Reducing CO_2 Emissions by Improving the Efficiency of the Existing Coal-fired Power Plant Fleet

DOE/NETL-2008/1329

July 23, 2008

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1 Executive Summary

In 2007 coal-fired power plants (CFPPs) accounted for 49% of total generation in the United States and 82% of power sector carbon dioxide emissions. These plants are low-cost and reliable, and very few are expected to retire over the coming decades. Under the Energy Information Administration's Annual Energy Outlook 2008 *Reference Case*, CFPPs built before 2007 generate 37% of all electricity in 2030 and account for 62% of power sector CO_2 emissions.

Figure 1 shows the range of efficiencies achieved by CFPPs in the United States in 2007. Power plants are grouped by their online year. For each online year group Figure 1 shows the minimum, maximum, and median efficiency. Later sections of this paper show that aside from a unit's age and steam cycle type, plant attributes such as location and emissions control equipment do not account for variation in efficiency. This indicates that operational practices and maintenance play large roles in determining the efficiency of a unit and suggests that improvements are possible.

We frame the opportunity for CFPP efficiency improvements based on an assumption that the lower-performing CFPPs in each online year group ought to be able to do as well as the better performing plants. In 2007 the average CFPP efficiency was 32%. The efficiency of the top 10% performing power plants was five percentage points higher, 37%. If all CFPPs were improved to the efficiency of the top 10% of their online year group, emissions of more than 250 MMmt of CO2 could be avoided per year.

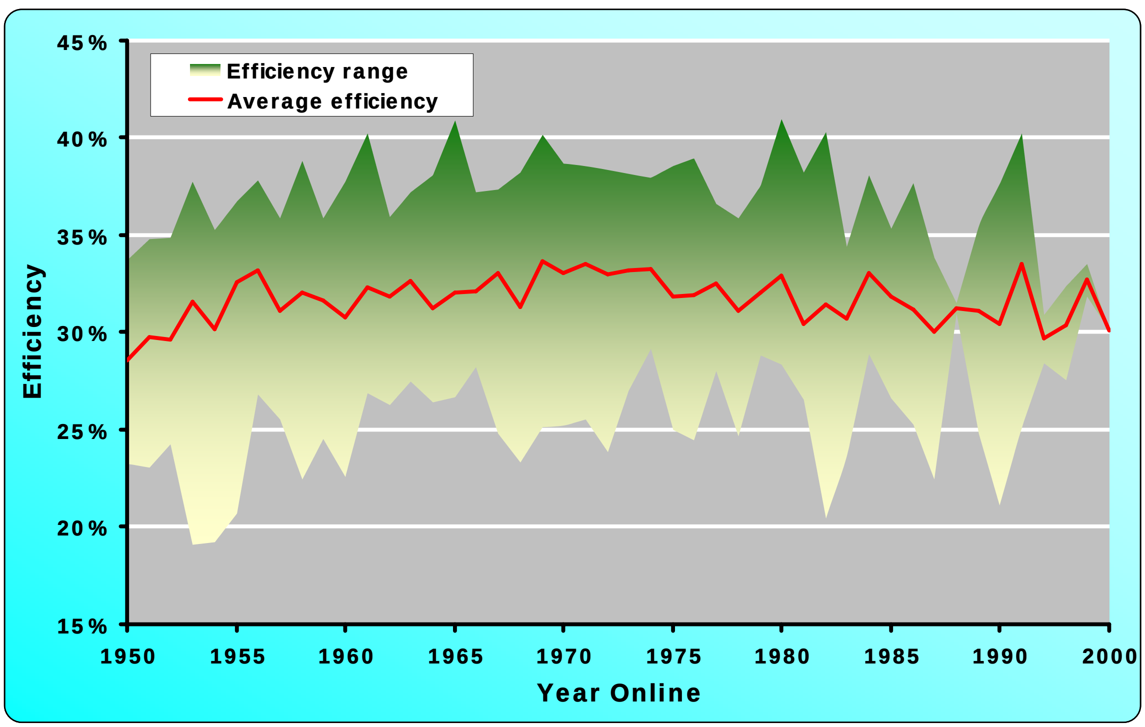

Figure 1. Average efficiency and range for CFPP's by online year for 2007[1]

2 Background

The existing coal-fired power plant fleet is remarkably old – in 2007 over 46% of all electricity in the U.S. was generated by coal-fired power plants (CFPP) over 20 years old. Figure 2 shows a projection of GHG emissions in the U.S. power sector from vintages of existing power plants and expected new builds. The amount of retirements and new builds through 2030 are taken from the reference case scenario in the Energy Information Administration's Annual Energy Outlook 2008. The GHG emissions from each class of assets are based on estimated capacity factors, with the older, less-efficiency power plants assumed to dispatch less than the newer, more efficient plants. In 2030, existing CFPP's contribute 62% of power sector CO_2 emissions.

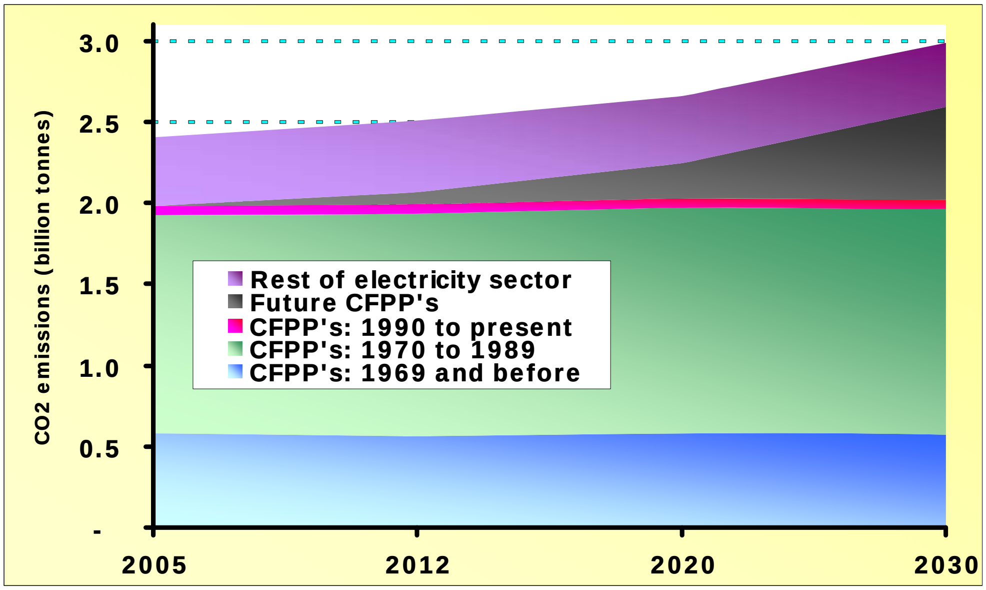

Figure 2. CO_2 emissions from the power sector forecast through 2030 (AEO 2008 reference case scenario)[2]

On the whole, the existing CFPP fleet is much less efficient at converting fuel into electricity than is technically and economically possible. The fleet average efficiency is around 32%. A new state-of-the-art pulverized coal power plant with a supercritical steam cycle will have design efficiencies of 39%[3]. Some PC power plants that came on line over 50 years ago achieved an efficiency of 37% or higher in 2007.

One reason for this discrepancy is that during the prime building time for CFPP's - from the 1950's through the 1960's – coal was relatively cheap, and there was little incentive to improve a plant's heat rate, especially if those improvements came at the expense of a plant's planned availability. During the 1970's, coal prices experienced a significant peak that corresponded with the construction of a large number of higher efficiency, supercritical plants, as seen in Figure 3. However, by about 1980, coal prices came back down and few supercritical plants have been built since then. State control of utility rates also likely contributed to lower efficiencies. Before electricity restructuring, regulatory commissions pressured electric utilities to keep rates low. Postponing, or even eliminating refurbishing projects was one method used to comply with state regulators.

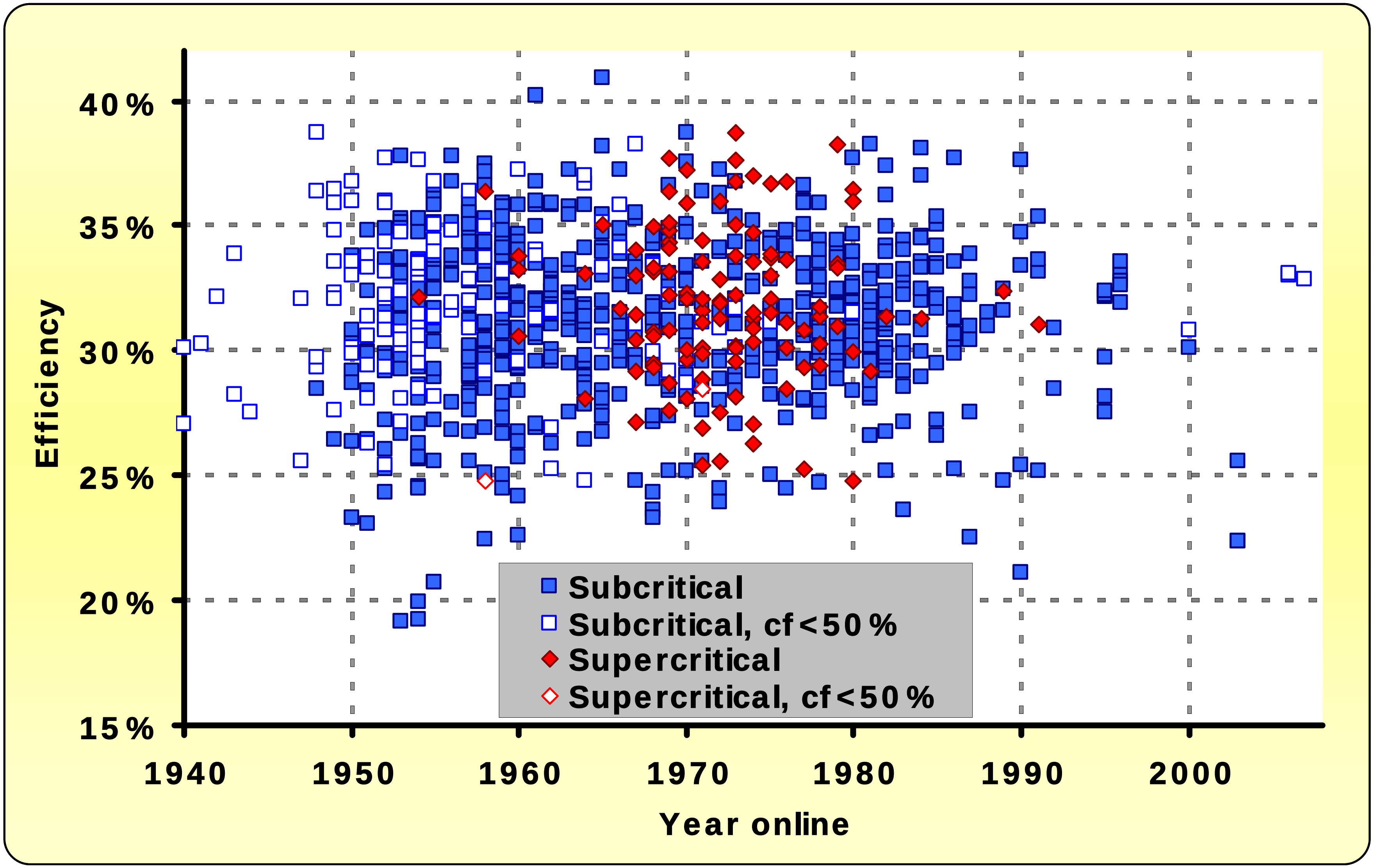

Figure 3. CFPP efficiency by steam cycle type, age and capacity factor for 2007

2.1 New Source Review

Established by Congress as part of the 1977 Clean Air Act Amendments, the New Source Review (NSR) was designed to prevent the degradation of air quality from the construction of new facilities or modification of existing ones which have potentially harmful emissions. The NSR process requires power plant operators to undergo a review for environmental controls if they build a new power generating unit. 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.[4, 5,6] In a 2002 report to the President, the Environmental Protection Agency (EPA) concurs, stating "that NSR as applied to existing plants discourages projects that would have provided needed capacity or efficiency improvements."[7]

There are two critical issues with respect to the NSR and efficiency improvements:

- the definition of "routine maintenance, repair, and replacement" (RMRR) projects, and
- 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 .

Several developments since the passing of the 1977 CAA Amendments have failed to clarify these issues and made efficiency improvements risky and less appealing to plant operators. Following are major events in NSR related to power plant maintenance:

- In 1990, the U.S. Court of Appeals for the Seventh Circuit issued a defining decision in a suit involving the EPA and Wisconsin Electric Power Company (WEPCo).[8] In response to an application from WEPCo to replace deteriorating plant components at five units within its Port Washington generating plant, the EPA decided that this maintenance was not routine and therefore triggered a NSR. In addition, the EPA took the position that WEPCo's planned improvement projects would increase the units' utilization and therefore increase their potential future emissions. In an appeal of this decision, the Court ruled that the EPA should instead base its decision on projected actual emissions based on historical operating data of the unit. The Court did support the EPA's positions that the "massive" overhaul of the existing unit was not routine, establishing a precedent.
- In 1998, the EPA released a proposed modification to the enforcement of the NSA provisions. In the Federal Register, the EPA commented it was dissatisfied with the precedent established in the WEPCo case with regard to

estimating future emissions. It stated that since operators make changes to generating units "in order that they may improve their market position", and due to deregulation within the electric industry "any physical or operational change will result in an emissions increase to the extent that there is market demand for additional power" [9] that all potential future emissions from a unit should be considered during the NSR process, setting the stage to reverse the WEPCo precedent.

