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Increasing the Efficiency of Existing Coal-Fired Power Plants

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Summary

Coal has long been the major fossil fuel used to produce electricity. However, coal-fired electric power plants are one of the largest sources of air pollution in the United States, with greenhouse gas (GHG) emissions from burning of fossil fuels believed to be the major contributor to global climate change. Regulations under development at the Environmental Protection Agency (EPA) would impose new requirements on fossil-fueled (mostly coal-fired) power plants (CFPPs) to control GHG emissions. The first of these requirements was issued in September 2013 with proposed standards for the control of carbon dioxide (CO_2) emissions from new electric generating units burning fossil fuels. EPA's proposals for control of GHG emissions from existing power plants are expected by June 2014, with many options under consideration. EPA may target emissions on a state or plant-by-plant basis, with companies likely given choices for compliance. Within such a system, efficiency improvements can be an important contributor.

The overall efficiency of a power plant encompasses the efficiency of the various components of a generating unit. Minimizing heat losses is the greatest factor affecting the loss of CFPP efficiency, and there are many areas of potential heat losses in a power plant. Efficiency of older CFPPs becomes degraded over time, and lower power plant efficiency results in more CO_2 being emitted per unit of electricity generated. The options most often considered for increasing the efficiency of CFPPs include equipment refurbishment, plant upgrades, and improved operations and maintenance schedules.

Cost of the improvements is often compared to the expected return in increased efficiency as a primary determinant of whether to go forward with a program. A study by the Asia-Pacific Working Group (APWG) found that at the low to medium end of cost expenditures are combustion, steam cycle, and operations and maintenance improvements. Replacing the older CFPPs with new power plants was not generally seen as being practical because the expenditure for a new plant could not be justified by the improved performance. Instead, efficiency and operational improvements were seen as a possible alternative considering a range of equipment upgrades and refurbishment options to various CFPP systems.

The National Energy Technology Laboratory (NETL) took APWG's analysis a step further, finding that while the average efficiency of U.S. plants was 32% in 2007, the efficiency of the top 10% was five points higher at 37.4%. NETL suggested that if GHG emissions reduction was a goal, then heat rate efficiency improvements could enable a power plant to generate the same amount of electricity from less fuel and decrease CO_2 emissions.

In 2010, NETL completed a new study of U.S. CFPP efficiency, concluding that if generation levels were held constant at 2008 levels, overall fleet efficiency could be raised from 32% to 36%, resulting in an overall reduction in U.S. GHG emissions of 175 million metric tonnes per year, or 2.5% of total U.S. GHG emissions in 2008.

According to subsequent analyses, NETL concluded that retirements of lower efficiency units combined with increased generation from higher efficiency refurbished units, and advanced refurbishments with improved operation and maintenance, would be necessary to achieve this goal. These improvements would generally be considered low to medium cost upgrades. However, at the higher cost end are major plant retrofits and upgrades (i.e., conversion of subcritical CFPP units to super- or ultra-supercritical CFPP units), which would raise efficiencies more substantially.

One possible approach to achieve fleet-wide efficiency improvement might be to follow NETL's suggestion of using the top decile of CFPP efficiency as a benchmark for the U.S. fleet, and establish an "efficiency frontier" that would be revisited periodically to reset the benchmark. This could be combined with possible incentives to improve efficiency or retire less efficient power plants. Other federal approaches could use tax incentives to encourage greater efficiency, or employ energy efficiency standards focused on improving efficiency of CFPPs. The overall cost of these or other programs to increase CFPP efficiency has yet to be determined.

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Introduction

Coal has long been the major fossil fuel used to produce electricity. However, the Environmental Protection Agency (EPA) lists coal-fired electric power plants as one of the largest sources of air pollution in the United States, with greenhouse gas[1] (GHG) emissions from burning fossil fuels believed to be the largest contributor to global climate change.

Regulations under development at EPA would impose new requirements on power plants to control GHG emissions. First, in September 2013 EPA proposed standards for the control of carbon dioxide (CO_2) emissions from new electric generating units burning fossil fuels. EPA has suggested that utilization of carbon capture and storage (CCS) is a viable means for new coal-fired power plants to comply with the proposed standards.[2] But higher efficiency components and processes are unlikely to be sufficient to meet the proposed new plant standards. As requirements for new sources (i.e., new power plants), EPA's proposed standards do not directly apply to existing power plants currently producing electricity. EPA's proposals for control of GHG emissions from existing power plants are expected by June 2014,[3] with many options for reducing GHGs under consideration. EPA may target emissions on a state or plant-by-plant basis, with companies likely given choices for compliance, and increasing coal-fired power plant (CFPP) efficiency may be one of those choices.

Improving the efficiency of existing coal plants could potentially result in significant reductions of CO_2 emissions per unit of electricity produced. However, certain modifications to power plants to increase power output can potentially increase pollutant emissions, thus triggering new source review[4] (NSR) requirements. Therefore, any modifications made must be shown to reduce pollutants if NSR is to be avoided. Expenditures to increase efficiency would likely be evaluated on a cost vs. benefits approach, with modifications to improve efficiency varying according to

[1] Greenhouse gases, according to EPA, are any gas that absorbs infrared radiation in the atmosphere. There are six greenhouse gases addressed by EPA regulatory actions: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases—sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Carbon dioxide is the most prevalent GHG produced by combustion of fossil fuels. See http://www.epa.gov/climatechange/ghgemissions/gases.html.

[2] EPA's proposed standard for new power plants would require new coal units to achieve the emissions of a natural gas combined-cycle unit, which would likely require coal units to employ CCS. Environmental Protection Agency, *2013 Proposed Carbon Pollution Standard for New Power Plants*, September 23, 2013, http://www2.epa.gov/carbon-pollution-standards/2013-proposed-carbon-pollution-standard-new-power-plants.

[3] "The President directed EPA to propose such guidelines by June 2014 and to finalize them a year later. Using these guidelines, states will be required to develop performance standards for existing sources. These could be less stringent than the NSPS—taking into account, among other factors, the remaining useful life of the existing source." For a discussion of current EPA regulations and coal-fired power plant GHG emissions, see CRS Report R43127, *EPA Standards for Greenhouse Gas Emissions from Power Plants: Many Questions, Some Answers*, by (name redacted).

[4] Congress established the New Source Review permitting program as part of the 1977 Clean Air Act Amendments. NSR is a preconstruction permitting program that serves two important purposes. First, it ensures that air quality is not significantly degraded from the addition of new and modified factories, industrial boilers and power plants. In areas with unhealthy air, NSR assures that new emissions do not slow progress toward cleaner air. In areas with clean air, especially pristine areas like national parks, NSR assures that new emissions do not significantly worsen air quality. Second, the NSR program assures people that any large new or modified industrial source in their neighborhoods will be as clean as possible, and that advances in pollution control occur concurrently with industrial expansion. NSR permits are legal documents that the facility owners/operators must abide by. The permit specifies what construction is allowed, what emission limits must be met, and often how the emissions source must be operated.

See Environmental Protection Agency, *New Source Review*, June 11, p. 2013, http://www.epa.gov/NSR/.

many factors, including the type of fuel burned, and the age and the physical condition of the power plant.

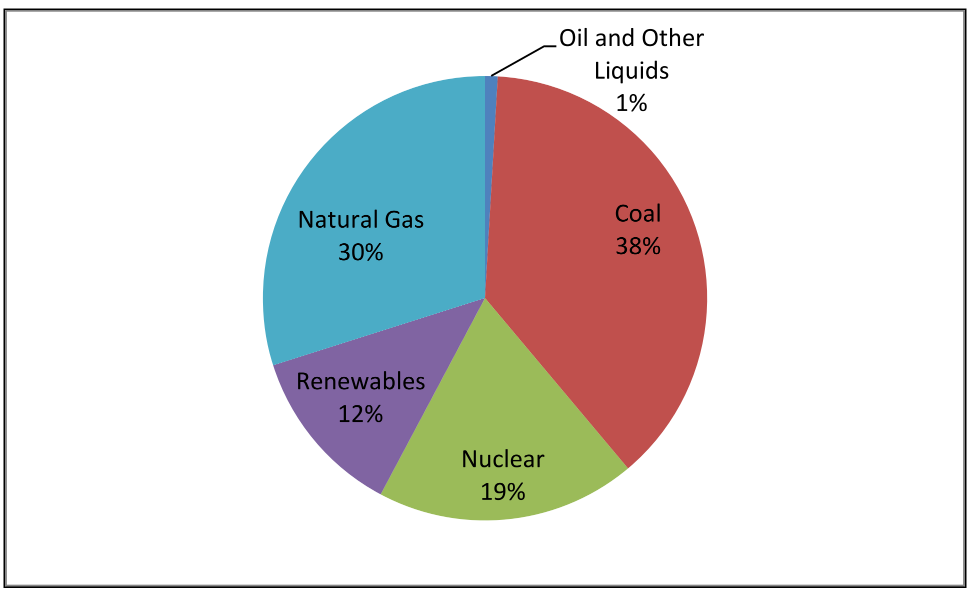
Carbon capture and sequestration (CCS) will not be a focus of improvements discussed in this report, as there are no CCS technologies considered as commercially available for full-scale application to the broad majority of existing coal-fired power plants,[5] and EPA has stated that it does not expect to require CCS at *existing* plants.

This report focuses on efficiency improvements to power plants, and discusses retrofits, technologies, and other modifications to facility operations which offer the potential to improve power plant efficiency and reduce CO_2 emissions. Some in Congress have expressed concerns about the potential impacts on electricity reliability and fuel diversity from retirements of coal plants due to pending and new environmental regulations. Increasing efficiency of coal plants may help to address these concerns by reducing emissions without reducing output. Additionally, Congress may want to consider whether such efficiency improvements could be accelerated if these were implemented in a program focused on increasing the efficiency of the coal-fired power plant sector.

