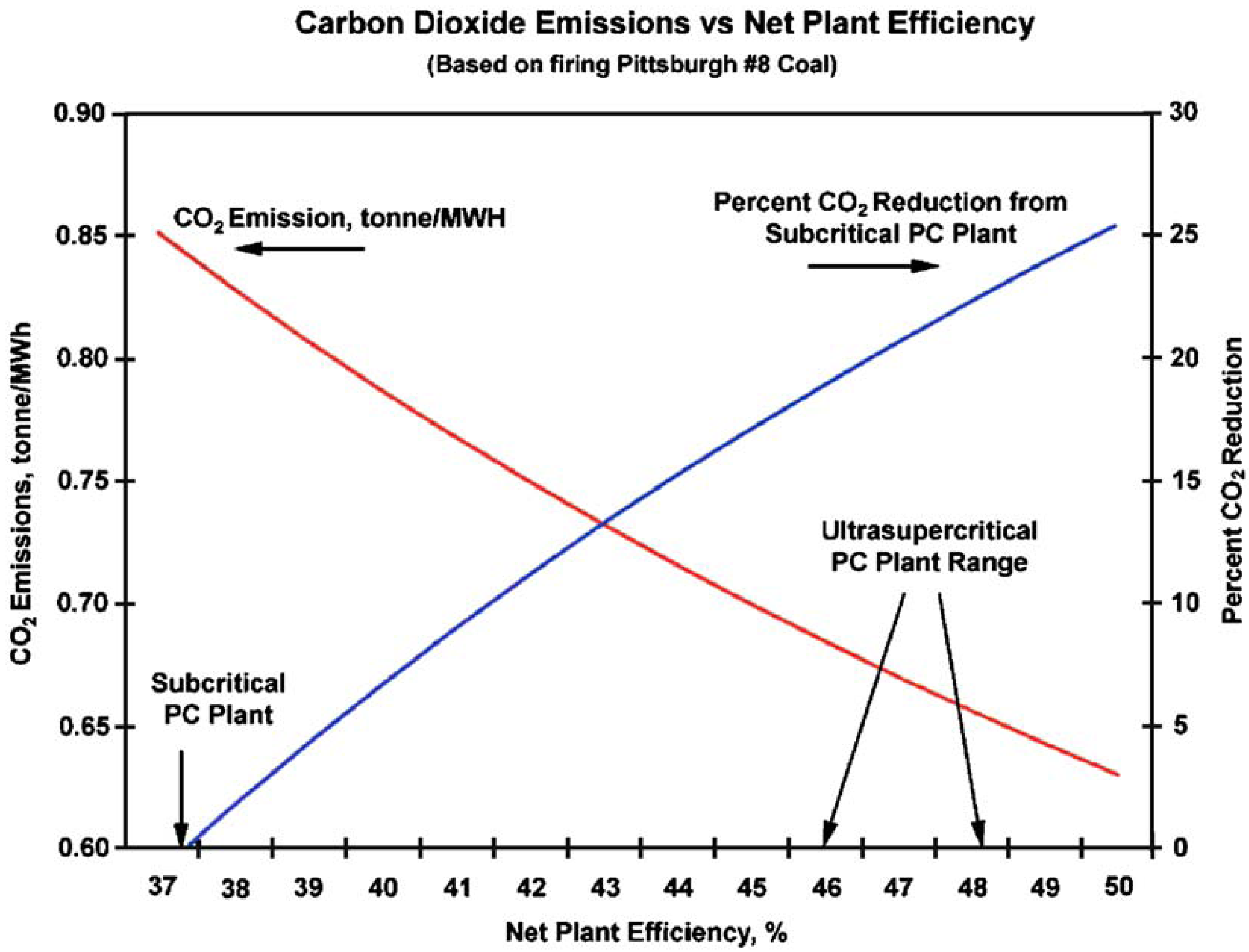


**Figure 1.$CO_2$ Emission vs. Plant Efficiency (HHV) ( Booras and Holt (2004)**

| **Performance** | **Subcritical** | **PC/Supercritical** | **PC/Ultra-supercritical** |
|---|---|---|---|
| **Heat Rate Btu/kWe-h** | **9950** | **8870** | **7880** |
| **Gen. Efficiency (HHV)** | **34.3%** | **38.5%** | **43.3%** |
| **Coal use ($10^6$t/y)** | **1.548** | **1.378** | **1.221** |
| **$CO_2$ emitted ($10^6$t/y)** | **3.47** | **3.09** | **2.74** |
| **$CO_2$ emitted (g/kWe-h)** | **931** | **830** | **738** |

**Assumptions: 500 MW net plant output ; Illinois #6 coal ; 85% Capacity Factor**

**Table 1. Comparative Coal Consumptions and Emissions of Airblown Pulverized Coal Combustion Technologies** without CCS **( MIT Coal Study 2007)**

| CCS | Supercritical Without | Supercritical With | Ultra supercritical Without | Ultra supercritical With | PC/oxy With | IGCC Without | IGCC With |
|---|---|---|---|---|---|---|---|
| $CO_2$ emitted g/kWh | 830 | 109 | 738 | 94 | 104 | 824 | 101 |
| Efficiency % HHV | 38.5 | 29.3 | 43.4 | 34.1 | 30.6 | 38.4 | 31.2 |
| TCR $/kW | 1937 | 3120 | 1976 | 3042 | 2990 | 2080 | 2756 |
| COE c/kWh | 5.50 | 8.84 | 5.39 | 8.44 | 7.93 | 5.90 | 7.50 |

**Table 2. $CO_2$ emission, efficiency and costs of advanced power generation technologies without and with CCS ( Holt 2004)***

*cost data have been modified to include the effect of a 30% recent increase in construction costs