- Between November 1999 and December 2000, the U.S. Department of Justice, acting on behalf of EPA, filed lawsuits against eight utility companies, charging that 17 of the companies' power plants performed maintenance projects which should have triggered NSR and improved pollution controls. Also, in May 2000, the EPA ruled that an upgrade of turbine blades which would increase fuel efficiency at Detroit Edison's Monroe power plant would be a non-routine change.[10]
- In October 2003, the EPA published the Equipment Replacement Provision (ERP) rulemaking which attempted to establish a "bright-line" test for determining routine maintenance activities. However, on March 17, 2006, the U.S. Court of Appeals for the D.C. Circuit vacated the ERP rule, leaving the EPA back in the position of determining routine maintenance in a case-by-case basis.[11]
- An April 2007 decision by the U.S. Supreme Court further increased the chance that efficiency projects could trigger an NSR.[12] The case originated with a 2000 filing by the EPA against Duke Energy. The EPA asserted that boiler tube replacements preformed by Duke Energy on various units violated the NSR provisions of the CAA since the projects could increase overall yearly emissions. The Supreme Court agreed with the EPA that it did not have to consider the units' hourly emissions rates, but could instead use the total yearly emissions in its determination of emissions increase.

This report does not explore the NSR issue further and does not advocate for a particular policy. Our goal is to set forth the nature of the increased energy and fuel saving associated with improving the efficiency of PC power plants. Under 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.

2.2 Efficiency improvement literature search

NETL conducted a literature search of published articles and technical papers that identified potential coal-fired power plant efficiency improvement methods resulting in the development of an electronic library of over 110 references. Efficiency improvement methods were identified for most power plant components/systems. Advanced process control systems – particularly combustion controls and furnace sootblower controls – have become popular choices to improve power plant efficiency. Another recent development to improve efficiency is the use of coal drying for plants that use low rank coals. A summary of the range of efficiency improvement performance data for a variety of power plant components/systems obtained from the literature search is presented in

Table 1. It is unlikely that all of these improvements could be implemented at every plant – the type and number of projects available will depend on a number of factors specific to each plant such as original design, coal type and location. Detailed descriptions of each type of efficiency improvement identified in Table 1 as well as a full listing of the source documents can be found in Appendix B.

Table 1. Power plant efficiency improvements[13]

Power Plant Improvements	**Efficiency Increase (percentage points)**[14]
Air Preheaters (optimize)	0.16 to 1.5
Ash Removal System (replace)	0.1
Boiler (increase airheater surface)	2.1
Combustion System (optimize)	0.15 to 0.84
Condenser (optimize)	0.7 to 2.4
Cooling System Performance (upgrade)	0.2 to 1
Feedwater Heaters (optimize)	0.2 to 2
Flue Gas Moisture Recovery	0.3 to 0.65
Flue Gas Heat Recovery	0.3 to 1.5
Coal Drying (Installation)	0.1 to 1.7
Process Controls (installation/improvement)	0.2 to 2
Reduction of Slag and Furnace Fouling (magnesium hydroxide injection)	0.4
Sootblower Optimization	0.1 to 0.65
Steam Leaks (reduce)	1.1
Steam Turbine (refurbish)	0.84 to 2.6

CFPP Efficiency Improvement Examples

- A Global Energy Decisions July 2005 report discussing deregulation found that "new competitive owners were able to achieve a 6 percent heat rate improvement"[15] for coal-fired units.
- A Power Engineering article examining building new power plants suggested that "Most generators might be better off evaluating opportunities in efficiency improvements [than building new plants]." [16]
- In a 1998 paper by Economic Sciences Corporation utilizing a similar methodology to this paper, the authors found that for coal-fired units, "approximately an 8% improvement in heat rate could be achieved if all coal generating units could reach the average thermal conversion performance of the 274 most efficient generating units."[17]
- An on-going effort to improve heat rates at coal-fired power plants in India and China sponsored by the Agency for International Development and supported by NETL has shown 1 to 2 percentage point increases in efficiency from about 6 months of effort and around $250,000 investment in equipment.[18]
- Wisconsin Electric (WE) Power Company implemented a series of projects at its coal-fired power plants during the 1990's, resulting in efficiency improvements ranging from 2 to 11%.[19]

2.3 Results

The relationship between age, steam cycle type and efficiency is presented in Figure 3. As shown by the pink diamonds, supercritical plants are more efficient on the whole than subcritical units, indicated by the blue squares. Hollow symbols for super- and subcritical units indicate those units with a capacity factor of less than 50% in 2007. These plants were excluded from the efficiency analysis.

Table 2 displays the characteristics and efficiencies of generating units by their steam cycle type: super- or sub-critical; and by three age vintages: pre-1970, 1970-1989, and post-1990. The variation within the classes provides the window for efficiency improvements – if units within each age band and steam cycle type are able to achieve higher efficiency, it is reasonable to assume that other units within that same band could also achieve similar levels. The average efficiency of the top 10% for each age group and steam cycle type was assumed to be the improved efficiency the rest of the units could potentially reach. The average potential for improvement of around 5 percentage points resulting from the analysis summarized in Table 2 (i.e., improving the average plant efficiency from 31.8% to 37.4%) corresponds well with a combination of the examples of actual improvement projects discussed above.

Once a plant has improved its efficiency, there are two main options that operators are likely to pursue. They may choose to (1) generate the same amount of electricity and produce less CO_2 or, (2) generate more electricity at the same CO_2 emissions level. Option 1 may raise less issues with respect to NSR.

Table 2. Analysis of coal-fired units with capacity factor greater than 50% in 2007[20]

Steam cycle type	Age band	Number of Units	Nameplate capacity (MW)	Generation (BkWh)	Avg. eff.	Eff. Range	Eff. Top 10%
Subcritical	1969 and before	410	77,789	447	31.3%	19.1 – 40.9%	*36.3%*
	1970 to 1989	273	127,675	824	31.4%	20.5 – 38.7%	*36.3%*
	1990 to present	27	7,477	51	29.9%	21.1 – 37.6%	*35.9%*
Subcritical subtotal		**710**	**212,942**	**1,322**	**31.3%**	**19.1 – 40.9%**	***36.4%***
Supercritical	1969 and before	34	19,467	114	34.9%	22.5 – 40.1%	*38.8%*
	1970 to 1989	74	60,169	398	35.1%	29.8 - 41.0%	*39.1%*
	1990 to present	1	1,426	10	40.2%	N/A	*N/A*
Supercritical subtotal		**109**	**1,061**	**522**	**35.1%**	**22.5 – 41.0%**	***39.3%***
Grand Total		***819***	***294,003***	***1,844***	***31.8%***	***19.1 – 41.0%***	***37.4%***

The actual outcome will likely be a combination of the two options and will be a plant-specific decision based on carbon regulations, fuel costs, electricity price and other factors. If carbon emissions are constrained by regulation, the first option allows the operator to reduce payments for CO_2 emissions, while collecting the same amount of revenue for its electricity. The second option provides more revenue from increased electricity generation, which may offset the outlays required for CO_2 emissions. The following calculations were used to determine the benefits of efficiency improvements for the two scenarios described above.

For the constant power and fewer CO_2 emissions scenario the following equation was used for each age band/steam cycle type:

> (CFPP generation 2030) * [1- (new heat rate) / (old heat rate)] * (CO_2 emissions factor) = reduction in CO_2 emissions.

In 2030, this scenario yields a reduction of approximately 250 million metric tons of CO_2 and avoids the use of 88 million short tons of coal as compared to the business as usual baseline.[21]

For the scenario of generating more electricity at the same CO_2 emissions level, the following equation was used:

> (BTU of coal used in 2030)/(new heat rate)/(old heat rate) = increase in electricity generation.

In 2030, over 250 billion kWh of additional electricity could be generated with no increase in CO_2 emissions over the baseline in this scenario. Figures 4 and 5 show the benefits graphically.

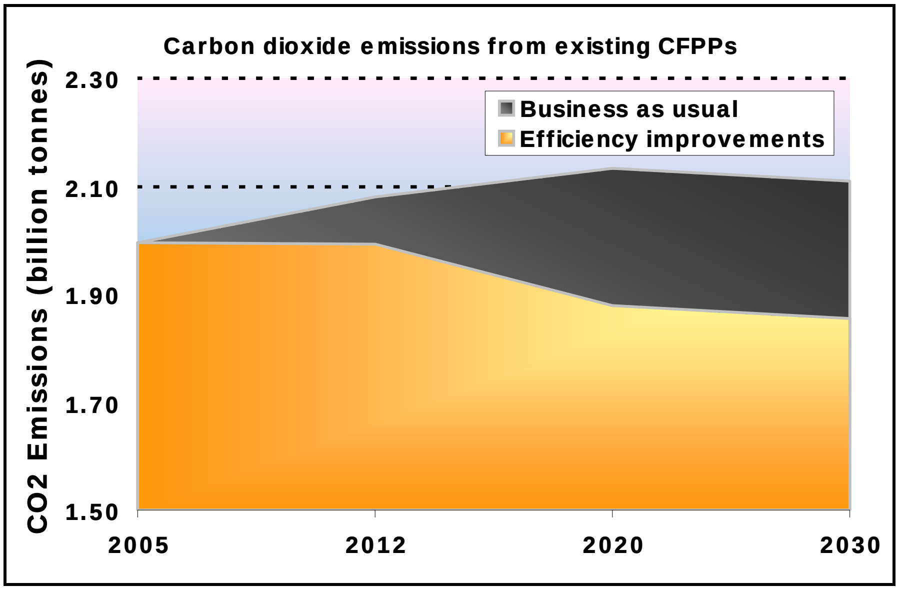

Figure 4. Carbon dioxide emissions in the constant power scenario

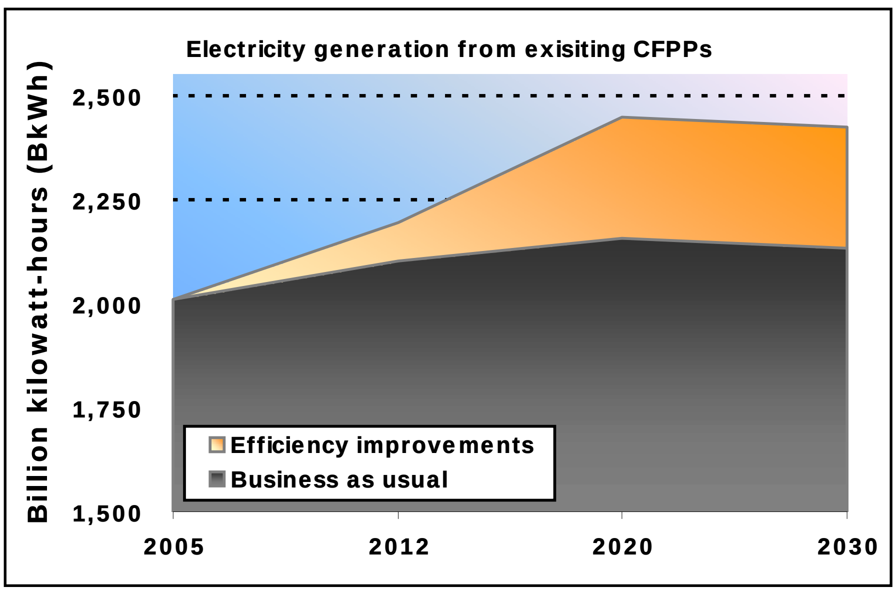

Figure 5. Electricity generation in the constant emissions scenario

2.4 Impacts at the plant level

Although significant benefits accrue at a national level from efficiency improvements to the entire fleet, these improvements will not be implemented unless they are attractive at the power plant level. In order to validate that these types of projects are beneficial to individual operators, a unit-level analysis was conducted using a typical plant in the 1970 to 1989 band. For the year 2006, this unit had the following characteristics:

- 473 MW capacity,
- 32.6% efficiency,
- 84% capacity factor, and
- 3,506,265 tonnes CO_2 emissions.

Assuming that this unit achieves a target efficiency of 37.6%and that generates the same amount of electricity as it did in 2006, it would reduce its CO_2 emissions by 447,608 tonnes. At a moderate $30/tonne CO_2 value this equates to $13.4 M savings in avoided emission payments for one year.

3 Next steps

While this analysis shows that significant reductions in CO_2 emissions are possible by improving the heat rate of existing CFPP's there are a number of other issues which must be considered in the context of efficiency improvements. The following are ideas for follow-on work to complement this analysis:

- Examine the economics of efficiency improvements
- Assess potential regulatory roadblocks to performing them
- Examine the economics of efficiency upgrades in a situation where an existing pulverized-coal fired power plant is being retrofitted for CO_2 capture

Appendix A

Analysis Methodology and Discussion of the Effects of Power Plant Characteristics on Efficiency

One goal of this analysis was to determine how much the coal-fired power plant fleet's average could reasonably be improved. The average efficiency of the top ten percent of plants within each vintage class was selected as the goal for the rest of the class to achieve. This value is consistent with absolute percentage point improvements cited in actual case study data.