Coal and Existing U.S. Coal Power Plants

For most of the history of power generation in the United States, coal has been the dominant fuel used to produce electricity. In 2012, coal was used to fuel approximately 38% of power generation in the United States, as shown in **Figure 1**. Coal has been the fuel of choice for many decades because of its wide availability, and the relatively low cost of producing electricity in large, coal-burning power plants. Coal's low-priced, high energy content enabled the building of power plants able to take advantage of economies of scale in steam-electric production.

Figure 1. Electricity Generation by Fuel, 2012



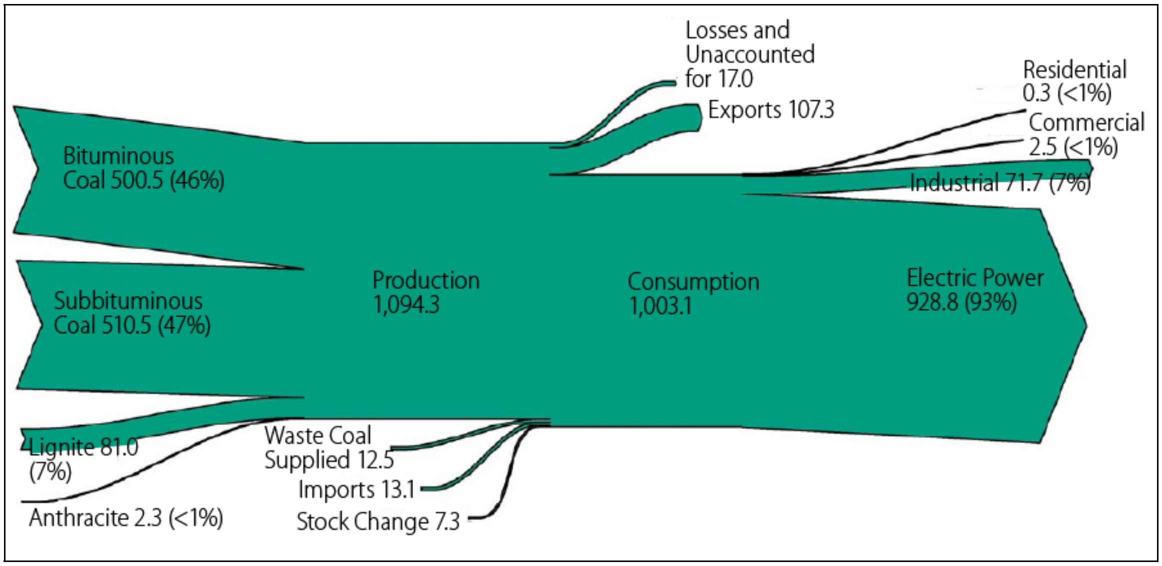
Source: U.S. Energy Information Administration, Electric Power Monthly, September 2013.

[5] See CRS Report R41325, *Carbon Capture: A Technology Assessment*.

In a steam power plant, coal (or other combustible fuel) is burned to provide heat for turning water into steam in a boiler.[6] The steam is then forced under pressure into a steam turbine-driven generator which produces electricity. As of 2012, the U.S. coal-powered generation fleet consisted of 1,337 units[7] with a nameplate capacity of almost 313 gigaWatts (GW) of generating capacity.[8]

Figure 2. Flow of U.S. Coal Consumption for 2011

(Million Short Tons)



Source: U.S. Energy Information Administration. See http://www.eia.gov/totalenergy/data/annual/pdf/sec7_3.pdf.

Coal and Greenhouse Gas Emissions

Coal is largely composed of carbon, hydrogen and oxygen, with varying amounts of carbon, sulfur, ash, and moisture content in the different types of coal mined in the United States. **Figure 2** shows the use of the four major types (also called "ranks") of coal produced in the United States, with bituminous and subbituminous coal dominating electric power generation.

Bituminous is the most abundant form of coal in the United States, and is the type most commonly used to generate electricity. Bituminous coal has a carbon content ranging from 45% to 86%, and a heat value between 10,500 British Thermal Units (BTUs)[9] and 15,500 BTUs per pound.

[6] A simple cycle natural gas power plant burns natural gas in a combustion turbine (like a jet engine) to turn a generator which produces electricity. When used in a combined cycle mode, the hot exhaust gases from the combustion turbine are used to generate steam to turn a steam turbine to efficiently create additional electricity. Nuclear fuel does not "combust," but it does produce heat to make steam.

[7] See 2012 Form EIA-860 Data - Schedule 3, 'Generator Data' (Operable Units Only).

[8] See Electric Generating Capacity, U.S. Energy Information Administration's Annual Energy Outlook at http://www.eia.gov/forecasts/aeo/er/early_elecgen.cfm.

[9] The heating value of any fuel is the energy released per unit mass or per unit volume of the fuel when the fuel is completely burned. Higher heat value fuels liberate more energy per unit of mass or volume.

Subbituminous coal is mostly found in six western states and Alaska. It has a carbon content of between 35% and 45%, and a heat value of between 8,300 BTUs and 13,000 BTUs. Subbituminous coal generally has a lower sulfur content than other types of coal.

Lignite has the lowest carbon content of the four types of coal generally used for electric power generation, averaging between 25% and 35%, and a high moisture and ash content. It also has the lowest heat value, ranging between 4,000 BTUs and 8,300 BTUs.

Anthracite has the highest carbon content (between 86% and 98%), and a heat value of about 15,000 BTUs. Anthracite coal is a small part of the electric power market, and is mostly found in the Appalachian region of Pennsylvania.

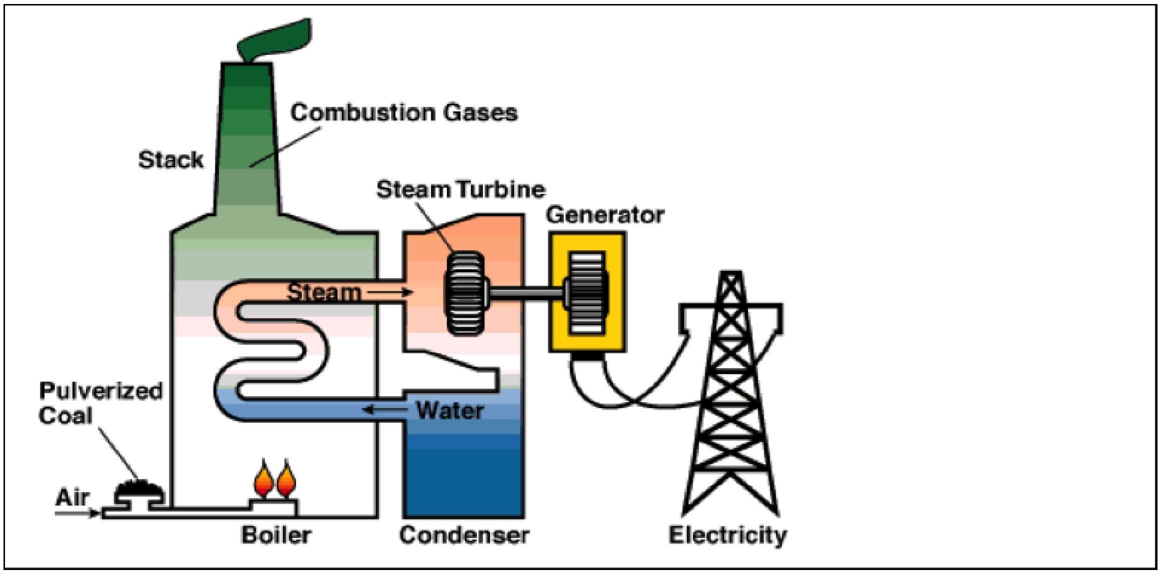
The amount of CO_2 emitted from a coal-fired power plant (CFPP) varies with the type of coal burned. The combustion of coal in the presence of oxygen causes its carbon and hydrogen constituents to react, releasing CO_2 emissions and water, with varying amounts of other products such as oxides of nitrogen and sulfur, carbon monoxide, and fine particulate matter. Carbon dioxide is the primary emission of concern when considering GHG emissions from power plants.[10]

Generally, anthracite emits the largest amount of CO_2 per million BTUs (MMBTU) of coal burned, followed by lignite, subbituminous coal, and bituminous coal. Carbon dioxide emissions from coal-fired power plants could thus be reduced by burning a better grade of coal, or by increasing the efficiency of the power plant and reducing overall coal consumption, without a need to completely repower the plant (in, say, a coal to natural gas conversion). Fuel switching may be necessary if a greater degree of CO_2 emissions reduction is desired.

[10] "To optimize overall efficiency for a given [power plant or electric generating unit] EGU, the unit is operated under conditions such that nearly all of the fuel carbon is converted to CO_2 during the combustion process. Methane is emitted during the mining and transport of coal but is not a significant by-product of EGU coal combustion. Fluorinated gases are not formed by coal combustion. Sulfur hexafluoride might be used at the power plant switchyard, but the switchyard is not typically considered part of the EGU." Sector Policies and Programs Division, *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Coal-Fired Electric Generating Units*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, October 2010, http://www.epa.gov/nsr/ghgdocs/electricgeneration.pdf.

Figure 3. Electric Power Generation

(Steam Turbine-Generator)



Source: Oncor Electric Delivery Company. Steam Turbine.

Note: See http://www.c2es.org/technology/overview/electricity.

Types of U.S. Coal-Fired Power Plants

Steam turbines are at the heart of coal-fired power plants. As shown in the simplified schematic of a pulverized coal plant in **Figure 3**, a steam electric power plant consists of a number of basic components. Coal is crushed and fed into a boiler where it is burned to heat water into steam. The steam is injected under pressure into a turbine which turns a generator (where essentially a magnet turns in a coil of wire causing electrons to flow thus creating an electric current). Steam returning from the turbine is then cooled in a condenser, and the water is fed back by a feedwater pump to the boiler to continue the process. The expansion of water into steam vapor (and condensation back into liquid water) in this manner is called a Rankine Cycle,[11] and is the basis for most electric power generation in the United States.

A typical coal-fired power plant has multiple generating units, each with its own steam generating boiler. Usually, coal is pulverized by a combination of crushing and grinding until a desired degree of fineness is achieved. The coal is sieved, and dried using heated air before it is conveyed to a furnace where it is burned to produce steam. Steam pressure and temperature are specifically related, as steam's temperature rises with increasing steam pressure. The pressure and temperature of the steam produced have been rising steadily over the years, ranging from yesterday's sub-critical units to today's ultra-super critical units.