These aspirational goals were then used as inputs to CARBEN, a model developed by NETL to estimate future energy market conditions. The improvements were assumed to begin in 2012 and continue to 2020, when the efficiencies of each plant class would remain at the aspirational levels. The differences between emissions and electricity generation in the cases with and without efficiency improvements were then compared in order to quantify the impacts of these improvements.

CARBEN

The Carbon Sequestration Benefits Tool (CARBEN) provides a rigorous and transparent framework for evaluating the economic and environmental benefits that carbon sequestration technology development can provide the United States under future scenarios in which U.S greenhouse gas emissions are constrained. CARBEN provides a 50-year analysis horizon, which is long enough to capture the effects of population and economic growth on reference case emissions. Using data from the National Energy Modeling System (NEMS) along with published cost and supply curves for various greenhouse gas mitigation options, CARBEN estimates the relative contributions from a number of technologies and/or sectors in reaching greenhouse gas emission reductions. A copy of CARBEN is available at NETL's Energy Analysis/Benefits Analysis website, http://www.netl.doe.gov/energy-analyses/benefit.html. A screenshot of CARBEN can be seen in Figure 6, showing the ability to modify power plant efficiency by plant vintage and calculate the resulting electricity or CO_2 emissions.

Energy Velocity

Energy Velocity (EV) is a subscription-based database-driven product containing data on various aspects of the energy industry. EV uses data from the Energy Information Administration (EIA), Environmental Protection Agency (EPA) and Federal Energy Regulatory Commission (FERC) to build a database of power plant operations and characteristics, then combines this data with internal expert analysis and input from industry. This product was used to produce tables containing data about the U.S. CFPP fleet. As required, EV data was combined with other data sources to examine attributes of interest.

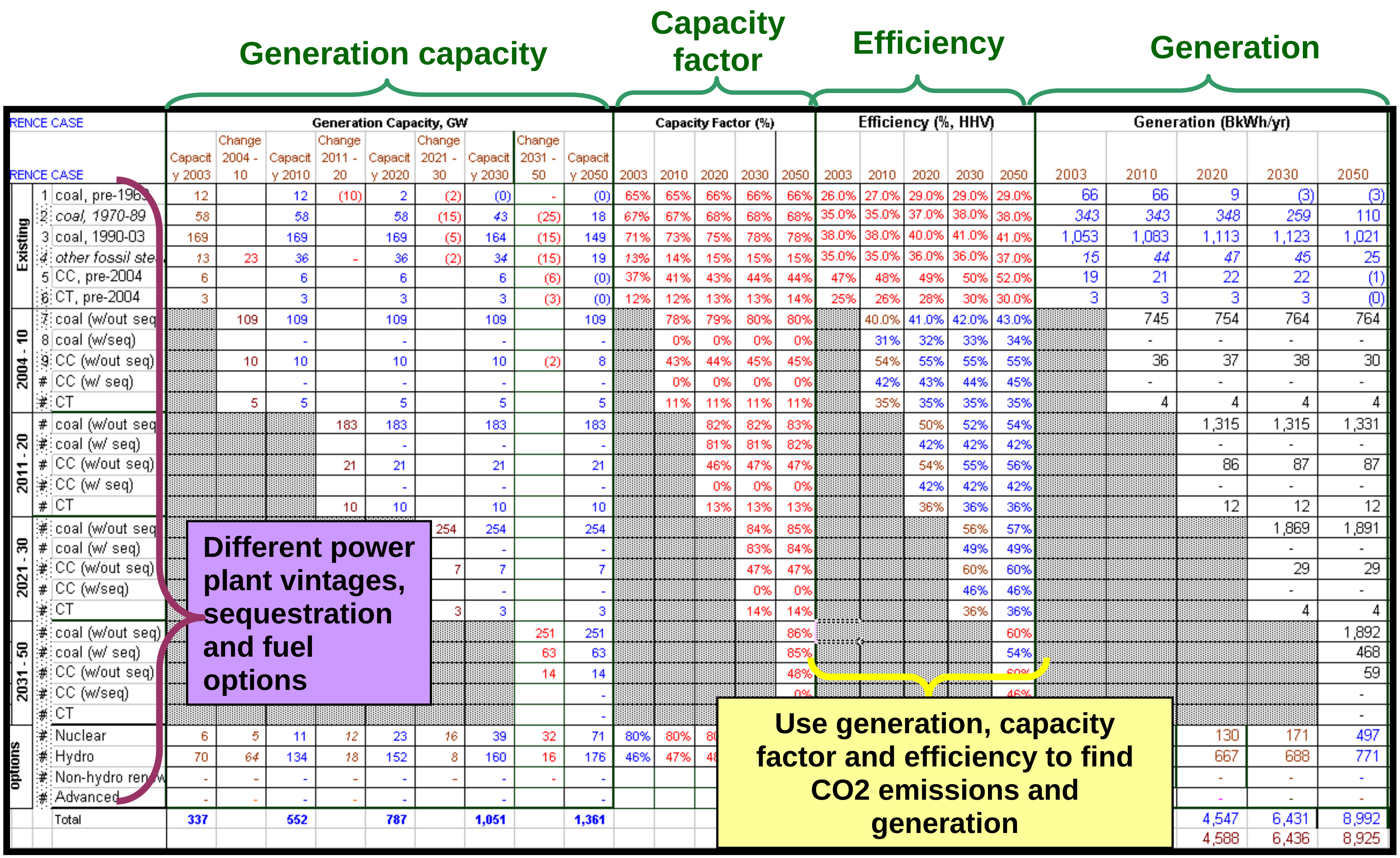

Figure 6. CARBEN model screenshot

Factors affecting power plant efficiency

This paper examines the energy conversion efficiency of CFPP's, or how much electricity can be produced from a given unit of fuel input. This is not to be confused with end-use efficiency, which is implemented by the consumer's use of electricity produced at a power plant. Typically, operators refer to the heat rate of their plants when discussing energy conversion efficiency. A plant's heat rate is the measurement of how many BTU's of fuel are required to generate a kilowatt-hour of electricity and expressed in units of BTU/kWh. Using the conversion factor that 1 kWh of electricity is equivalent to 3,412 BTUs, it is then possible to determine a plant's overall efficiency by dividing the heat rate into this conversion factor.

Due to thermodynamic limitations with the steam cycle used for power generation, CFPP's could at best achieve about 63% efficiency. Currently, a state of the art supercritical pulverized coal plant could expect to achieve around 39% efficiency.[22] An average operating CFPP today achieves only around 32%. There are a number of factor that could cause this gap, including:

- Plant design – age, steam cycle, cooling system, pollution control
- Plant location – elevation and ambient temperature
- Major equipment manufacturer – boiler and generator
- Operational practices – combustion optimization, control of steam leaks, clean heat exchange surfaces, etc.

One of the major limiting factors in the design of CFPP's is the type of steam cycle employed by the plant. With advances in high-temperature materials, newer CFPP's are able to employ supercritical steam cycles which are more efficient than the subcritical steam cycles used by older plants.

However, even identical plants operated by different companies in different parts of the country may have different efficiencies. Different companies may have different operational philosophies – one operator may have a rigorous preventative maintenance plan in place which finds small steam leaks and improves the overall plant efficiency while another operator may not. Also, geography can play an important role in overall plant efficiency as both elevation and ambient temperatures directly affect the performance of steam boilers.

Finding the critical variables

One hypothesis central to the development of this paper was that there were only a few critical variables which were statistically significant in driving power plant efficiencies. Also, since a central tenet of this paper is that there is significant room to improve power plant efficiency, it was important to identify these critical variables and determine which ones could be controlled by the operator. The analysis showed that there are no clear trends of efficiency among most of the variables that operators cannot control, such as the plant's elevation, original equipment models and pollution control regimen. However, two factors – plant age and steam cycle type – were found to have the clearest relationship to a plant's efficiency. This study found that, even within a group of plants with the same steam cycle type and age band, there is a wide range of power plant efficiencies indicating that there is significant opportunity for operational improvements to a plant's heat rate.

Regression analysis

Linear regression analysis was used to determine the level of correlation of various plant characteristics with a plant's efficiency. The "R^2" value, or the square of the correlation coefficient, was calculated for each parameter where numerical data was available to compare to the efficiency. These parameters were:

- Elevation in meters
- 2006 average summer temperature in degrees F
- Capacity factor in percent
- Fuel energy content in BTU/ton

The "R^2" value is a measure of the correlation of two sets of variables. R^2 varies between 1 and 0, with values closer to 1 suggesting high correlation.

Other factors considered which did not have numeric values were:

- Boiler and generator manufacturer
- Cooling system type
- SO_2, NO_x, and particulate matter control equipment

The impact of these parameters was examined by taking the average efficiency of each category and looking for significant differences between the average values.

Table 3. Correlation of various parameters to efficiency

Age Band	Supercritical?	R^2 (square of correlation coefficient)			
		Elevation	Temperature	Capacity factor	Fuel heat content
1969 and before	N	0.008	0.022	0.187	0.058
	Y	0.012	0.003	0.045	0.060
1970 to 1989	N	0.002	0.012	0.051	0.032
	Y	0.022	0.252	0.033	0.460
1990 and later	N	0.020	0.106	0.001	0.138
	Y	N/A	N/A	N/A	N/A

As seen in Table 3, although there are some combinations of age band, steam cycle type and other parameters which yield moderate correlation, there is no strong correlation for any of these parameters to efficiency.

Table 4 shows the efficiencies of plants with and without emissions control equipment. For most combinations of age and steam cycle type, the efficiencies do go down when emissions control equipment is added, but average reductions in efficiency are typically less than 1% point, and some average efficiencies are higher for plants with emissions control.

Table 4. Efficiencies of plant with and without emissions control equipment

Age band	Supercritical?	Emission control?	Plant efficiency		
			SO_2	NO_x	PM
1969 and before	N	N	30.7%	27.7%	29.8%
		Y	29.0%	31.2%	30.5%
	Y	N	35.2%	None	None
		Y	35.1%	34.8%	34.8%
1970 to 1989	N	N	31.5%	30.5%	32.2%
		Y	30.9%	29.9%	31.3%
	Y	N	35.1%	34.2%	None
		Y	35.2%	34.1%	35.1%
1990 to present	N	N	31.3%	30.3%	31.2%
		Y	30.6%	30.1%	29.8%
	Y	Y	40.2%	40.2%	40.2%

Although emissions controls do contribute to lower efficiency, they are likely not responsible for the wide variation seen in each of the age groups.

A more detailed examination of some of these factors follows.

Elevation

At higher elevations, air pressure is lower and less oxygen is available for combustion than at lower altitudes.

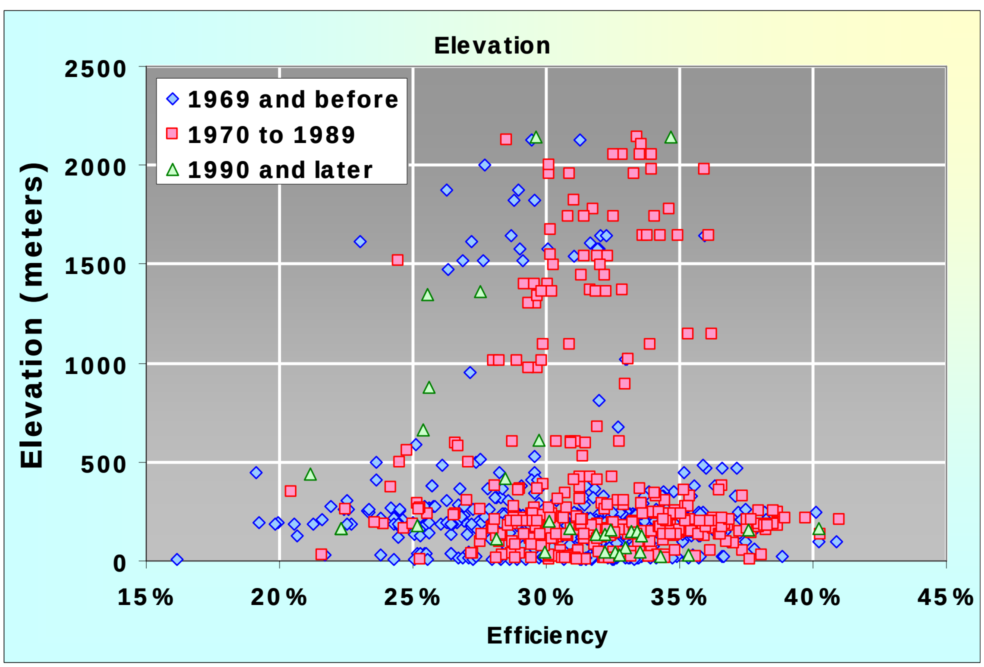

Figure 7. Elevation and efficiency of coal fired power plants[23]

It would be reasonable to assume that power plants at higher altitudes are in general less efficient than lower ones. An analysis of the data does not bear this out, however. As seen in Figure 7, there is no definitive relationship between elevation and efficiency. It is likely that the difference in air pressure from elevation differences is not significant enough to drive efficiency down at higher plants.

Ambient temperature

Ambient temperature at a power plant's location has the potential to have a significant impact on the efficiency of a combustion-based process. Cooler conditions can increase the draft pressure of the exhaust gases and the condenser vacuum, both of which should increase the plant's overall efficiency. In addition, lower ambient temperatures could increase the efficiency of a plant's cooling system. The temperature of the cooling water as it enters the condenser can have significant impacts on turbine performance by changing the vacuum at discharge from the steam turbine. However, as seen in Figure 8, there is no clear relationship between the average maximum summer temperature (for 2006) at the plant's location and its efficiency.

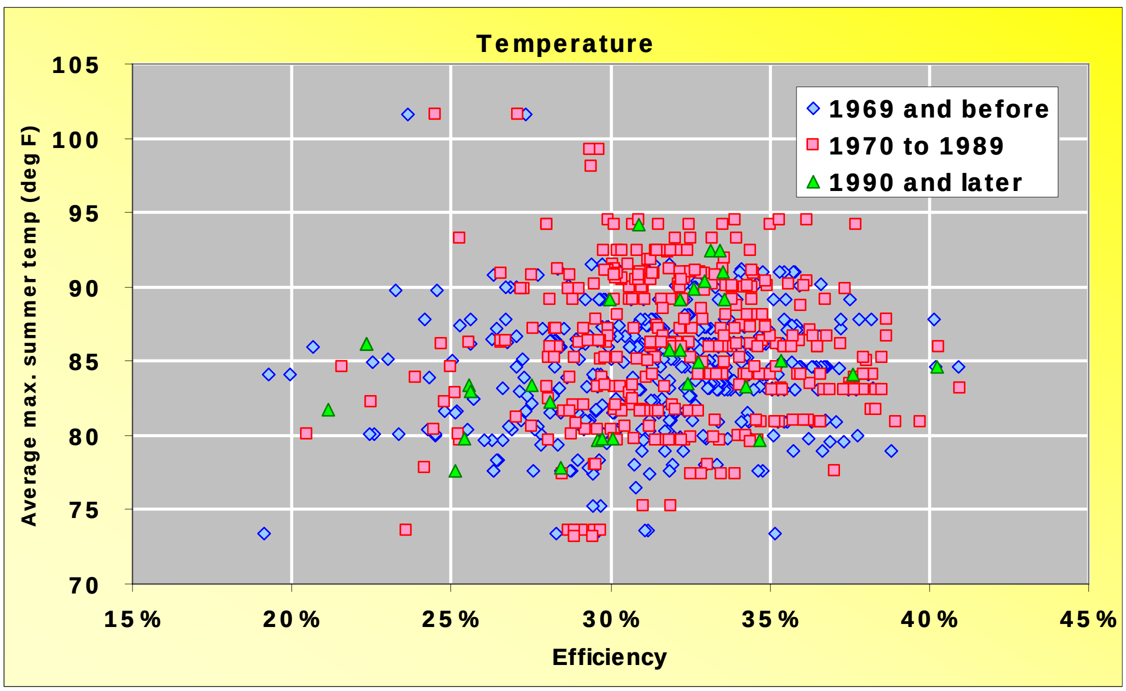

Figure 8. Ambient temperature and efficiency of coal fired power plants[24]

Almost all power plants lie within a 20° F range of average maximum summer temperature. This temperature range does not appear to impact power plant heat rate.

Cooling system

The temperature and flow rate of the condenser cooling water theoretically has a significant impact on a steam cycle's overall efficiency. A larger flow of cooler water should increase the plant's efficiency. Also, cooling systems which take advantage of natural water and air flows would also improve the overall efficiency of the plant.

Systems which utilize large pumps or fans to provide circulation of the cooling medium, though, would be expected to somewhat penalize the overall power plant's efficiency.

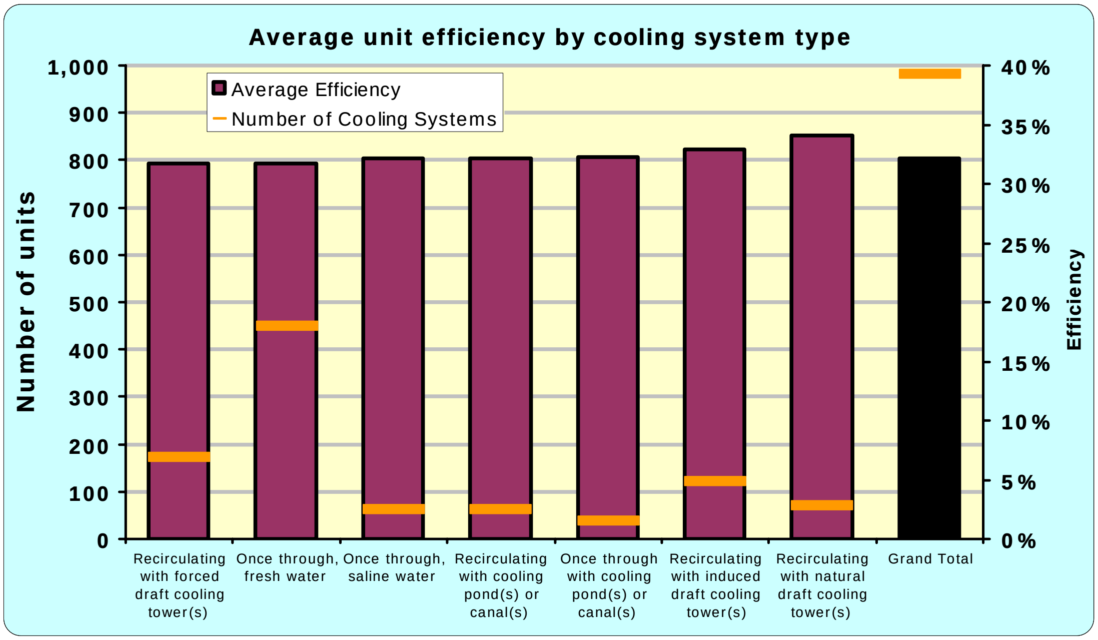

Figure 9. Cooling system and efficiency of coal fired power plants[25]

As seen in Figure 9, plants utilizing recirculating cooling systems with natural and induced draft are slightly more efficient than those with other systems, but given the number of plants utilizing these systems and the scale of the efficiency difference, it is not likely that this is a critical factor.

Equipment manufacturer

Just as different brands of any product have different characteristics, it would be reasonable to assume that a plant's overall efficiency could be dependent on the manufacturer of the major plant components, the boiler and generator. However, as seen in Figure 10 and Figure 11, overall plant efficiency appears to be very consistent among the major manufacturers. For generators, Siemens and General Electric dominate the CFPP fleet, and on average have nearly identical plant efficiencies. The other generator manufacturers have more variation, but it is likely that there are not enough of them to be statistically relevant.

The boiler design and parameters of a power plant are likely to have an even more profound effect on the overall efficiency, but again, the average efficiencies are very close among the top four boiler manufacturers. Plants using ALSTOM boilers do appear to be slightly more efficient than the other top four manufacturers, but it does not appear to be significant compared to the variation in efficiencies across the entire fleet.

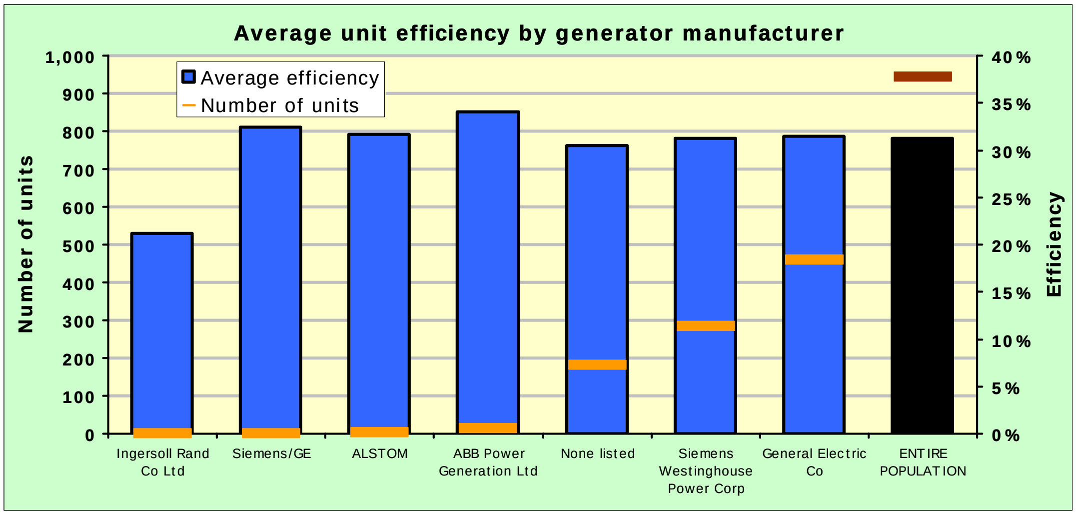

Figure 10. Generator manufacturer and efficiency of coal fired power plants

The lack of variation among manufacturers is likely explained by the fact that the power plant equipment manufacturing market is a relatively mature one, and intense competition combined with mergers have forced the small number of original equipment manufacturers left to match the performance of their competitors' products.

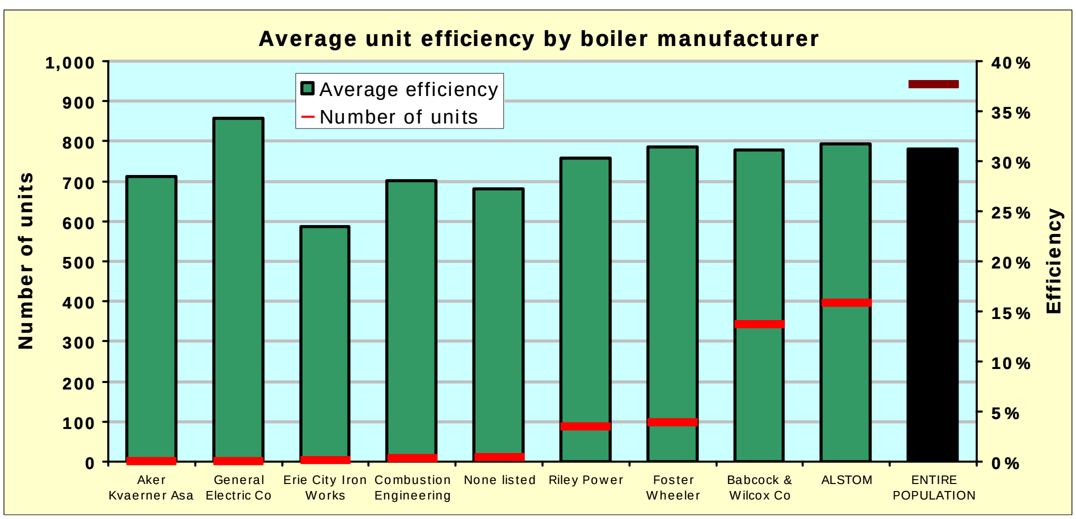

Figure 11. Boiler manufacturer and efficiency of coal fired power plants

Emissions control equipment

Equipment controlling the emissions of sulfur dioxide (SO_2), nitrogen oxides and particulate matter from CFPPs has the potential to reduce a plant's overall output and therefore lower its efficiency. For plants with flue gas desulphurization (FGD), a method to control SO_2, there does appear to be a slight reduction in efficiency compared to those units without such equipment. Plants utilizing NOx-limiting selective catalytic reduction (SCR) are on average more efficient than those without it, an initially surprising result.

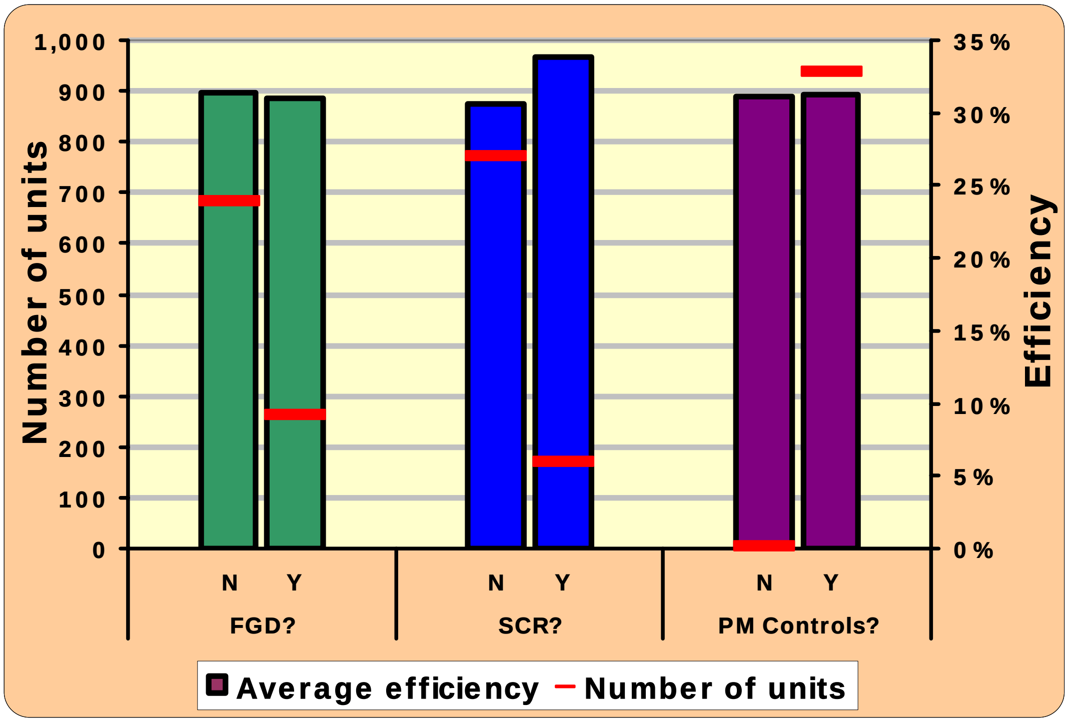

Figure 12. Emissions control equipment and efficiency of coal fired power plants

Two factors are responsible for this. First, plants with SCR are younger on average, at around 34 years, compared to plants without SCR that have an average age of around 40 years. Also, out of the 171 plants identified with SCR, 100 are supercritical units, which are inherently more efficient than subcritical units. These factors skew the overall average of all plants with SCR. Plants with particulate matter (PM) control have about the same efficiency as plants which do not.