> **Subcritical steam** generation units operate at pressures such that water boils first and then is converted to superheated steam. At **supercritical** pressures, water is heated to produce

[11] The thermodynamic cycle that is an ideal standard for comparing performance of heat-engines, steam power plants, steam turbines, and heat pump systems that use a condensable vapor as the working fluid. See http://www.eia.gov/tools/glossary/index.cfm.

> superheated steam without boiling. Due to the improved thermodynamics of expanding higher pressure and temperature steam through the turbine, a **supercritical steam** generating unit is more efficient than a subcritical unit.
>
> **Ultra-supercritical steam** (USC) generation currently is the most efficient technology for producing electricity fueled by pulverized coal. A USC unit operates at supercritical pressure and at advanced steam temperatures of 1,100 ºF ...These temperatures and pressures enable more efficient operation of the turbine cycle. This increase in efficiency reduces fuel (coal) consumption, and thereby reduces emissions, solid waste, water use and operating costs.[12]

While pulverized coal units are most common in the United States, coal-fired power plants use other technologies to burn coal including cyclone-fired boilers,[13] fluidized bed combustion,[14] and integrated coal gasification/combined cycle[15] technologies.

U.S. Coal Power Plants Are Aging

According to EIA, approximately 73% of U.S. coal-fired power plants were age 30 years or older at the end of 2010. The service life for CFPPs normally averages between 35 and 50 years, and varies according to boiler type, maintenance practices, and the type of coal burned, among other factors.

Vintages of existing power plants can be seen in **Figure 4**, which illustrates the age and capacity of coal-fired and other power plants. Most of this generating capacity was built between 1950 and 1990. The aging majority of U.S. coal-fired capacity contrasts against the recent surge in younger wind power and natural gas-fired capacity additions whose generating capacity is mostly less than 10 years old.

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[12] Subcritical steam operating conditions are generally at pressures of 2,400 pounds per square inch gage (psig) [i.e., relative to atmospheric pressure] per 1,000 [degrees Fahrenheit] ºF of superheated steam. Supercritical steam cycles typically operate at 3,600 psig, with 1,000 ºF to 1,050 ºF steam conditions. See American Electric Power Company, *Pulverized Coal Technologies*, 2013, http://www.aep.com/about/IssuesAndPositions/Generation/Technologies/PulverizedCoal.aspx.

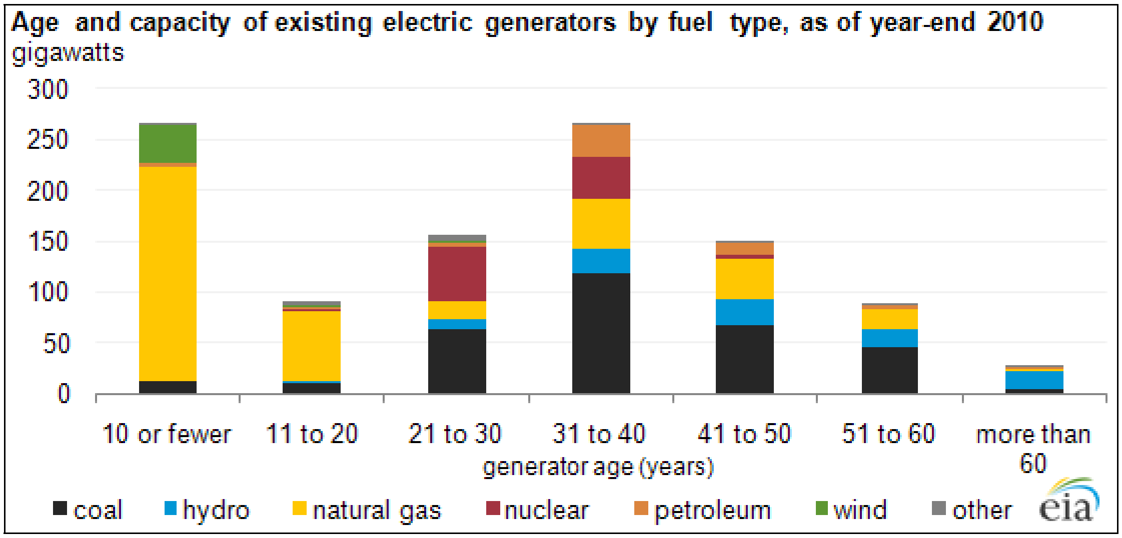
[13] Cyclone-fired boilers are used for coals with a low ash fusion temperature which are difficult to use with pulverized coal combustion (PCC). 80-90% of the ash leaves the bottom of the boiler as a molten slag, thus reducing the load of fly ash passing through the heat transfer sections to the precipitator or fabric filter to just 10-20% of that present. As with PCC, units operate at close to atmospheric pressure, simplifying the passage of coal and air through the plant. Steam is generated in heat transfer tubes, driving a steam turbine and generator. See http://www.iea-coal.org.uk/site/2010/database-section/ccts/cyclone-fired-wet-bottom-boilers?

[14] A method of burning particulate fuel, such as coal, in which the amount of air required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of mineral ash in the proportions of one part fuel to 200 parts ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid. See http://www.eia.gov/tools/glossary/index.cfm.

[15] Coal, water, and oxygen are fed to a gasifier, which produces syngas. This medium-Btu gas is cleaned (particulates and sulfur compounds removed) and is fed to a gas turbine. The hot exhaust of the gas turbine and heat recovered from the gasification process are routed through a heat-recovery generator to produce steam, which drives a steam turbine to produce electricity. See http://www.eia.gov/tools/glossary/index.cfm.

Figure 4. Vintages of U.S. Generating Capacity

(As of 2010)



Source: U.S. Energy Information Administration. Today in Energy.

Note: See http://www.eia.gov/todayinenergy/detail.cfm?id=1830.

The efficiency of coal-fired power plants, in particular, decreases with age. While good maintenance practices can keep power plant efficiency high in the early years of life, as the plant ages, power plant performance and efficiency erode after about 25 to 30 years of operation,[16] and substantial work may be required to keep the plant operating efficiently and economically.

All power plants are subject to retirement when they reach the end of their useful service life. As power plants age, they are generally upgraded to continue operations, but the least efficient plants may be retired. Other plants may be shifted from base load operations (in which they essentially operate around the clock) to less demanding intermediate or peaking schedules. The cost of building a power plant is generally recovered over the depreciable life of the asset, such that operations and maintenance (O&M) expenses become the major component of an older power plant's continuing costs. A major component of O&M is the cost of fuel, and the expectation of continued lower prices for natural gas is weighing on decisions concerning whether many older, less efficient coal power plants will be mothballed or closed altogether. The costs of modernizing older power plants to meet new regulatory requirements can be relatively high. When the cost of upgrades to meet new environmental requirements is considered along with (perhaps increasing) O&M expenses, many older coal power plants are likely to face outright retirement decisions.[17]

[16] International Energy Agency, *Upgrading and efficiency improvement in coal-fired power plants*, No. 13/9, August 2013, http://www.iea-coal.org.uk/documents/83185/8784/Upgrading-and-efficiency-improvement-in-coal-fired-power-plants,-CCC/221.

[17] CRS Report R42950, *Prospects for Coal in Electric Power and Industry*, by (name redacted), (name redacted), and (name redacted).

Efficiency of Power Plants and Power Plant Systems

Improving the efficiency of existing coal plants could potentially result in large reductions of CO_2 emissions per unit of electricity produced. Since GHG emissions from electricity generation are essentially composed of CO_2 emissions, improvements in efficiency are a direct means of reducing GHG emissions.

The performance of a power plant can be expressed by a number of measures, including heat rate (i.e., the efficiency of conversion from fuel energy input to electrical energy output), and thermal efficiency. In its simplest form, a plant's heat rate (for a particular period) can be defined as follows:

$HR = F / E$

where,

HR = *heat rate (Btu/kWh)*

F = *heat energy input supplied by fuel to the power plant for a period (BTU)*

E = *energy output from the power plant in a period (kWh)*

Since the equivalent BTU content of a single kWh of electricity is 3,412 BTU, thermal efficiency[18] can be calculated as:

$TE = (100)\,(3412) / HR$

where,

TE = *thermal efficiency (%)*

As an example, using the average heat rate in 2011 of 10,444 BTU/kWh for coal-fired power plants (i.e., all coal types), the average efficiency for coal-fired plants was 33%.[19]

A lower heat rate represents a more efficient generating unit, since it requires less heat input to generate a kWh of electric energy. A generating unit can thus improve its efficiency by reducing the fuel it uses relative to a specific amount of electricity generated, thus reducing the amount of CO_2 emitted.

[18] Efficiency can be calculated using the higher heating value (HHV) or the lower heating value (LHV) determined for the fuel. The HHV is the heating value directly determined by calorimetric measurement of the fuel in the laboratory. The LHV is calculated using a formula to account for the moisture in the fuel (i.e., subtract the energy required to vaporize the water in the coal and thus not available to produce steam) that is a smaller value than the HHV. Consequently, the HHV efficiency for a given EGU is always lower than the corresponding LHV efficiency, because the reported heat input is larger for the same output.

[19] Therefore, 10,444 BTU of energy from coal produces 3,412 BTU per each kiloWatt-hour of electricity. See EIA, What is the efficiency of different types of power plants? at http://www.eia.gov/tools/faqs/faq.cfm?id=107&t=3. Coal includes anthracite, bituminous, subbituminous and lignite coal. Waste coal and synthetic coal are also included.