Examining the top 10% and bottom 90% split

The central hypothesis of this paper is that within an age/steam cycle class, power plants will be able to raise their efficiency to the average of the top 10% in that class. It is proposed that since no significant variations in efficiency were discovered by regression analysis of other plant characteristics, those plants in the top 10% are there primarily because of their operation and maintenance practices. However, the argument could be made that the top 10% plants share some combination of external factors which make them inherently more efficient. A detailed examination of the characteristics of units within and outside the top 10% group for each age/steam cycle class was performed to address this argument. Table 5 shows the average values for unit characteristics, broken out by age/steam cycle class and whether the unit is in the top 10% or not.

Table 5. Characteristics of top 10% units

Unit parameters	Subcritical Top 10%? N	Subcritical Top 10%? Y	All sub-critical	Supercritical Top 10%? N	Supercritical Top 10%? Y	All super-critical
1969 and before						
Elevation (Meters)	249	186	245	160	283	223
2006 Summer Max Temp (°F)	83.9	85.2	84.0	83.6	83.8	83.7
Fuel BTU/pound	10,657	11,565↑	10,714	11,521	11,671	11,598
Nameplate capacity (MW)	147	265↑	155	509	636↑	574
Online year	1957	1960	1957	1965	1967	1966
1970 to 1989						
Elevation (Meters)	414	182	393	281	201	255
2006 Summer Max Temp (°F)	86.1	84.2	85.9	87.1	83.7	86.0
Fuel BTU/pound	9,787	11,760↑	9,966	10,168	12,089↑	10,792
Nameplate capacity (MW)	472	752↑	498	802	827	810
Online year	1979	1975	1978	1974	1974	1974
1990 and later						
Elevation (Meters)	274	588	294	N/A	161	161
2006 Summer Max Temp (°F)	84.5	83.0	84.4	N/A	84.6	84.6
Fuel BTU/pound	9,387	8,368	9,324	N/A	12,395	12,395
Nameplate capacity (MW)	179	465↑	196	N/A	1,426	1,426
Online year	1995	1993	1995	N/A	1991	1991

Elevation, ambient temperature and year online do not appear to differ significantly whether or not the unit is among the top 10%. However, for most of the classes, average nameplate generation capacities and fuel energy densities are higher for plants in the top 10%. In the case of the fuel energy content, efficiency improvements could be achieved by refurbishments to allow units to burn higher rank coal. The fact that units in the top 10% typically have higher generation capacities is unsurprising since these units use the advantages of scale. However, it also likely that operators may have elected to perform efficiency improvement projects on larger capacity units since the gross benefit is larger. Future analyses may benefit from further classification of coal-fired units by fuel type and generation capacity; but due to limitations within the CARBEN tool, model, more detailed classification of this type was not explored for this report.

Table 6. Percentages of units showing emissions controls and cooling systems

Unit configurations		Subcritical Top 10%? N	Subcritical Top 10%? Y	All sub-critical	Supercritical Top 10%? N	Supercritical Top 10%? Y	All super-critical
1969 and before							
SO_2 control?	N	88.7%	6.2%	94.9%	2.3%	2.8%	5.1%
	Y	88.3%	3.9%	92.2%	5.2%	2.6%	7.8%
NO_x control?	N	98.6%	1.4%	100.0%	0.0%	0.0%	0.0%
	Y	85.9%	7.2%	93.0%	3.4%	3.6%	7.0%
Cooling system	N/A	100.0%	0.0%	100.0%	0.0%	0.0%	0.0%
	Once-through	88.0%	7.4%	95.4%	2.5%	2.1%	4.6%
	Recirculating	83.8%	4.6%	88.5%	4.6%	6.9%	11.5%
Overall percentage		***88.7%***	***5.9%***	***94.6%***	***2.6%***	***2.8%***	***5.4%***
1970 to 1989							
SO_2 control?	N	77.2%	2.3%	79.5%	14.6%	5.9%	20.5%
	Y	78.7%	3.4%	82.0%	11.2%	6.7%	18.0%
NO_x control?	N	91.4%	0.0%	91.4%	8.6%	0.0%	8.6%
	Y	76.5%	3.0%	79.6%	13.5%	6.9%	20.4%
Cooling system	N/A	91.4%	2.9%	94.3%	5.7%	0.0%	5.7%
	Once-through	72.7%	4.0%	76.8%	19.2%	4.0%	23.2%
	Recirculating	77.9%	2.3%	80.2%	11.8%	8.0%	19.8%
Overall percentage		***77.8%***	***2.8%***	***80.6%***	***13.1%***	***6.3%***	***19.4%***
1990 and later							
SO_2 control?	N	92.3%	7.7%	100.0%	N/A	0.0%	0.0%
	Y	92.5%	5.7%	98.1%	N/A	1.9%	1.9%
NO_x control?	N	100.0%	0.0%	100.0%	N/A	0.0%	0.0%
	Y	91.5%	6.8%	98.3%	N/A	1.7%	1.7%
Cooling system	N/A	96.4%	3.6%	100.0%	N/A	0.0%	0.0%
	Once-through	100.0%	0.0%	100.0%	N/A	0.0%	0.0%
	Recirculating	87.1%	9.7%	96.8%	N/A	3.2%	3.2%
Overall percentage		***92.4%***	***6.1%***	***98.5%***	***N/A***	***1.5%***	***1.5%***

Also of interest with respect to the top 10% of units are the presence of emissions controls and cooling system configuration. It could be reasonably assumed that units within the top 10% are less likely to have emissions controls due to the parasitic load imposed by emissions control systems. Additionally, as seen in Figure 9 above, units utilizing recirculating cooling with natural draft seem to have slightly higher efficiency than other configurations, and the conclusion could be drawn that units with these configurations are more likely to be in the top 10% group. However, as seen in Table 6, there are no clear trends indicating that the top 10% plants preferentially have certain emissions control or cooling system configurations. For the pre-1970 and post-1990 groups, there are slightly more units that are in the top 10% that do not have SO_2 controls than the rest of the comparable population. However, reflecting results from above, units *with* NO_x controls seem to be more likely to be in the top 10% group. Cooling system configuration does not seem to have a clear trend at all.

Appendix B
Power Plant Efficiency Improvement Examples and Electronic Library

During the literature search, a number of papers, presentations and other documents were collected detailing the results of efficiency improvement projects performed at CFPP's. Major types of these projects are described below.

Boiler Combustion Control Optimization

In its simplest form, boiler combustion control is accomplished by adjustments to coal and air flow to maintain adequate steam production for the turbine to maintain the desired level of electrical generation. However, boiler combustion control is extremely complex and can impact a number of important plant operating parameters including combustion efficiency, steam temperature, furnace slagging and fouling, and NO_x production.

A total of eight documents were identified that report on technologies to improve combustion system efficiencies. 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. The reported efficiency improvements ranged from 0.15 to 0.84 percentage points.

Sootblower Control 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. As with boiler combustion control, advanced process control systems are being used to optimize sootblower operation.

A total of eleven documents were identified that report on technologies to improve efficiencies by sootblower optimization. Most of the documents deal with intelligent or neural-network sootblowing which describes sootblowing in response to real-time conditions in the boiler. One article describes detonation sootblowing. Efficiency improvements reported for this technology range from 0.08 to 0.65 percentage points.

Steam Turbine Upgrades

In addition to the inherent energy loss associated with the thermodynamics of the Rankine steam cycle, there are other recoverable energy losses that result from the steam turbine's mechanical design or physical condition. For example, steam turbine manufacturers have improved the design of turbine blades and steam seals through upgrades that are now available to existing plants, which can increase both efficiency and output.

Seven documents were identified that address efficiency improvements from steam turbine optimization: these improvements ranged from minimizing leaks to reblading, to replacing turbines, resulting in increases of 0.84 to 2.6 percentage points. Power magazine describes turbine upgrades as one of the efficiency improvement efforts where "the return on investment will be biggest."[26]

Flue Gas Heat Loss Recovery

The air preheater is typically the last heat exchanger used to extract energy from the combustion flue gas prior to discharge from the stack. A power plant's design flue gas exit temperature from the air preheater can range from 250°F 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 flue gas desulfurization (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.

Three articles were identified describing flue gas heat recovery and flue gas moisture recovery included with air preheating along with several documents dealing with overall efficiency improvements. Improvements ranged from 0.3 to 1.5 percentage points. The articles that mentioned specific technologies (as opposed to general refurbishing) dealt with reducing flue gas temperatures enough for the condensation of acid or water, which would require corrosion resistant heat exchangers.

Cooling System Heat Loss Recovery

As discussed above, most of the steam condenser cooling system's energy loss is an inherent result of the thermodynamics of the Rankine steam cycle. However, it is possible to recover a portion of the heat loss from the warm cooling water exiting the steam condenser prior to its discharge or recycle to the cooling tower depending on the type of cooling system used at a plant. An example of cooling system heat loss recovery is low rank coal drying, which is discussed next.

Three documents were identified that address cooling system improvements although they covered efficiency in general and thus only mentioned cooling systems in passing. The two specific actions mentioned in these documents were to replace the cooling tower fill (heat transfer surface) and to better tune the cooling tower and condenser. Cooling system improvements are expected to achieve benefits from 0.2 to 1 percentage points.

Low Rank Coal Drying

Sub-bituminous and lignite coals contain relatively large amounts of moisture (15 percent to 40 percent) compared to bituminous coal (less than 10 percent). 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. Methods are now being developed to utilize waste heat from the flue gas and/or cooling water systems to dry low rank coal prior to combustion.

Coal drying technology is still in the prototype stage and likely to have high capital costs, but its benefits to power plants that burn low-rank coal could be enormous. Eight documents were found reporting on coal drying, with improvements ranging from 0.1

percent to 1.7 percent. An additional Australian study published in 2000 claimed that coal drying could achieve efficiency improvements as high as 4.5 percent although these optimistic expectations have not been duplicated elsewhere.

Listing of Efficiency Improvement Project Documents

Project Category	Publication Date	Source	Author	Title	Brief Description
Air and flue gas fans & drives	2004	Danfoss Drives	Foree, Rick	Reducing Mechanical Equipment Failures by Utilizing Variable Frequency Drives	A presentation covering how variable speed drives increase efficiency and equipment life
Air preheater	2001	Cegco	Cegco	Efficiency Improvements in Power Plants	Efficiency improvements to air preheaters in Jordan
Boiler components	1991	EPRI	D'Agostini, M. et al.	The Effect of Burner Tilt Angle on Unit Performance at PEPCO's Morgantown Unit 2	Study from the 1991 Heat Rate Improvement Conference found that the reheat spray flow rate varied with burner tilt angle. Over the tilt range from -17° to 12°, the average increase in spray flow was found to be ~ 72,000 lbs/hr - resulting in an increase in net unit heat rate of ~ 30 Btu/kWh.
Boiler components	2003	Power Engineering	Smith, Douglas	Improved Damper Drive Lowers Heat Rate	By precisely controlling the boiler dampers it is possible to maintain an optimal negative draft inside the firebox and subsequently optimize the superheater and reheater temperatures.
Boiler components	2006	EPRI	EPRI	Endesa Installs a Dry Bottom Ash Removal System at Los Barrios 1 Unit Strongly Reducing O&M Costs at the 552 MW Coal Fired Unit	New ash removal system for the boiler
Combustion system	2005	Promecon	Conrads, Hans	Instrumentation for Improving Combustion System Operation and Fly Ash Quality	This paper discusses the application of state-of-the-art, on-line carbon-in-ash as well as coal and air flow measurement instrumentation to large combustion systems. These measurements are critical for truly optimizing firing system and thermal performance while maximizing the quality of fly ash generated.
Combustion system	2006	Monroe Power Plant	Dobrzanski, Andrew	Updates and Improvements in the Monroe Power Plant Firing Systems	During 2004 – 2005, Monroe Power Plant (MPP) made numerous improvements to the firing systems for its four units. The firing system consists of fuel blending, the fuel silos, the pulverizers, the burners, and associated instrumentation. Improvements were made to the blending system and its instrumentation, to the classifiers in the mills, to the burners, and to the instrumentation. This paper summarizes the improvements made and documents the results.

Project Category	Publication Date	Source	Author	Title	Brief Description
Combustion system	2006	Institute of Process Engineering	Greissl, O	Optimization of Combustion and Prevention of Water Wall Corrosion at a Pulverised Coal fired Power Plant	To enhance the efficiency of a power plant by reducing stack loss, without running the risk of water wall corrosion, it is necessary to control the water wall atmosphere. Water wall corrosion is a well known problem in coal fired boilers. Combustion modifications to reduce stack loss increase the probability of water wall corrosion in coal-fired boilers. Minimizing the excess air often leads to reducing conditions at the water wall, what causes the typical chemical reactions, taking place during the corrosion process. Investigations have been carried out at a 1225 MWth pulverized coal fired boiler. For this purpose the investigated boiler was equipped with 110 measuring ports, for oxygen and carbon monoxide measurements, equally distributed at the boiler walls. The water wall atmosphere was measured at different combustion conditions.
Combustion system	2006	Plasma Power Technologies	Karpenko, E.	Plasma Enhanced Pulverized Coal Combustion	Plasma assisted coal combustion is a relatively unexplored area in coal combustion science. Coal fired utility boilers face two problems, the first being the necessity to use expensive oil for start-up and the second being the increased commercial pressure requiring operators to burn a broader range of coals, possibly outside the specifications envisaged by the manufacturer's assurances for the combustion equipment.
Combustion system	2003	Lehigh University	Sarunac, Nenad	Sensor and Control Challenges for Improved Combustion Control, Performance and Reduced Power Plant Emissions	Some combustion control challenges and their effect on plant performance and emissions are discussed in this paper. An advanced combustion control scheme is proposed for coal-fired boilers and instrumentation and control needs for its implementation are discussed.
Combustion system	2007	POWER magazine	R.F. Storm, Stephen K. Storm, and Stephen G. Hall, Storm Technologies	Managing air to improve combustion efficiency	Discusses an approach for assessing the performance of a coal-fired steam generator and then details how to manage the airflow and fuel flow to obtain the best combustion results possible given the constraints of the boiler design.
Combustion system	2004	Clyde Bergemann	Johnson, Rabon	Superheater Fouling Monitor System	Strain gages are being used to sense slag deposits in the superheat sections by measuring weight increases as the deposits grow.
Combustion system	2006	Doosan	Hyeok-Pill, Kim	The Development of Tangential Coal-Fired Burner to Reduce Unburned Carbon and Enhance Flame Stability	This report presents a study of the development of an advanced coal nozzle used in burners to reduce unburned carbon (UBC) in a tangential coal-fired boiler.
Condenser	2008	Conco	Conco	Southern California Utility Improves Plant Heat Rate by More than Two Percent	An evaluation of five possible cleaning techniques on two sample tubes removed from a power plant condenser

Project Category	Publication Date	Source	Author	Title	Brief Description
Condenser	2006	EPRI	EPRI	Midwest Generation Engineers Study Plugged Condensers and Find that, Above 25% Plugged Tubes, the Unit Generation Significantly Decreases	A model looking at the effect on plant efficiency of unclogging plugged condenser tubes
Condenser	2006	EPRI	EPRI	Mirant Improve Condenser Performance at Chalk Point by Solving Leakage and Fouling Problems	This is an important example of how to correct condenser performance problems at the Chalk Point power plant, where several issues combined to reduce unit efficiency and power.
Feedwater heaters	2006	EPRI	EPRI	Dynegy Removes Top Feedwater Heater at Hennepin, Gains MW and Improves Heat Rate While Removing PRB Coal Limitations	The most unexpected result of removing the feedwater heater was improvement in unit heat rate, which is counter to conventional wisdom. Plant staff been able to account for a portion of the observed gains, finding improvements in boiler efficiency and IP and LP turbine performance.
Fuel Preparation	Feb-07	EPRI	Tony Armor	Coal Creek Prototype Fluidized Bed Coal Dryer: Performance Improvement, Emissions Reduction, and Operating Experience	EPRI presentation covering a coal dryer that uses waste heat to dry the fuel
Fuel Preparation	Dec-06	NETL	NETL	Increasing Power Plant Efficiency: Lignite Fuel Enhancement	Fact Sheet for a coal drying technology being demonstrated at the Coal Creek Station
Fuel Preparation	2006	Great River Energy	Bullinger, Charles	Full-Size Prototype Fluidized Bed Coal Dryer: Performance Improvement, Emission Reduction, and Operating Experience at Coal Creek	Lignite and sub-bituminous coals from the Western U.S. are attractive due to their low cost and emissions. Unfortunately, these low-rank coals typically contain high amounts of moisture. The high-moisture content results in higher fuel and flue gas flow, higher parasitic power and mill maintenance, and lower plant efficiency, compared to the Eastern bituminous coals.
Fuel Preparation	2006	Great River Energy	Bullinger, Charles	Full-Size Prototype Fluidized Bed Coal Dryer	The presentation associated with "Other Great River Energy 2006"
Fuel Preparation	2006	James River Power Plant	Stodden, Steve	Atrita Pulverizer System Upgrade for PRB Coal Conversion	This paper presents an upgrade implemented on the Atrita pulverizer system at James River Power Plant of City Utilities of Springfield to accommodate a desire to fire 100% PRB coal. Discussion will focus on mill system design considerations exclusively for PRB coal application, operational results of the upgraded mill system and the latest mill design improvement for better coal fineness, improved emissions and lower fly ash unburned carbon.

Project Category	Publication Date	Source	Author	Title	Brief Description
Fuel Preparation	2007	POWER magazine	Storm, Dick	To optimize performance, begin at the pulverizers	The three significant ways in which optimizing pulverizer performance can contribute to a reduction in a coal-fired boiler's NO_x emissions are described
Fuel Preparation	2006	Lehigh University	Project led by Edward Levy and Nenad Sarunac	Use of Power Plant Waste Heat to Reduce Coal Moisture Provides Plant Performance and Environmental Benefits	This fact sheet describes the project - drying system uses a combination of thermal energy from boiler and condensing cooling water as the heat source for coal drying
Fuel Preparation	2007	POWER magazine	Richard F. (Dick) Storm, PE, and Stephen K. Storm, Storm Technologies Inc	To optimize performance, begin at the pulverizers	This article explores opportunities for raising a unit's efficiency by improving the performance of its pulverizers.
Fuel Preparation	2007	POWER magazine	Robert E. Sommerlad and Kevin L. Dugdale, Loesche Energy Systems	Dynamic classifiers improve pulverizer performance and more	Article discusses that by adding a dynamic classifier to the pulverizers, coal particle sizing and fineness can be better controlled and pulverizer capacity can be increased.
Fuel Preparation	2005	Lehigh University	Bilirgen, Harun	Improved Combustion Control Through Coal Flow Balancing	Poor coal flow distribution to the burners is a common problem in pulverized coal boilers and has been considered as a potential area that needs to be addressed for improving unit performance, emissions, operations, and maintenance.
Fuel Preparation	2005	Lehigh University	Levy, Edward	Operational and Environmental Benefits of Retrofitting a Low Rank Coal-Fired Power Plant with a Coal Drying System	This paper deals with use of waste heat from pulverized coal power plants to dry coal prior to feeding it to the pulverizers. Fuel moisture affects heat rate, emissions of pollutants, and the consumption of water needed for evaporative cooling. Reduction of fuel moisture can also reduce fuel handling problems and maintenance costs of some components.
Fuel Preparation	2007	Department of Energy	Department of Energy	Power Plant Optimization Demonstration Projects	The objective of this project is to demonstrate an economic process of moisture reduction of lignite, thereby increasing its value as a fuel in power plants.
Fuel Preparation	2006	EPRI	EPRI	Outstanding Results Obtained from the Great River Energy Prototype Lignite Dryer at Coal Creek Station	Initial results from Great River Energy's Coal Creek Station in Underwood, ND, are showing that the system could be the first to demonstrate that pre-drying high-moisture coals before they are fed to a power plant's boiler offers a practical and economical way to generate more power from a lower quantity of coal and reduce air emissions.
Heat Recovery	Apr-08	Lehigh University	Levy, Edward	Recovery of Water from Boiler Flue Gas	A Lehigh University presentation to NETL on water recovery from boiler flue gas
Heat Recovery	Jul-07	NETL	Levy, Edward	Recovery of Water from Boiler Flue Gas: Quarterly Report July 2007	July 2007 Quarterly Report on designs for heat exchangers designed to operate below the acid dew point.

Project Category	Publication Date	Source	Author	Title	Brief Description
Other	2006	EPRI	EPRI	Report # 1013355, "2006 Updated Cost and Performance Estimates for Clean Coal Technologies Including CO_2 Capture "	This EPRI report does not contain heat rate improvements suggestions. It does compare heat rates for different coal-fired generation technologies and coals. It also compares and explains the difference in reported heat rates between the U.S. and European plants.
Other	2005	Makel Engineering	Makel, Darby	Harsh Environment eNose Enabling High Performance Control of Combustion Efficiency and Emissions Monitoring	Makel Engineering's product development effort will provide a high-temperature, small form-factor platform that allows multiple gas micro-sensors to perform in-situ measurements applicable to industrial burners, boilers, power generation turbines, and other engines. Data provided by these sensors can be used to control combustion parameters improving efficiency and minimizing pollution. The platform design will provide flexibility to incorporate sensors for the species relevant to the demands of a particular system, selected from a suite of sensor technologies.
Other	2005	Fuel Tech	Smyrniotis, Chris	Slag Inhibition Success Utilizing Targeted In-Furnace Injection at a PRB Coal Burning Utility Boiler	This paper discusses technology that helps control slagging, fouling and tube cracking in boilers firing western coals. It examines on-going field experience in controlling slag and fouling problems in a 475 MWe western coal fired boiler.
Other	2005	Energy Research Company	Weisberg, Arel	Laser-Based Coal and Ash Composition Sensor for Coal-Fired Boilers and Gasifiers	Energy Research Company (ERCo) is developing a laser based analyzer for simultaneously measuring the elemental composition and heating value of pulverized coal. In addition, the analyzer measures unburned carbon in ash.
Other	2006	Champagne Coal Consulting	Champagne, Philippe	Evolution and Application of Slagging, Fouling and Boiler Performance Indices	This paper will provide an overview of the complexity of the chemical and physical processes involved in ash deposition during coal combustion as well as an approach to manage the detrimental performance impacts. Specifically, the paper will provide an example of how the combination of the Full Stream Elemental Analysis (FSEA) combined with appropriately derived indices provides understanding and prediction of the potential ash-related impacts of coal characteristics on performance.
Other	2003	Eskom	Statham, Brian	The Use of Benchmarking to Improve the Performance of Coal Fired Power Plants	A new approach to planning was developed which was based on planning back from the future and the key planning question became: "What is preventing us from achieving target performance immediately?"

Project Category	Publication Date	Source	Author	Title	Brief Description
Other	2008	Santee Cooper	Davis, Michael	Controlling SO_3, Slag, and Fouling Resulting in Improved Heat Rates, Better Efficiency and Allowing for Fuel Flexibility - Santee Cooper, Cross Station Case Study	Santee Cooper and Fuel Tech have cooperated over the past 18 months to demonstrate the capabilities of the TIFI Targeted In-Furnace Injection program.
Other	2008	Santee Cooper	Davis, Michael	Controlling SO_3, Slag, and Fouling Resulting in Improved Heat Rates, Better Efficiency and Allowing for Fuel Flexibility - Santee Cooper, Cross Station Case Study	A presentation to go with the paper of the same name
Other	2000	Babcock & Wilcox	Kitto, J.	Upgrades and Enhancements for Competitive Coal-Fired Boiler Systems	This paper highlights a variety of boiler system upgrades and enhancements which are being utilized to make aging coal-fired boilers low cost competitors in the 1990s.
Other	2001	Environmental Protection Agency	Perrin Quarles Associates	Review of Potential Efficiency Improvements at Coal-Fired Power Plants	This is a review of readily available data on potential and actual efficiency improvements at coal-fired utilities. The objective was to identify heat rate reductions or efficiency improvements that have taken place due to either optimization efforts at existing utility boilers or due to the use of newer advanced technologies for coal combustion.
Other	2007	Roberts, B.F.	Economic Sciences Corporation	Efficient Heat Rate Benchmarks for Coal-Fired Generating Units	The objective of this study was to analyze the potential for heat rate improvement among coal-fired generating units in the United States.
Other	2004	Roth, Eike	Energie Fakten	Why Thermal Power Plants Have a Relatively Low Efficiency	It is often concluded that thermal power stations are inadequate, waste energy, and need to be replaced by 'better' facilities. To evaluate this conclusion, one needs to look at the physical properties of heat energy, as well as at the fine-print in efficiency calculations, defined by man.
Other	2004	Waryasz, Richard	Alstom	Economics and Feasibility of Rankine Cycle Improvements for Coal-Fired Power Plants	An analysis of the most cost effective performance potential available through improvement in the Rankine Cycle steam conditions and combustion systems while at the same time ensuring that the most stringent emission performance based on CURC (Coal Utilization Research Council) 2010 targets are met.
Other	2002	Portland General Electric	Rodgers, David	Performance Improvements at the Boardman Coal Plant as a Result of Testing and Input/Loss Monitoring	This paper presents methods and practices of improving heat rate through testing and heat rate monitoring.