> A percentage improvement in heat rate is nearly equivalent to an equal percentage improvement in the emissions rate in terms of the change in CO_2 emissions. The difference stems from the small variation in carbon per Btu across coal varieties. The heterogeneity in heat rates across coal-fired generation units can partly be explained by technical characteristics determined at the time of plant construction that cannot be changed without a major overhaul. This category includes size, age, firing type, and the technology employed. Higher efficiency is generally associated with plants that are used more heavily because efficient units are less costly to operate.
>
> A second factor is how the boiler is used. The relationship between the heat rate and utilization is nonlinear, as efficiency tends to be lower at very low and very high levels of utilization ... Units with lower utilization may be ramped up and down more frequently, which requires additional fuel input as temperature in the boiler fluctuates. The result could involve efficiency losses at least partly outside the control of plant decision makers. Plant managers control several other factors that affect heat rates. Techniques, management, or technology may improve the efficiency of the plant by targeting the major components of the coal combustion process: oxygen, temperature, and pressure. Excessive deviations in any of these areas may decrease efficiency through waste or shortfalls ...Maintenance and performance testing are also critical for identifying and preventing losses.[20]

Therefore, in practical terms, a power plant's heat rate can be affected by a number of factors and power plants systems. Heat rate may present one measure of efficiency, but when considering power plant GHG emissions, measuring carbon dioxide emissions per unit of energy output (i.e., per kWh or per MWh of generation) may provide a more useful measure.[21]

Each power plant thus presents a unique opportunity when looking at the issue of increasing efficiency, and reducing emissions. **Figure 5** illustrates a relationship between efficiency improvement and CO_2 emissions (for CFPPs using bituminous coal) highlighting the lower emissions of higher pressure CFPPs. Upgrading from subcritical operation to supercritical steam conditions (with required pollution technology) could add at least 20 years to a plant's service life,[22] depending on the regulatory and environmental regime in place. A subcritical plant could achieve at best 40% efficiency (on an LHV basis), while a supercritical steam plant could potentially achieve an efficiency two points higher and emit 4% less CO_2.[23] Advancing the technology from a supercritical to an advanced ultra-supercritical CFPP could see an efficiency of 46% to 48%, which could mean as much as 18% to 22% less CO_2 per MWh generated than an equivalent-sized subcritical PC unit.[24] However, "[m]ajor plant upgrading involving conversion of subcritical to supercritical or ultra-supercritical ... has seldom progressed beyond studies because of the high cost."[25]

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[20] Joshua Linn, Erin Mastrangelo, and Dallas Burtraw, *Regulating Greenhouse Gases from Coal Power Plants under the Clean Air Act*, Resources for the Future, RFF DP 13-05, February 2013, http://www.rff.org/RFF/documents/RFF-DP-13-05.pdf.

[21] János Beér, *High Efficiency Electric Power Generation; The Environmental Role*, Massachusetts Institute of Technology, October 17, 2006, http://mitei.mit.edu/system/files/beer-combustion.pdf. (BEF).

[22] Deborah Adams, *Efficiency Upgrades for Existing Coal-fired Power Plants*, International Energy Agency—Clean Coal Centre, Presentation, Gliwice, Poland, September 24, 2009, p. 8, http://cleancoal.polsl.pl/pdf/Adams.pdf.

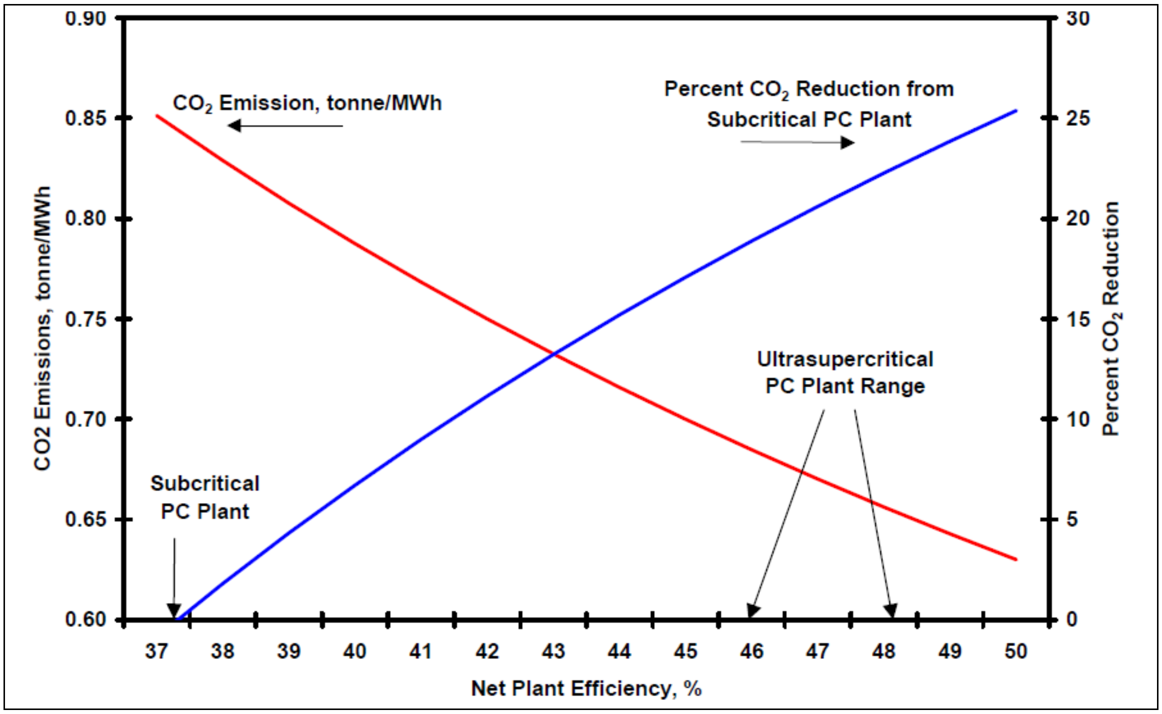
[23] Ibid.

[24] George Booras and Neville Holt, *Pulverized Coal and IGCC Plant Cost and Performance*, Electric Power Research Institute, Gasification Technologies 2004, October 2004, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.168.2103&rep=rep1&type=pdf.

[25] International Energy Agency, Bulletin No. 13/9, *Upgrading and efficiency improvement in coal-fired power plants*, (continued...)

Figure 5. Carbon Dioxide Emissions vs. Net Plant Efficiency

(Based on Burning Pittsburgh #8 [Bituminous] Coal)



Source: Booras, G. and N. Holt, Pulverized Coal and IGCC plant Cost and Performance Estimates, Gasification Technologies Conference Washington D.C. 2004.

Notes:

1. One tonne (also known as a metric ton) is a unit of mass equaling 1,000 kilograms.

2. This chart assumes subcritical plants (using bituminous coal) would be near the top of the range for efficiency. Improvements at the higher end of the range are now considered to be based on advanced ultrasupercritical technology, which while technologically possible, is unlikely to be implemented in the next few years.

Efficiency Improvements to Reduce GHG Emissions

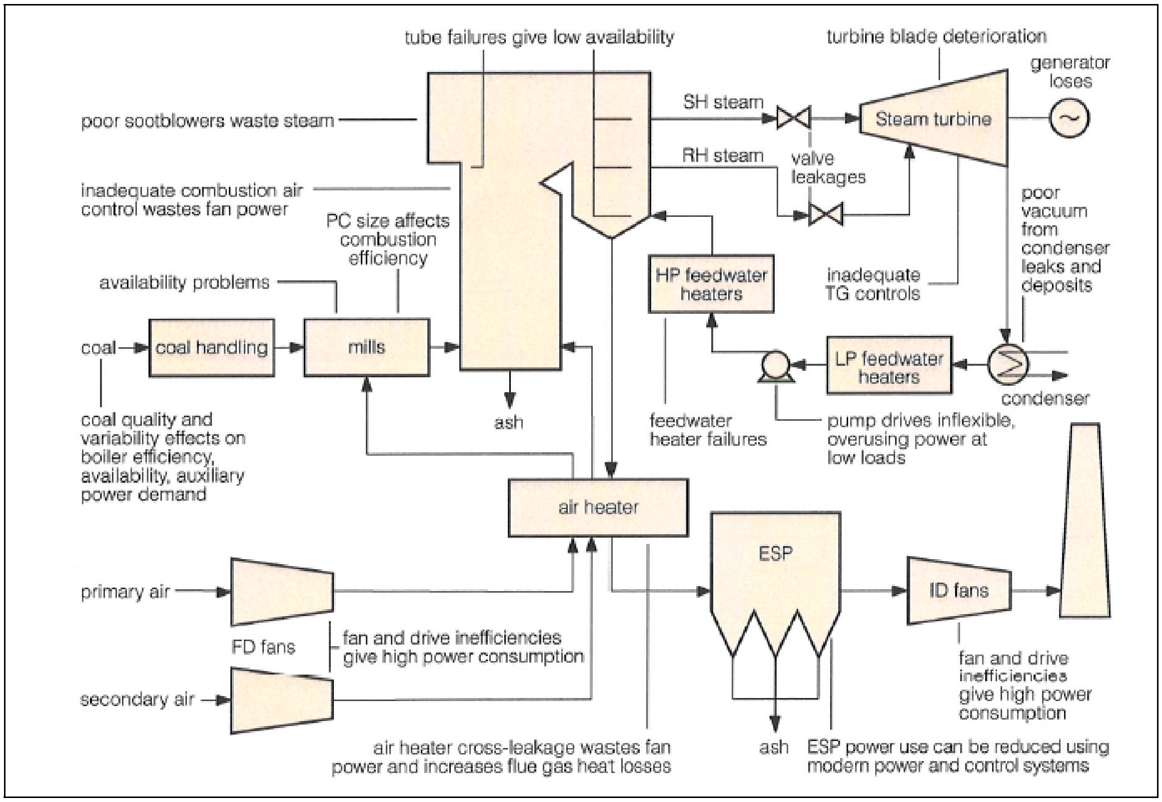
The overall efficiency of a power plant encompasses the efficiency of the various components of a particular generating unit. Sometimes these systems are unique to a generating unit, while in other instances these systems may be shared between generating units at a power plant site. This section will summarize the results of several U.S. and international studies which present options for improvements to power plant systems capable of increasing system heat rate efficiency and reducing GHG emissions. While the focus of this report is improving the efficiency of U.S. coal-fired power plants, studies from the international community are also presented as suggested improvements apply generally to coal-fired power plants. Further, a key report from an Asia-Pacific Economic Cooperation (APEC) working group report laid the groundwork for several U.S and international studies.

(...continued)

August 2013, http://www.iea-coal.org.uk/documents/83185/8784/Upgrading-and-efficiency-improvement-in-coal-fired-power-plants,-CCC/221.

As coal-fired power plants age, they lose efficiency. Much of this loss in efficiency is due to mechanical wear on a variety of components resulting in heat losses, as can be seen in **Figure 6**. Lower power plant efficiency results in more CO_2 being emitted per unit of electricity generated. The mode of operation (i.e., base load[26] vs. cyclical) also has a large effect on efficiency and fuel use. The options most often considered for increasing the efficiency of CFPPs include equipment refurbishment, plant upgrades, and improved O&M schedules. Cost of the improvements is often compared to the expected return in increased efficiency as a primary determinant of whether to go forward with a program.

Figure 6. Areas of a Pulverized Coal Plant where Efficiency Loss Can Occur



Source: International Energy Agency (IEA), Clean Coal Centre. Upgrading and Efficiency Improvement in Coal-fired Power Plants. Clean Coal Reports at http://www.iea-coal.org.uk/site/2010/publications-section/reports.

Notes: ID = induced draft fans are used to create a vacuum or negative air pressure in a system or stack; ESP = an electrostatic precipitator is a particulate collection device that removes particles from a flowing gas (such as air) using the force of an induced electrostatic charge; FD = a forced draft fan is used to provide a positive pressure to a system ; LP = low pressure; HP = high pressure; PC = pulverized coal; RH = reheated ; SH = superheated; TG = turbine generator.

In 1999, the APEC region was responsible for 59% of the world's carbon dioxide emissions from fossil fuel combustion. Pulverized coal technologies accounted for 94% of coal-fired capacity in

[26] Base load plant: A plant, usually housing high-efficiency steam-electric units, which is normally operated to take all or part of the minimum load of a system, and which consequently produces electricity at an essentially constant rate and runs continuously. These units are operated to maximize system mechanical and thermal efficiency and minimize system operating costs. See http://www.eia.gov/tools/glossary/index.cfm.

the region.[27] The 21 countries comprising APEC include Australia, Canada, China, Japan, the United States, and Russia. According to an Asia-Pacific Economic Cooperation Working Group (APWG) study in 2001, projects to improve combustion, steam cycle, and O&M required low to medium costs, and these expenditures were predicted to produce as much as a 3.5% net overall efficiency improvement.[28] These improvements could also result in the largest overall reduction in CO_2 emissions of all the scenarios considered by the APWG study, since lower cost improvements were more likely to be adopted.

However, if reduction of carbon intensity is the goal (measured in grams of CO_2 emission per kiloWatt-hour of generation), the study found that switching of CFPPs to biomass ranked highest among the options considered (as biomass was considered carbon neutral), followed by fuel-switching to natural gas.

A subsequent APWG study in 2005[29] found that many older power plants in the Asia-Pacific region were operating well below their design efficiency. However, the study found that replacing the older CFPPs with new power plants was not practical because the expenditure for a new plant could not be justified by the improved performance. Instead, efficiency and operational improvements were seen as a possible alternative considering a range of equipment upgrades and refurbishment options to various CFPP systems.

Table 1. Existing Coal-Fired EGU Efficiency Improvements

(Improvements Reported for Actual Improvement Projects)

Efficiency Improvement Technology	Description	Reported Efficiency Increase See Note
Combustion Control Optimization	Combustion controls adjust coal and air flow to optimize steam production for the steam turbine/generator set. However, combustion control for a coal-fired EGU is complex and impacts a number of important operating parameters including combustion efficiency, steam temperature, furnace slagging and fouling, and NO_X formation. The technologies include instruments that measure carbon levels in ash, coal flow rates, air flow rates, CO levels, oxygen levels, slag deposits, and burner metrics as well as advanced coal nozzles and plasma assisted coal combustion.	0.15% to 0.84%

[27] See Table 3-7, Distribution of Existing Capacity by Fuel and Type of Energy Technology for APEC Economies as of November, 2000 at http://www.egcfe.ewg.apec.org/projects/CO2_Phase1_Study_2000.pdf.

[28] See Scenario E-4, Options to reduce CO2 Emissions from Electricity Generation in the APEC Region. Energy Working Group Project EWG 04/2000.

[29] Asia-Pacific Economic Cooperation Working Group, Costs and Effectiveness of Upgrading and Refurbishing Older Coal-Fired Power Plants in Developing APEC Economies, Energy Working Group Project EWG 04/2003T, June 2005, http://www.egcfe.ewg.apec.org/projects/UpgradePP_Report_2005.pdf.

Efficiency Improvement Technology	Description	Reported Efficiency Increase See Note
Cooling System Heat Loss Recovery	Recover a portion of the heat loss from the warm cooling water exiting the steam condenser prior to its circulation thorough a cooling tower or discharge to a water body. The identified technologies include replacing the cooling tower fill (heat transfer surface) and tuning the cooling tower and condenser.	0.2% to 1%
Flue Gas Heat Recovery	Flue gas exit temperature from the air preheater can range from 250 to 350°F depending on the acid dew point temperature of the flue gas, which is dependent on the concentration of vapor phase sulfuric acid and moisture. For power plants equipped with wet FGD systems, the flue gas is further cooled to approximately 125°F as it is sprayed with the FGD reagent slurry. However, it may be possible to recover some of this lost energy in the flue gas to preheat boiler feedwater via use of a condensing heat exchanger.	0.3% to 1.5%
Low-Rank Coal Drying	Subbituminous and lignite coals contain relatively large amounts of moisture (15% to 40%) compared to bituminous coal (less than 10%). A significant amount of the heat released during combustion of low-rank coals is used to evaporate this moisture, rather than generate steam for the turbine. As a result, boiler efficiency is typically lower for plants burning low-rank coal. The technologies include using waste heat from the flue gas and/or cooling water systems to dry low-rank coal prior to combustion.	0.1% to 1.7%
Sootblower Optimization	Sootblowers intermittently inject high velocity jets of steam or air to clean coal ash deposits from boiler tube surfaces in order to maintain adequate heat transfer. Proper control of the timing and intensity of individual sootblowers is important to maintain steam temperature and boiler efficiency. The identified technologies include intelligent or neural-network sootblowing (i.e., sootblowing in response to real-time conditions in the boiler) and detonation sootblowing.	0.1% to 0.65%

Efficiency Improvement Technology	Description	Reported Efficiency Increase See Note
Steam Turbine Design	There are recoverable energy losses that result from the mechanical design or physical condition of the steam turbine. For example, steam turbine manufacturers have improved the design of turbine blades and steam seals which can increase both efficiency and output (i.e., steam turbine dense pack technology).	0.84% to 2.6

Source: NETL. Available at Office of Air and Radiation, *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Coal-Fired Electric Generating Units*, U.S. Environmental Protection Agency, October 2010, http://www.epa.gov/nsr/ghgdocs/electricgeneration.pdf.

Note: Reported efficiency improvement metrics adjusted to common basis by conversion methodology assuming individual component efficiencies for a reference plant as follows: 87% boiler efficiency, 40% turbine efficiency, 98% generator efficiency, and 6% auxiliary load. Based on these assumptions, the reference power plant has an overall efficiency of 32% and a net heat rate of 10,600 Btu/kWh. As a result, if a particular efficiency improvement method was reported to achieve a 1% increase in boiler efficiency, it would be converted to a 0.37% increase in overall efficiency. Likewise, a reported 100 Btu/kWh decrease in net heat rate would be converted to a 0.30% increase in overall efficiency.

National Energy Technology Laboratory Studies

The APWG results were amplified by a U.S. National Energy Technology Laboratory (NETL) study in 2008 which identified a list of potential methods to improve overall CFPP heat rate efficiency.[30,31] The results are shown in **Table 1**. The NETL study found that aside from a unit's age and steam cycle type, plant attributes such as location and emissions controls equipment did not account for the variations observed in plant efficiency. NETL then undertook an analysis of the efficiency of U.S. CFPPs, concluding that while the average efficiency was 32% in 2007, the efficiency of the top 10% was five points higher at 37.4%.[32]

NETL suggested that if GHG emissions reduction was a goal, then heat rate efficiency improvements could enable a power plant to generate the same amount of electricity with lower CO_2 emissions.[33]

[30] DOE—National Energy Technology Laboratory, *Reducing CO_2 Emissions by Improving the Efficiency of the Existing Coal-fired Power Plant Fleet*, DOE/NETL-2008/1329, July 2008, http://www.netl.doe.gov/energy-analyses/pubs/CFPP%20Efficiency-FINAL.pdf. (NETL)

[31] It is important to note that improved efficiency in one area of a power plant can also help improve efficiency in other areas. "... [O]ptimization of the combustion process can give valuable benefits in efficiency and costs. The gain may typically be about 0.1% to 0.15% in fuel cost saving, efficiency and CO_2 emissions ...Improvements in combustion efficiency can be achieved in parallel with other improvements, for example, reductions in primary NO_x production from replacement burners and new air supply arrangements." See Colin Henderson, Upgrading and Efficiency Improvement in Coal-fired Power Plants, International Energy Agency Clean Coal Centre, CCC/221, August 2013, http://www.iea-coal.org.uk/site/2010/publications-section/reports.

[32] See Table 2, Reducing CO2 Emissions by Improving the Efficiency of the Existing Coal-fired Power Plant Fleet. DOE/NETL-2008/1329.

[33] While all the listed areas for improvement could be targets, the actual improvements considered would depend on an evaluation of site-specific conditions.