Project Category	Publication Date	Source	Author	Title	Brief Description
Other	2004	World Energy Council	Richwine, Robert	Performance Improvement in Coal-Fired Power Stations -- the Southern Company Experience	The majority of the focus in improving heat rate should be on improving management practices.
Other	2008	Alstom	Stein, Stephan	Rehabilitation of Steam Power Plants An Approach to Improve the Economy of Thermal Power Generation	ALSTOM Power is demonstrating that the rehabilitation of steam power plant units is an attractive solution for national utilities and Independent Power Producers to improve the plant economy and to keep production cost competitive.
Other	2007	NPC	Bellman, David	Electric Generation Efficiency	The efficiency of existing power plants can be increased by only a few percentage points.
Other	2008	EUEC Conference	Romero, Mario	Waste Heat Recovery Power Plants	Wow Energy presentation onWOWGen® combined cycle turbo-expander system for converting waste heat to power in the 300°F to 700°F range.
Other	2008	Flame Technologies	Wagner, George	The Evolution of Innovative Boiler Technology 2006 to Today	A presentation covering an oxidant that is added to fuel or combustion air.
Other	2006	EPRI	EPRI	Rapid, Automatic, Continuous Diagnosis of Condenser Exhaust Helps Identify Air Leakage Sources at Georgia Power's Plant Yates Units 4-7 and Entergy's Sabine Station Unit 4	At the 530 MW Sabine Station Unit 4, the amount of air in-leakage rose from 165 to 570 cfm over a one hour period increasing condenser back-pressure from a little over 2 to almost 8 inches of mercury. The cause of the increase was subsequently identified as a ruptured gland steam pipe inside the condenser.
Overall	1986	EPRI	EPRI	Report # CS-4554, published 6/2/1986, "Heat Rate Improvement Guidelines for Existing Fossil Plants"	This report provides utility engineers and managers with procedures for establishing a heat-rate program where none exists or for improving one under way. Activities covered in the guidelines range from program planning to implementation. Also highlighted are ideas on organizational structure and performance monitoring systems to verify and quantify heat-rate improvement.
Overall	Jul-98	EPRI	EPRI	Report # TR-109546, "Heat Rate Improvement Reference Manual"	This reference manual supplements the EPRI Heat Rate Improvement Guidelines published in May of 1986. It includes detailed heat rate monitoring, accounting, and calculation methodology not covered in the guidelines. In addition, the manual highlights the results of heat rate improvement guideline demonstration projects conducted at five member utility plants.

Project Category	Publication Date	Source	Author	Title	Brief Description
Overall	May-98	EPRI	EPRI	Report # TR-111316, "Proceedings: Second Annual EPRI Workshop on Power Plant Optimization"	These proceedings include a summary of the highlights of the EPRI workshop, as well as EPRI's overview of industry experience. Descriptions of the following commercially available optimization software are included: Boiler OP by Lehigh University, GNOCIS by Radian International and Southern Company Services, NeuSIGHT by Pegasus Technologies, Power Insights by Pavilion Technologies, ProcessLink by NeuCo, PECOS by Praxis Engineers, TOPAZ by DHR Technologies, and ULTRAMAX by Ultramax Corp.
Overall	Jan-01	EPRI	EPRI	Report # 1004118, "EPRI's Twelfth Heat Rate Improvement Conference Proceedings"	Areas addressed in the individual sessions include: The effectiveness and usefulness of on-line heat rate monitors; The trend for optimization software tools to use heat rate as an input into total plant cost minimization efforts; The potential for incorporating intelligent sootblowing applications into optimization efforts; The possibilities for heat rate improvements from upgrades in turbines and auxiliaries; The latest trends in heat rate testing; Actual plant experiences with heat rate improvement projects.
Overall	Nov-03	EPRI	EPRI	Report # 1009239, "Productivity Improvement for Fossil Steam Power Plants: Industry Case Studies"	This report assembles more than sixty case studies on subjects spanning the power plant from the boiler and the steam turbine, through plant auxiliaries and environmental control equipment. Improvements are described in reliability, performance, plant flexibility, and equipment life.
Overall	Jul-05	EPRI	EPRI	Report # 1012098, "Productivity Improvement for Fossil Steam Power Plants 2005: One Hundred Case Studies"	This report assembles one hundred case studies on subjects spanning the power plant from the boiler and the steam turbine, through plant auxiliaries and environmental control equipment. Improvements are described in reliability, performance, plant flexibility, and equipment life.
Overall	Dec-05	EPRI	EPRI	Report # 1011794, "Power Plant Optimization Industry Experience"	This study briefly surveys commercially available optimization software, provides an overall assessment of the extent optimization is currently used in the U.S. utility industry, summarizes the experience of U.S. electric utilities, and details the lessons learned, focusing on what makes a project successful.
Overall	Dec-06	EPRI	EPRI	Report # 1014598, "Productivity Improvement for Fossil Steam Power Plants 2006"	This report assembles numerous case studies on subjects spanning the power plant from the boiler and the steam turbine, through plant auxiliaries and environmental control equipment. Improvements are described in reliability, performance, plant flexibility, and equipment life.

Project Category	Publication Date	Source	Author	Title	Brief Description
Overall	Apr-03	EPRI	EPRI	Report # 1004118, "Proceedings: 2003 EPRI Heat Rate Improvement Conference"	The meeting reflects those topics considered most important by EPRI members in their continual efforts to improve heat rate and overall plant performance. Deregulation and the current activity in merger, acquisition, and restructuring have set the stage for electric power generation. In addition to combustion optimization, the utility industry uses a variety of options to improve steam turbine and balance-of-plant equipment performance to best position their plants for competitive generation.
Overall	Apr-05	EPRI	EPRI	Report # 1010321, "2005 EPRI Heat Rate Improvement Conference"	Conference presentations reflect those topics considered most important by participating EPRI members in their continual efforts to improve heat rate and overall plant performance. Deregulation and the current activity in merger, acquisition, and restructuring have set the stage for electric power generation. In addition to combustion optimization, the utility industry uses a variety of options to improve steam turbine and balance-of-plant equipment performance to best position their plants for competitive generation.
Overall	Mar-07	EPRI	EPRI	Report # 1014799, "2007 EPRI Heat Rate Improvement Conference Proceedings"	Conference presentations reflect those topics considered most important by participating EPRI members in their continual efforts to improve heat rate and overall plant performance. In addition to combustion optimization, the utility industry uses a variety of options to improve steam turbine and balance-of-plant equipment performance to best position their plants for competitive generation.
Overall	2006	Lehigh University	Sarunac, Nenad	Opportunities for Improving Efficiency of Existing Fossil-Fired Power Plants	The cost-effective efficiency improvement approaches described in this paper include: utilization of waste heat to enhance coal quality by removing coal moisture, combustion efficiency improvement by improving distribution of coal and combustion air to individual burners, improvements to combustion sensors and controls, and improvement in heat rejection.
Overall	2002	EPA	Mussati, Daniel	Regulatory Impact Analysis for the Specification of Categories of Activities as Routine Maintenance, Repair and Replacement for the New Source Review Program	Attachment 2 of this document titled "Potential for Efficiency Improvements at Existing Coal-Fired Power Plants. Gives estimates of the technology and related efficiency improvement with a short concept description.
Overall	2000	Australian Greenhouse Office	Sinclaif Knight Merz Pty. Ltd.	Integrating Consultancy - Efficiency Standards for Power Generation p. 30	Report commissioned by the Australian Greenhouse Office (AGO) in relation to the Efficiency Standards for Power Generation.

Project Category	Publication Date	Source	Author	Title	Brief Description
Overall	2001	National Coal Council	Leer, Steve F.	Increasing Electricity Availability from Coal-Fired Generation in the Near-Term	Report by that makes suggestions for many plant improvements, including older plants.
Overall	2008	Connell Wagner	Boyd, Rod	Performance Improvement opportunities for Coal Based Power Generation	A presentation discussing the range of improvements that can improve heat rate.
Overall	2008	Lehigh University	Levy, Edward	Opportunities for Heat Rate Reductions in Existing Coal-Fired Power Plants: A Strategy to Reduce Carbon Capture Costs	There are numerous opportunities in the boiler, turbine cycle and heat rejection system of existing units for heat rate reduction. The overall level of improvement which can be achieved will vary with unit design, maintenance condition, operating conditions and type of coal.
Overall	2008	Balcke Durr	Horrighs, Wolfgang	Little Green Steps	A presentation on power plant efficiency improvements written in German. Patrick Le translated this into English. See slide 14.
Process controls	2007	Emerson Process Management	Emerson Marketing	SmartProcess® Combustion Optimizer	Data Sheet on Emerson's SmartProcess® Combustion Optimizer. Process control improvement for the combustion system with details including cost.
Process controls	2007	Emerson Process Management	Emerson Marketing	SmartProcess® Global Performance Advisor for the Power Industry	Data Sheet on Emerson's SmartProcess® Global Performance Advisor for the Power Industry. Process control monitoring software for indicating where plant needs improvements. No cost information.
Process controls	2007	Emerson Process Management	Emerson Marketing	SmartProcess® Sootblower Optimizer	Data Sheet on Emerson's SmartProcess® Sootblower Optimizer. Process control improvement for the sootblowers with details including cost.
Process controls	Aug-05	Emerson	Emerson Process Management	Plant Optimization & Performance Software	A presentation covering Emerson software modules designed to improve plant performance.
Process controls	Apr-01	EPRI	Robert Frank	Current Research and Future Needs in Power Generation	A presentation describing a process control retrofit at Kingston Unit 9.
Process controls	2005	NeuCo	Kirk, Peter	Implementation Results for Integrated Optimization at Dynegy's Baldwin Energy Complex	This paper discusses the current implementation results for integrated optimization at Dynegy's Baldwin Energy Complex. This project is part of the first round of the Clean Coal Power Initiative, a ten-year, $2 billion initiative to demonstrate advanced coal-based power generation technologies in the field.
Process controls	2005	Lehigh University	Romero, Carlos	Comprehensive Approach to Performance Improvement and Emissions Reduction on a 400 MW Tangentially-Fired Boiler part 1	A comprehensive approach to performance improvement and emissions reduction of a tangentially-fired unit is described in this paper. Technical approach to combustion tuning and combustion optimization and achieved results are described and discussed on Part 1 of the paper. Part 2 deals with Electrostatic Precipitator (ESP) performance improvement and sootblowing

Project Category	Publication Date	Source	Author	Title	Brief Description
					optimization.
Process controls	2005	Lehigh University	Sarunac, Nenad	Comprehensive Approach to Performance Improvement and Emissions Reduction on a 400 MW Tangentially-Fired Boiler part 2	A comprehensive approach to performance improvement and emissions reduction of a tangentially-fired unit is described in Parts 1 and 2 of the paper. Part 2 deals with the Electrostatic Precipitator (ESP) performance improvement and sootblower characterization and optimization. Technical approach and results are described and discussed. The ERC approach to combustion tuning and combustion optimization is described in Part 1.
Process controls	2008	Invensys	Invensys	Invensys Optimizes Heat Rate with Model Predictive Control for Southern Mississippi Electric Power Association	Heat rate improvement while maintaining low NOX emissions is the objective at SMEPA's R.D. Morrow Generating Station. To this end, a supervisory control system was installed over the modern DCS to improve performance for these Riley turbo fired units with ball mills.
Process controls	2008	Burns and Roe	Keller, George	Innovative boiler master design improves system response	The new boiler control arrangement is much more stable than traditional throttle pressure firing. It has been successfully deployed on several units and should be of great interest to owners of subcritical coal-fired units because it offers a quick and inexpensive solution to pressure stability problems.
Process controls	2003	POWER magazine	Rodgers, David	Improving Heat Rate by Input/Loss Monitoring	Heat rate was improved through monitoring and process control.
Process controls	2007	POWER magazine	Keller, George et al.	Innovative boiler master design improves system response	Description of a boiler master that uses a throttle pressure controller for steady-state/slow responses and a drum pressure controller for dynamic response and anticipation. Following a discussion of the new boiler control strategy, this article presents three studies detailing its installation at four coal-fired units owned and operated by the Kentucky Utilities (KU) subsidiary of E.ON U.S.: The 495-MW Unit 3 of E.W. Brown Generating Station; the 75-MW Unit 3 of Tyrone Generating Station; and the 75-MW Unit 3 and 100-MW Unit 4 of Green River Generating Station.
Process controls		Emerson	Jeffery J. Williams and Steven J. Schilling	Advanced Neural Network Control Platforms in Power Generation Applications	This paper describes the emergence of open computing platforms that has allowed the development of advanced process control applications using neural networks for Low NO_x optimization, soot blowing, and boiler cleanliness optimization.

Project Category	***Publication Date***	***Source***	***Author***	***Title***	***Brief Description***
Process controls		Emerson	Jeffery J. Williams	Optimization Software Offers Coal-Fired Power Plants Balanced Nox Reductions	This white paper describes case studies of plants that used this optimization software to reduce NOx and found in one case a small but measurable increase in boiler efficiency, also.
Process controls	2004	Emerson	Harry Winn, et al.	Optimization of Cyclone Boilers Using Neural Network Technology	White paper discusses the project with Constellation Energy to improve boiler efficiency at two units at its C.P. Crane Station in Baltimore, MA.
Process controls	2008	NeuCo	Piche, Steve	Combustion and Sootblowing Optimization at OMU Elmer Smith	A presentation describing efficiency improvements due to combustion and sootblowing optimization.
Process controls	2008	NeuCo	Spinney, Peter	Using Low-Cost Optimization Technologies to Reducing Carbon Footprint	A presentation describing overall plant optimization.
Process controls	2007	DOE	DOE	Power Plant Optimization Demonstration Projects	Pegasus Technologies will apply sensors at key locations to evaluate the mercury species (elemental and oxidized mercury), develop optimization software that will result in the best plant conditions to promote mercury oxidation and minimize emissions in general.
Process controls	2007	DOE	DOE	Power Plant Optimization Demonstration Projects	NeuCo is designing and demonstrating an integrated online optimization software system for the Dynegy Midwest Generation power plant using advanced computational techniques that are expected to achieve peak performance from the three coal-fired units at the energy complex.
Process controls	2006	EPRI	EPRI	RWE Monitor Fouling and Slagging Using Neural Networks in a 636 MW Lignite Fired Boiler in Germany	The boiler was equipped with online video monitoring systems and a steam generator diagnostic system. The diagnostic system monitors boilers by means of thermodynamic balances. This permits the determination of the fouling and slagging pattern of each heating surface online.
Process controls	2006	EPRI	EPRI	Kansas City Power and Light Install State of the Art Web-Based Performance Monitoring at Three Power Plants	KCP&L have installed a Web-based performance monitoring systems that allow both management and plant operators to monitor and evaluate the economic performance of their production at three of its generation plants: La Cygne, Iotan, and Hawthorne by installing software from Wonderware, a business unit of Invensys Systems, Inc.
Process controls	2006	EPRI	EPRI	Utilization of Artificial Intelligence Reduces NO_X and Opacity at Reliant Energy's New Castle and Cheswick Plants	Neural networks, such as these at Cheswick and New Castle, have proved useful tools for optimizing unit operation to meet one or several environmental and/or performance objectives.
Sootblowers	Dec-06	NETL	NETL	Big Bend Power Station Neural Network Intelligent Sootblower Optimization	A factsheet describing the development of an intelligent sootblower at the Tampa Electric Big Bend Unit #2.