Table 2. Segmentation Analysis of U.S. Coal-Fired Power Plants

(Efficiency vs. Power Plant Type)

Segment Criteria			Sub-Population Characteristics			Efficiency	
Unit Type	**Coal Type**	**Size** (MW)	**Capacity** (GW)	**No. of Units**	**Generation** (Billion, kWh)	**Average**	**90th Percentile**
Low Pressure Subcritical (600 – 1,600 psig)	Bit.	0 - 200	10.3	127	44	29.6%	33.0%
	Subbit.		4.6	59	26	27.5%	29.8%
	Other		0.6	7	2	27.4%	30.5%
High Pressure Subcritical (1,800 – 2,600 psig)	Bit.	0 – 200	21.6	134	112	32.1%	34.8%
		200 – 500	33.4	103	189	32.8%	35.6%
		500 +	29.7	48	176	32.7%	35.0%
	Subbit.	0 – 200	7.2	47	42	30.7%	32.5%
		200 – 500	31.2	97	191	31.4%	35.6%
		500 +	64.4	98	401	31.6%	33.8%
	Other		11.1	28	72	31.7%	35.1%
Supercritical (Over 3,334 psig)	Bit.		60.7	79	372	35.1%	37.3%
	Subbit.		15.0	20	90	35.2%	37.2%
	Other		8.1	13	55	31.8%	34.9%
Whole Fleet			**298**	**860**	**1,772**	**32.5%**	**37.6%**

Source: Figure 3, Segmentation Analysis of the CFPP Fleet. Improving the Efficiency of Coal-Fired Power Plants for Near Term Greenhouse Gas Emissions Reductions, DOE/NETL-2010/1411.

Notes: Bit. = Bituminous; subbit. = subbituminous.

In 2010, NETL completed a new study of U.S. CFPP efficiency,[34] dividing the results into 10 deciles of equal capacity (see **Table 2**). The generating units in the top 10% are diverse (i.e., they are not all new, large, supercritical plants), which NETL believes indicates an opportunity for overall fleet improvement.

While on average the top decile consisted of units with larger capacities, higher steam pressures, higher load factors, and a higher percentage burning bituminous coal, there was significant overlap with the rest of the fleet. For example, the average steam pressure at the turbine of the top decile is around 3,000 psig, but there are ten units within the top decile with steam pressures in the 1,800 psig to 2,000 psig range. Also, the net nameplate capacity of the units in the top decile, while larger on average, ranged from 114 MW to 1,426 MW, indicating that even small plants can achieve higher than average efficiencies.

The fleet generation-weighted average efficiency is 32.5%, while the top performing decile is over five percentage points higher (see **Table 3**). NETL therefore projected that average

[34] Phil DiPietro, Katrina Krulla, DOE/National Energy Technology Laboratory, *Improving the Efficiency of Coal-fired Power Plants for Near Term Greenhouse Gas Emissions Reductions*, DOE/NETL-2010/1411, April 16, 2010, http://www.netl.doe.gov/energy-analyses/pubs/ImpCFPPGHGRdctns_0410.pdf. (NETL2).

efficiency of the CFPP fleet could be raised from an average plant heat rate of 32.5% in 2008 to 36% overall.

Table 3. Generation Weighted CFPP Efficiency

(By Decile, 2008)

Decile	Number of Units	Capacity (GW)	Capacity Factor	2008 Total Generation (Billion kWh)	2008 Generation-Weighted Efficiency (HHV)
1	194	30.5	62%	165	27.6%
2	102	30.3	67%	179	29.9%
3	88	30.7	65%	176	30.8%
4	86	30.6	69%	185	31.6%
5	75	30.7	70%	189	32.2%
6	83	30.8	66%	178	32.9%
7	71	31.0	68%	186	33.8%
8	79	30.6	68%	183	34.7%
9	61	30.8	67%	181	35.7%
10	53	30.7	74%	201	37.6%
OVERALL	892	307	69%	1,823	32.5%

Source: Improving Efficiency of Coal-fired Power Plants for Near Term CO_2 Reductions, NETL2.

NETL sets forth a vision of 36% based on retirements of low efficiency units, and improvements within the best-in-class. Under a scenario where generation from coal is constant at the 2008 level, increasing the average efficiency from 32.5% to 36% reduces U.S. GHG by 175 MMmt/year or 2.5% of total U.S. GHG emissions in 2008.

According to NETL's analysis, retirements of lower efficiency units combined with increased generation from higher efficiency refurbished units, and advanced refurbishments with improved operation and maintenance, would be the key to potentially increasing average fleet efficiency beyond the best-in-class units.

The low pressure subcritical units and the 0-200 MW subbituminous units, in the sample studied, had 90th percentile efficiencies that were significantly lower than the rest of the fleet. Retiring these units and relying on increased generation from the more efficient segments to maintain constant coal generation yields a fleet efficiency target of 35.6%.

NETL conceded that the fleet efficiency target of 36% did not consider installing scrubbers (to control emissions of sulfur oxides) at facilities without such controls.

> If efficiency upgrades were done in conjunction with installing sulfur scrubbers on 165-250 GW of the fleet, the efficiency target would be reduced 0.5 to 1 percentage points... NETL expects that the fleet achieving efficiencies approaching the best-in-class will require a

> combination of improved operational and maintenance practices, capital investments in unit refurbishments, and application of advanced technologies.[35]

NETL concluded its report on the opportunity to increase CFPP efficiency with the following suggestions on how to improve its analysis:

- Verification of coal generating unit efficiency data.
- Estimates of the cost of efficiency upgrades.
- Unit-specific data to enable estimation of the design heat rate for each generating unit.
- Case studies of efficiency upgrades at generating units, including modeling, to provide concrete examples of the opportunity to improve efficiency.
- Detailed analyses of scenarios where some of the generating units are retired, some are refurbished and up-rated, and others are fixed with sulfur, oxides of nitrogen, and mercury controls.
- Analyses of how more efficient coal plants will dispatch, what other generating sources will be displaced, and the overall effect on GHG emissions.

Environmental Protection Agency Study

The U.S. Environmental Protection Agency (EPA) issued a report[36] in 2010 which affirmed that there was a direct relationship between CFPP efficiency and CO_2 emissions. EPA recognized that the level of CO_2 emissions potentially released from a given coal-fired electric generating unit (EGU) (i.e., power plant) depends on the type of coal burned, the overall efficiency of the power generation process, and use of air pollution control devices.

> In addition to the lower CO_2 emissions rate per unit of heat input (lbs CO_2/MMBtu), due to the inherent moisture in subbituminous and lignite coals, all else being equal a bituminous coal-fired boiler is more efficient than a corresponding boiler burning subbituminous or lignite coal. Therefore, switching from a low to a high-rank coal will tend to lower GHG emissions from the utility stack.[37]

As the thermal efficiency of a coal-fired power plant is increased, less coal is burned per kWh of electricity generated, and there is a corresponding decrease in CO_2 and other air emissions. The greater the output of electric energy for a given amount of fuel energy input, the higher the efficiency for the electric generation process. Heat rate is another common way to express efficiency. Power plants that are more efficient typically have lower heat rates.[38]

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[35] Ibid.

[36] Office of Air and Radiation, *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Coal-Fired Electric Generating Units*, U.S. Environmental Protection Agency, October 2010, http://www.epa.gov/nsr/ghgdocs/electricgeneration.pdf. (EPAEff).

[37] Ibid.

[38] Bituminous coals thus tend to have a lower HHV efficiency than LHV efficiency, and higher moisture content subbituminous coals and lignite have HHV efficiency approximately 3 to 5 percentage points lower than the corresponding LHV efficiency.

Although EPA states there is a direct relationship between coal-fired EGU efficiency and CO_2 emissions, EPA recognized that other factors must be considered when comparing the effectiveness of GHG control technologies to improve the efficiency of a given coal-fired EGU. The study states that the actual overall efficiency that a given coal-fired EGU achieves is determined by the interaction of a combination of site-specific factors that impact efficiency to varying degrees, including the following.

> EGU thermodynamic cycle—EGU efficiency can be significantly improved by using a supercritical or ultra-supercritical steam cycle.
>
> EGU coal rank and quality—EGUs burning higher quality coals (e.g., bituminous) tend to be more efficient than EGUs burning lower quality coals (e.g., lignite).
>
> EGU plant size—The electric-generating capacity of EGUs ranges from approximately 25 to 1,300 MW. Assuming an EGU efficiency of 33% (a typical efficiency for existing coal-fired EGUs), this corresponds to a heat input range of 250 to 13,400 MMBtu/hr.
>
> EGU efficiency generally increases with size because the boiler and steam turbine losses are lower for larger equipment. However, as equipment size increases [beyond a certain point] the differences in these losses start to taper off.
>
> EGU pollution control systems—The electric power consumed by air pollution control equipment reduces the overall efficiency of the EGU.
>
> EGU operating and maintenance practices—The specific practices used by an individual electric utility company [including] combustion optimization, equipment maintenance, can affect EGU efficiency.
>
> EGU cooling system—The temperature of the cooling water entering the condenser can have impacts on steam turbine performance. Once-through cooling systems can have an efficiency advantage over recirculating cooling systems (e.g., cooling towers). However, once-though cooling systems typically have larger water related ecological concerns than recirculating cooling systems.
>
> EGU geographic location—The elevation and seasonal ambient temperatures at the facility site ... may have a measureable impact on EGU efficiency. At higher elevations, air pressure is lower and less oxygen is available for combustion per unit volume of ambient air than at lower elevations. Cooler ambient temperatures theoretically could increase the overall EGU efficiency by increasing the draft pressure of the boiler flue gases and the condenser vacuum, and by increasing the efficiency of a condenser recirculating cooling system.
>
> EGU load generation flexibility requirements—Operating an EGU as a base load unit is more efficient than operating an EGU as a load cycling unit to respond to fluctuations in customer electricity demand.
>
> EGU equipment manufacturers—The efficiency specifications of major EGU components such as boilers, turbines, and electrical generators provided by equipment manufacturers can affect EGU efficiency.

> EGU plant components—EGUs using the optimum number of feedwater heaters, high efficiency electric motors, variable speed drives, better materials for heat exchangers, etc. tend to be more efficient.[39]

Based on the factors above, EPA concludes that coal-fired power plants "identical in design but operated by different utility companies in different locations may have different efficiencies. Thus, the level of effectiveness of a given GHG control technology used to improve the efficiency at one coal-fired EGU facility may not necessarily directly transfer to a coal-fired EGU facility at a different location."[40]

EPA recognized in the study that a number of technologies to improve power plant efficiency are available for application to existing coal-fired EGU projects which can incrementally improve thermal overall efficiency, and expanded on the efficiency improvements reported by NETL in its 2008 report on efficiency improvement projects (shown in **Table 1**).

International Energy Agency Study

The International Energy Agency released a study[41] in 2013 looking at opportunities to reduce CO_2 emissions using upgrades and efficiency improvements at CFPPs. IEA concluded that substantial improvements (i.e., retrofits) may be seen as cost-effective if these economically restore the efficiency of a power plant.

> Despite involving substantial outlay (typically US$100–200 million), retrofits will provide a payback in restored generation, fuel saving, extended plant life, and, in some countries, CO_2 emissions cost savings. There are also benefits of reduced specific emissions of other pollutants.[42]

Retrofits include turbine upgrades, condenser optimization, increasing the capacity and efficiency of air-cooled condensers, boiler system improvements, and improvements to other systems where energy losses can occur (as shown in **Figure 6)**.

However, IEA affirmed that major plant retrofits and upgrades (i.e., conversion of subcritical PC units to super- or ultra-supercritical PC units) would raise efficiencies more substantially. IEA used the example of a conversion of a subcritical 500 MW unit in the United Kingdom to a supercritical pressure, which was projected to raise net generation efficiency from 38% to 44% (on a lower heating value basis). The upgrade was projected to reduce CO_2 emissions by 500,000 tonnes per year.

Using Renewables to Improve Coal Plant Efficiency

Heat rate improvement could potentially be achieved using renewable technologies to either provide heat to reduce heat losses at various points in the steam cycle, or to provide power to the

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[39] EPAEff.

[40] EPAEff.

[41] *Upgrading and Efficiency Improvement in Coal-fired Power Plants*. Clean Coal Reports at http://www.iea-coal.org.uk/site/2010/publications-section/reports.

[42] Ibid.

equipment used to curb these heat losses, thus curbing on-site equipment electricity use. One such hybrid coal-solar power plant is already in operation in the United States, at the Xcel Cameo Generating Station in Colorado.

> The demonstration project is expected to cut the use of coal at the power plant by around two or three percent, and could be scaled up to cut it by 10 percent. The system works through a series of parabolic trough solar collectors made of glass mirrors. On sunny days the mirrors concentrate the solar radiation onto a line of receiver tubes filled with a heat transfer fluid (mineral oil). The solar energy heats the circulating oil to about 300°C (575°F). The heated oil is then fed to a heat exchanger where the heat is transferred to water to heat it to around 200°C (407°F) before it enters the boiler. Having hotter water entering the boiler means less coal is needed to heat it and produce the steam that turns the turbine to generate electricity.[43]

Alternatively, using biomass has been suggested to co-fire with coal in a CFPP, or to replace coal altogether.

> Combining the use of biomass with coal can be beneficial, particularly from an environmental standpoint although any such process may have its limitations or drawbacks. Each coal type and biomass feedstock has different characteristics although by combining the two, it may be possible to capitalize on the advantages of each, and minimize their individual disadvantages. An effective way is via [gasification and production of syngas, a mixture of hydrogen and carbon monoxide], and useful operating experience has been achieved in a number of large-scale coal-fuelled gasification and IGCC plants ... It also has the potential to form the basis of systems that combine coal and biomass use with other renewable energy technologies to create clean, efficient energy-production systems. Thus, various hybrid energy concepts, some based on coal/biomass [gasification], have been proposed or are in the process of being developed or trialed. Some propose to add yet another element of renewable energy to the system, generally by incorporating electricity generated by intermittent renewables such as wind or solar power. A number also aim to incorporate some form of carbon capture and storage.[44]

As biomass is generally considered carbon neutral,[45] co-firing coal with biomass can provide advantages for electric power generation. However, using biomass on a large, commercial scale has a number of potential issues. Since the heating value and bulk density of biomass is lower than coal, the necessary volumes to be harvested and handled can be substantial, and the type and availability of different biomass materials tends to vary considerably with location. A potential source of biomass in the United States could be wastes from the forest products industry.[46]

[43] Lin Edwards , *First ever hybrid solar-coal power plant operating* , PhysOrg.com, July 12, 2010, http://phys.org/news198135102.html.

[44] Stephen Smith, *Combining Renewable Energy with Coal*, IEA Clean Coal Centre, CCC/223, September 2013, http://www.iea-coal.org.uk/site/2010/publications-section/reports,CCC/223.

[45] There are challenges to EPA's decision to treat biomass as carbon neutral. See CRS Report R41603, *Is Biopower Carbon Neutral?*, by (name redacted).

[46] CRS Report R40565, *Biomass Resources: The Southeastern United States and the Renewable Electricity Standard Debate*, by (name redacted).

Potential Barriers to Implementing Efficiency Upgrades

Government regulations, regulatory regimes (i.e., competitive markets or traditional cost of service regulation), and industry factors (such as growth or a lack of growth in demand) all affect the motivation for implementing improvement projects at coal-fired power plants. These external forces add to the internal evaluation of the costs vs. benefits of improvements for a particular unit. This section will look at a few of these external forces which may hamper the implementation efficiency projects.

New Source Review

The New Source Review program was designed to prevent the degradation of air quality from the construction of new facilities or modification of existing facilities which have potentially harmful emissions. NSR was established by Congress as part of the 1977 Clean Air Act Amendments (P.L. 95-95).

The NSR process requires power plant operators to undergo a review for environmental controls if they build a new power generating unit, and to impose the Best Available Control Technology, as defined by the state permitting authority (or in some cases EPA). Efficiency improvements to power plants that reduce regulated pollutants should not theoretically trigger NSR requirements, unless the improvements result in an increase in emissions (e.g., because the modified plant operates for more hours). Establishment of a pre-improvement emissions baseline before and a post-improvement emissions report after efficiency upgrades seems like a logical step, but may not be easily achievable on a consistent basis.[47] There are also ambiguities in the law which may serve to hamper efficiency projects from going forward.

> Power plants built prior to 1971 are exempted from the limits on criteria pollutant emissions contained in the Clean Air Act, but may lose that exemption and be forced to undergo an NSR if the EPA determines that the plant has undergone non-routine maintenance which increase emissions.
>
> The power generation industry widely views the NSR process as an obstacle to power plant efficiency improvement projects. In a 2002 report to the President, the Environmental Protection Agency concurs, stating "that NSR as applied to existing plants discourages projects that would have provided needed capacity or efficiency improvements."[48]

According to NETL, there are two critical issues with respect to the NSR and efficiency improvements:[49]

- The definition of "routine maintenance, repair, and replacement" projects, and

[47] International Energy Agency / Coal Industry Advisory Board, *Power Generation from Coal - Measuring and Reporting Efficiency Performance and CO_2 Emissions*, 2010, http://www.iea.org/ciab/papers/power_generation_from_coal.pdf.

[48] NETL, page 4.

[49] Ibid.

- Whether a unit's emission rate or its total emissions over a specified time should be used to determine if an efficiency improvement project increases emissions.

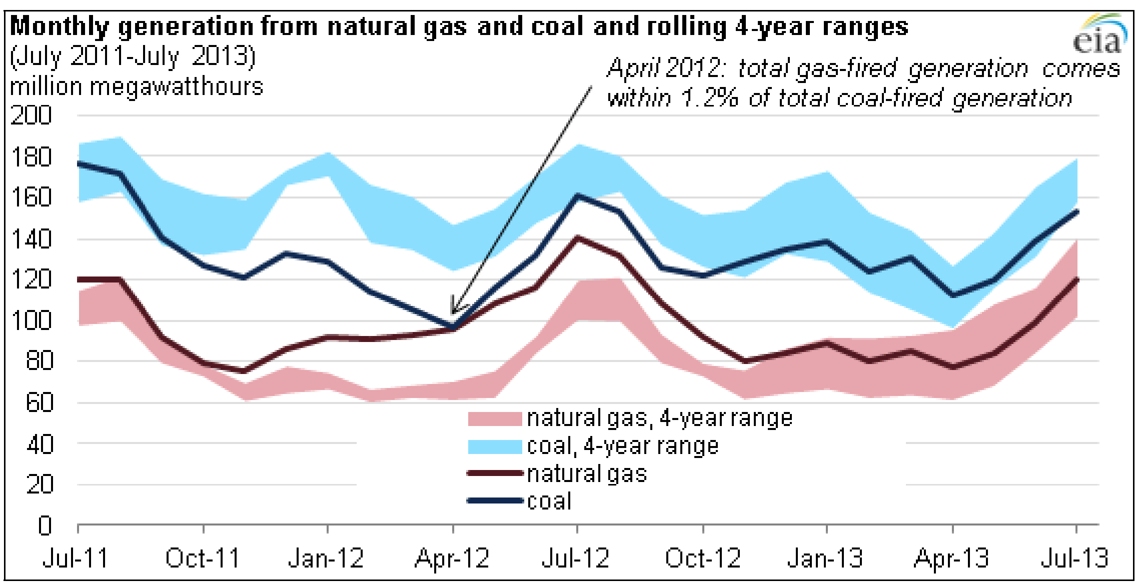
NETL further stated that several developments since the passing of the 1977 Clean Air Act Amendments have failed to clarify these issues and made efficiency improvements risky and less appealing to plant operators. On the other hand, NETL also stated that "[u]nder future scenarios, the added value of higher efficiency in meeting GHG emissions limits, may prevent the NSR from being utilized as a barrier to capital investments aimed at improving power plant efficiency."[50]

Fuel Prices for Electricity and Regulatory Uncertainty

Increases in the domestic production of natural gas (primarily due to hydraulic fracturing of gas shales) are causing a dramatic change in electric power production decisions. A recent decline in natural gas prices has come with increased production of natural gas, and the resulting decline in coal consumption for power generation. In April 2012, for the first time in U.S. history, the amount of electricity generation from natural gas equaled that of coal, according to EIA statistics, with each representing about 32% of the market.

Figure 7. Recent Electric Power Generation Trends

(July 2011 to July 2013)



Source: U.S. Energy Information Administration, Electric Power Monthly.

Notes: The rolling four-year range for each fuel source represents the maximum and minimum amount of each fuel source that is consumed for electricity generation for the same month during the previous four years.

However, as **Figure 7** illustrates, coal has recently rebounded and regained market share for electricity generation as natural gas prices have risen. EIA states that since May 2013, "a combination of higher prices for natural gas and increased demand for electricity during the

[50] Ibid.

summer months led electric systems across much of the country to increase their use of coal-fired units."[51]

Growth in demand for electricity is expected to be low over the coming decades.[52] By itself, this would ordinarily be expected to reduce new power plant construction, and might prompt some coal plant owners to consider projects to increase efficiency from existing plants. However, lower natural gas prices, higher coal prices, slower economic growth, and the implementation of new environmental rules[53] are all expected to play a role in the level of coal plant retirement decisions.[54]

Possible Approaches to Encourage Efficiency Improvement

As previously mentioned, EPA has been directed by the President to propose guidelines for GHG emissions reduction from existing coal-fired power plants. The general assumption is that EPA will establish some target for emissions on a state or plant-by-plant basis, with companies free to decide how they will achieve the reduction (i.e., with efficiency, fuel switching, retirement of older units, priority dispatch for cleaner units, etc.), and with emissions averaging, banking, and trading of emissions credits playing a role. Within such a system, efficiency improvements can be an important contributor.

While the details of the proposal are unknown at this time, the proposal may take into account a number of factors (such as the remaining useful life of the existing source), and could be less stringent than the proposal for new sources of power plants emissions of GHGs.[55]

Power plant efficiency may be another factor which EPA may potentially consider in its guidelines for existing sources. NETL observed in its 2010 report[56] that based on a scenario where CFPP generation was constant at the 2008 level, increasing the average efficiency from 32.5% to 36% could reduce U.S. GHG emissions by 175 MMmt per year or 2.5% of total U.S. emissions in 2008.[57] NETL conceded that barriers existed to achieving a higher average fleet efficiency level, citing the power generation industry's focus on availability (focused on the profitability of coal-fired generating units), inconsistent cost pass through possibilities (some deregulated areas have cost pass through clauses, and zero or negative incentives in many areas

[51] See EIA, Today in Energy, at http://www.eia.gov/todayinenergy/detail.cfm?id=11391.

[52] The long-run trend of slowing growth in electricity use relative to economic growth in the United States is expected to continue, with the rate of projected growth in electricity use at less than half the rate of economic growth. See http://www.eia.gov/todayinenergy/detail.cfm?id=1049.

[53] The EPA is obligated under Section 111(d) of the Clean Air Act to promulgate guidelines for GHG emission standards for existing coal-fired power plants. EPA has been directed by the President to propose such guidelines by June 2014, and to finalize them a year later.

[54] Energy Information Adminstration, *Projected retirements of coal-fired power plants*, July 31, 2012, http://www.eia.gov/todayinenergy/detail.cfm?id=7330.

[55] Op. cit. CRS R43127.

[56] Op. cit. NETL.

[57] NETL suggested that the cost of such improvements could be a point for further study.

for reduced fuel use), fear of triggering New Source Review, and uncertainty about GHG regulations (which could lead to very short payback periods for improvements).[58]

If power plant efficiency is an option EPA proposes for state consideration, the question then may be asked how a fleet-wide improvement program could be achieved in United States. One possible approach might be to follow NETL's suggestion of using the top decile of CFPP efficiency as a benchmark for U.S. fleet efficiency, used with an efficiency frontier.[59] Using statistical methods, benchmarks[60] could be used to improve efficiency of the CFPP fleet.[61] NETL observes that while some improvements could be "relatively inexpensive" (for example, improved O&M, more frequent or pro-active maintenance), other improvements could be "very expensive" (for example, improvements bundled with a new SO_2 scrubber, or turbine overhauls or heat exchanger replacement). But NETL notes that "if each plant achieved their maximum efficiency each year, 5% reduction in CFPP carbon dioxide emissions" could result.[62]

According to NETL's analysis, retirements of lower efficiency units combined with increased generation from higher efficiency refurbished units, and advanced refurbishments with improved operation and maintenance, would be the key to increasing average fleet efficiency.

Efficiency improvements could be incentivized using an efficiency frontier. The selection of appropriate incentives would then encourage CFPP owners to undertake improvements or retire lower efficiency units. Such incentives could include possible tax rate reductions for CFPP owners matched in some manner to the cost of the improvements, or accelerated book depreciation[63] rates for cost recovery. Penalties could perhaps be used to encourage prompt retirement of the lowest efficiency units.

The incentives could be in place over a defined period of years, with incentives reduced during the period to encourage action sooner rather than later. The effective period of incentives would have to be sufficiently long enough to allow equipment orders to be satisfied, and simultaneous work to progress at multiple CFPP sites across the country which might seek to make

[58] "With many different methods used to express efficiency performance, it is often difficult to compare plants, even before accounting for any fixed constraints such as coal quality and cooling-water temperature." See *Improving Efficiency of Coal-fired Power Plants for Near Term CO_2Reductions*, National Energy Technology Laboratory, Presentation, 2009 at http://www.netl.doe.gov/energy-analyses/pubs/Impr_Effcy_of_CFPP_CO2_Redctns_1109.pdf. (NETL3).

[59] According to Cambridge Economic Policy Associates, the "Efficiency Frontier" essentially relates technical efficiency (the ability to produce the maximum level of outputs from a given set of inputs) to allocative efficiency (reflecting the extent to which the inputs are optimal for a given set of prices using a given technology). These two measures are then combined to form a measure of total economic efficiency or total cost efficiency (not thermal efficiency), which represents a notion of "best practices" at a given point in time. By extension, those firms operating at or below the efficiency frontier are "efficient," and those firms operating above the frontier are "inefficient." See http://www.ppparbiter.org.uk/pdf_folder/cepa_r1ax1_0703.pdf.

[60] Benchmarking is the process of comparing an individual organization's business processes and performance metrics to best practices in the same industry or applicable best practices from other industries.

[61] NETL3, and B.F. Roberts and Lessly Goudarzi, *Efficient Heat Rate Benchmarks for Coal-Fired Generating Units*, 1998, http://www.onlocationinc.com/heatratepaper.pdf.

[62] NETL3.

[63] Book Depreciation is a regulatory accounting concept which involves the allocation of the cost of an asset over its expected useful service life in a manner that systematically charges the cost of the asset over the period of time it is in service. Book depreciation may be charged at a faster or slower rate than allowed by the Internal Revenue Service, in order to provide management with a realistic view of the gradually diminishing value of the company's assets.

improvements considering equipment lead times and workforce availability. The benchmark could be revised periodically. This could allow newer power plants to live out a service life matched to the most efficient operation achievable for a particular type of CFPP, based on industry statistics. This could allow companies that have made substantial investments in pollution controls an opportunity to recover these investments.

However, EPA's expected proposal on standards for GHG emissions from existing coal-fired power plants will be a primary factor in determining whether efficiency improvements will be cost effective in the near term.

Conclusions and Policy Options

The efficiency of coal-fired power plants decreases over time as components and systems degrade with age and use. Good O&M practices can slow down the loss of efficiency, but older power plants will not be as efficient as newer plants with more technologically advanced and newer systems. But simply replacing old power plants with newer plants is rarely cost effective as the relative increase in power output seldom justifies the cost. CFPPs that are more efficient emit less CO_2 per unit of electricity produced because they use less coal. Making improvements to increase the efficiency of CFPPs (while producing the same electrical output) could result in a significant reduction in CO_2 emissions. According to several of the studies summarized in this report, the major improvements in GHG emissions would likely result from major retrofits in technology, or conversions to natural gas (or possibly biomass) as a fuel.

Detailed information on the actual cost of efficiency-enhancing improvements is not readily available, as concerns over confidentiality and competitiveness with regard to actual projects has largely prevented the sharing of such information. The studies referenced in this report largely show relative information on cost (i.e., high, medium, low), estimate the cost effectiveness of improvements, or mention general cost levels. The case studies have reported costs of efficiency improvements and actual increases in efficiency for specific power plant.[64] But these are considered as useful for estimating a range of costs for improvements rather than actual guides for costs, since each power plant has its own design characteristics and maintenance history. Actual cost information would require a technical evaluation, and a cost vs. benefit analysis to obtain reliable cost estimates for the options under consideration, taking into account site-specific conditions.

Other potential roles exist for Congress. For example, legislation could use tax incentives to encourage energy efficient upgrades for CFPPs which were placed in-service after a certain date. This would allow newer units with environmental controls to recover the cost of scrubbers and other systems, and allow "newer" units to continue operations over a "reasonable" service life, and recover the cost of environmental improvements.

[64] As an example of what can be achieved, a 404 MW coal-fired plant reported a 4,523 kW plant capacity increase (1.1%) and 0.7% point improvement in plant efficiency from the following low-cost steam turbine upgrades:

- Replaced radial spiral strips on high-pressure (HP) and intermediate pressure (IP) sections.
- Installed retractable interstage packing.
- Repaired solid particle erosion (SPE) damage to stationary diaphragms.
- Repaired station diaphragm flow path SPE in IP section. APEC, page 72.

Another approach might be to use a federal energy efficiency standard to accomplish a similar goal as an efficiency frontier, but allow the states to design the program based on local fuel resources, the age of power plants under their jurisdiction, and other criteria defined in legislation. The efficiency standards could increase over time, and require CFPPs not meeting these standards to retire.

Deference to state authorities and regional compliance strategies have been suggested by observers with regard to EPA's deliberations over GHG reduction for existing CFPPs. State public utilities commissions (or similar entities) often require utilities to conduct book depreciation studies (either in connection with rate cases or independent of rate cases). Such studies commonly examine the physical condition of power plants, and the utility's recovery of its investment in electric plant. Federal legislation could tie incentives for efficiency improvements to such studies and direct states to meet individual or regional goals for GHG reduction.

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