Project Category	Publication Date	Source	Author	Title	Brief Description
Sootblowers	Apr-05	B&W	S. Piboontum	Boiler Performance Improvement Due to Intelligent Sootblowing Utilizing Real-Time Boiler Modeling on UP Boilers	A research Paper covering intelligent sootblowing on supercritical boilers.
Sootblowers	May-06	B&W	S. Swift	Boiler Performance Improvement Due to Intelligent Sootblowing Utilizing Real-Time Boiler Modeling on UP Boilers	A research Paper covering intelligent sootblowing on tangentially-fired boilers.
Sootblowers	2006	Lehigh University	Sarunac, Nenad	Sootblowing Optimization: Field Experience	The Lehigh University Energy Research Center (ERC) has developed a practical, knowledge-based approach to sootblowing optimization and has implemented it in the sootblowing optimization code called ***Intelli*CLEAN**. The ERC approach can deal with various optimization goals, such as: steam temperature control, opacity control, SCR inlet gas temperature control, thermal NOx reduction, and reduction of sootblower activation frequency. The approach, implementation at 500 and 400 MW tangentially-fired boilers, operating experience, and benefits to the plants are described here.
Sootblowers	2007	POWER magazine	Kirk Lupkes, A. Tofa McCormick, Pratt & Whitney MMI	Boiler Cleaning - Harness detonation waves to clean boiler tubes	Description of a detonation sootblower and its cost savings compared with traditional air and steam sootblowers and implications for efficiency.
Sootblowers	2005	NETL	Rockey, John	Big Bend Power Station Neural Intelligent Network Intelligent Sootblower Optimization DE-FC26-02NT41425	This is the same project as referenced above instead of the fact sheet here is a link to the final report.
Sootblowers	2004	Clyde Bergemann	Sandeep, Shah	Implementation of Intelligent Sootblowing	This paper presents a strategy to implement a comprehensive automatic control of soot blowing in power plant boilers.
Sootblowers	2007	Department of Energy	Department of Energy	Power Plant Optimization Demonstration Projects	A neural-network-driven computer system offers the potential to optimize sootblowing in coal plant boilers, reduce NOX emissions, improve heat rate and unit efficiency, and reduce particulate matter emissions.
Sootblowers	2006	EPRI	EPRI	Intelligent Sootblowing Demonstration at Texas Genco's W.A. Parish Plant Saves $30 Million Annually	Intelligent sootblowing (ISB) optimizes the cleaning of the walls and convection passes of fossil-fired power plants to maintain high heat transfer while keeping steam temperatures and pressures as constant as possible and minimizing erosion or corrosion of tubes.
Sootblowers	2006	EPRI	EPRI	Neural Network Optimizes Soot Blowing at Tampa Electric Company 445 MW Big Bend Station Unit 2 Wet	Neural Network Optimizes Soot Blowing at Tampa Electric Company 445 MW Big Bend Station Unit 2 Wet Bottom, Pressurized Turbo-Fired Boiler.

Project Category	Publication Date	Source	Author	Title	Brief Description
				Bottom, Pressurized Turbo-Fired Boiler	
Sootblowers	2006	EPRI	EPRI	Intelligent Sootblowing at 900 MW TVA Bull Run Plant Optimizes Plant Operation by Reducing Variations in Boiler Effluent Mass Flows Resulting from Sootblowing	Intelligent Sootblowing at 900 MW TVA Bull Run Plant Optimizes Plant Operation by Reducing Variations in Boiler Effluent Mass Flows Resulting from Sootblowing.
Steam turbine	2007	Endrizzi, Jeff	Big Stone Power Plant	Big Stone Power Plant Efficiency Improvements	Efficiency Improvements due to new turbines and fuel switching.
Steam turbine	2006	Power magazine	Peltire, Robert	Steam Turbine Upgrading: Low Hanging Fruit	The thermodynamic performance of the steam turbine, more than any other plant component, determines overall plant efficiency. Upgrading steam path components and using computerized design tools and manufacturing techniques to minimize internal leaks are two ways to give your tired steam turbine a new lease on life.
Steam turbine	2007	Sargent&Lundy	Furleger, Jurek	Older Turbine-Generators Maintaining Modernizing Purchasing New Units	Presentation from an Aug 13, 2007 EPRI Workshop, lists symptoms and solutions for steam turbines and discusses reblading.
Steam turbine	Jul-07	POWER Vol: 151 Issue: 7	Hopson, Warren	Finding and fixing leakage within combined HP-IP steam turbines: Part I	Abstract: By design, combined HP-IP turbines have a small amount of internal leakage from the high-pressure turbine to the intermediate-pressure turbine. When turbines are new, the amount of this leakage is close to the design heat balance. But as turbines age, the leakage increases considerably, causing a heat rate penalty and possibly a reliability problem. In Part 1, we explore the symptoms and causes of excessive leakage within GE steam turbines and how to correct the problem. Part 11, in next month's issue, will examine the same issues for Westinghouse and Allis-Chalmers turbines.
Steam turbine	Aug-07	POWER Vol: 151 Issue: 8	Hopson, Warren	Finding and fixing leakage within combined HP-IP steam turbines: Part II	Abstract: By design, combined HP-IP turbines have a small amount of internal leakage from the high-pressure turbine to the intermediate-pressure turbine. As turbines age, the leakage increases considerably and becomes excessive, creating a heat rate penalty and possibly a reliability problem. Last month we explored the symptoms and causes of steam leakage within GE steam turbines and how to correct the problem. In Part 11, we examine the same issues for Westinghouse and

Project Category	Publication Date	Source	Author	Title	Brief Description
					Allis-Chalmers turbines from both theoretical and practical angles.
Steam turbine	2006	Turbomachinery International	Hestermann, Rolf	Revamping coal-fired plants	Since the 1980s, steam turbine retrofitting has proven to be a reliable and cost-effective measure to enhance the performance and reliability of power plants. The scope may vary from a single cylinder retrofit up to the retrofit of a complete shaft line, comprising all cylinders.
Steam turbine	2006	EPRI	EPRI	HP/IP Steam Turbine Upgrades at Labadie Units 1 and 2	Ameren upgrades its HP/IP steam turbines at Labadie Units 1 and 2, changing from a reaction to an impulse design, and from partial arc to full arc admission, resulting in 27 MW unit increase. Units 3 and 4 were subsequently upgraded with new HP /IP and new LP turbines giving a 56 MW unit increase.

Notes and references

[1] Data source: Ventyx's Energy Velocity Suite. Unit-level statistics query joined with electricity generation query using 2007 data. Data was truncated for units online after 2000 since the small number of units per year did not create a statistically significant sample.

[2] Projection was developed using NETL's CARBEN tool based on input data from the EIA's AEO'08

[3] National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Power Plants study, Volume 1: Bituminous Coal and Natural Gas to Electricity" Report DOE/NETL-2007/1281, May 2007.
http://www.netl.doe.gov/energy-analyses/pubs/Bituminous%20Baseline_Final%20Report.pdf

[4] Edison Electric Institute, "What You Should Know About Electric Companies and New Source Review", July 2002
http://www.eei.org/industry_issues/environment/air/New_Source_Review/NSR_talking_points.pdf

[5] List, John A.; Millimet, Daniel L.; and McHone, Warren (2004) "The Unintended Disincentive in the Clean Air Act," *Advances in Economic Analysis & Policy*: Vol. 4 : Iss. 2, Article 2.
http://www.bepress.com/bejeap/advances/vol4/iss2/art2

[6] Duke Energy, "Statement from Duke Energy Chief Legal Officer Regarding 'New Source Review' Case Before U.S. Supreme Court" Press Release Nov. 1 2006
http://www.duke-energy.com/news/releases/2006/Nov/2006110101.asp

[7] Environmental Protection Agency, "New Source Review: Report to the President" June 2002.
http://www.epa.gov/NSR/documents/nsr_report_to_president.pdf

[8] *Wisconsin Electric Power Co. v. Reilly*, AD. EPA, 893 F.2d 901 (7th Cir. 1990).

[9] 63 Fed. Reg. 39,860 (1998)

[10] Letter from Francis X. Lyons, Regional Administrator, EPA, to Henry Nickel, Counsel for the Detroit Edison Company, May 23, 2000
http://www.epa.gov/ttn/nsr/gen/letterf3.pdf

[11] *New York v. EPA*, No. 03-1380 (D.C. Cir. 2006).

[12] *Environmental Defense v. Duke Energy Corp.*, No. 05-848 (Apr. 2, 2007)
http://www.supremecourtus.gov/opinions/06pdf/05-848.pdf

[13] Table developed from literature review of actual efficiency improvement projects as listed in Appendix B.

[14] Given that efficiency improvement metrics contained in the reference documents ranged from percentage point increases in boiler efficiency to absolute decreases in net plant heat rate, it was necessary to apply a data conversion methodology in order to tabulate all of the data using the same metric (i.e., percentage point increase in overall plant efficiency). The development of the conversion methodology required the assumption of individual component efficiencies for a reference plant as follows: 87 percent boiler efficiency, 40 percent turbine efficiency, 98 percent generator efficiency, and 6 percent auxiliary load. Based on these assumptions, the reference power plant has an overall efficiency of 32 percent and a net heat rate of 10,600 Btu/kWh. As a result, if a particular efficiency improvement method was reported to achieve a one percentage point increase in boiler efficiency, it would be converted to a 0.37 percentage point increase in overall efficiency. Likewise, a reported 100 Btu/kWh decrease in net heat rate would be converted to a 0.30 percentage point increase in overall efficiency.

[15] Global Energy Decisions, "Putting Competitive Power Markets to the Test
The Benefits of Competition in America's Electric Grid: Cost Savings and Operating Efficiencies" July 2005
http://www.globalenergy.com/competitivepower/competitivepower.pdf

[16] Blankinship, S. "So You Want to Build a Power Plant", Power Engineering, September 2007.

[17] Roberts, B.F. (Economic Sciences Corporation) and Goudarzi, L. (OnLocation, Inc.); "Efficient Heat Rate Benchmarks for Coal-Fired Generating Units" Power Market Analysis Working Paper 98-1
http://www.econsci.com/euar9801.html

[18] APEC Energy Working Group, Expert Group on Clean Fossil Energy, "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/Documents/Costs%26EffectivenessofUpgradingOlderCoal-FiredPowerPlantsFina.pdf

[19] Wisconsin Electric Power Company, Wisconsin Electric Power Company Climate Challenge Participation Accord", May 1996
http://www.climatevision.gov/climate_challenge/cc_accordxWISCEL.htm

[20] Data source: Ventyx Energy Velocity Suite. 2007 data. Plants with a capacity factor less than 50% were excluded from the analysis

[21] Data developed using NETL's CARBEN tool available at http://www.netl.doe.gov/energy-analyses/benefit.html. To calculate the emissions reduction scenario, "constant power" was selected in the efficiency gains cell in the "ER Electricity" tab, while "constant coal" was selected to determine the extra electricity generated at the baseline emissions levels after efficiency improvements.

[22] National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Power Plants study, Volume 1: Bituminous Coal and Natural Gas to Electricity" Report DOE/NETL-2007/1281, May 2007.
http://www.netl.doe.gov/energy-analyses/pubs/Bituminous%20Baseline_Final%20Report.pdf

[23] Plant elevations were determined by overlaying plant locations obtained from Global Energy Decision's Velocity Suite with a Digital Elevation Model (DEM) from ESRI. Elevations were then spot checked for a number of plants with topographic maps – typical accuracy was around 5%.
http://www.esri.com/data/index.html
http://www.globalenergy.com/products-vs-overview.asp

[24] Average maximum summer temperatures were determined by overlaying plant locations obtained from Global Energy Decision's Velocity Suite with a digital average maximum summer temperature map from the National Oceanographic and Atmospheric Administration. The average maximum summer temperature is the high daily average for the summer months averagedover the 1961 to 1990 time period.
http://www.ncdc.noaa.gov/oa/mpp/index.html

[25] Analysis of Energy Information Administration's (EIA) Form EIA-767, "Steam-Electric Plant Operation and Design Report" data and Energy Velocity's (EV) database. Data were joined based on the "Government ID" field. Cooling system characteristics from EIA were compared with efficiency data from EV.
http://www.eia.doe.gov/cneaf/electricity/page/eia767.html

[26] Power, Steam Turbine Upgrading: Low-Hanging Fruit, Vol. 150, No. 3, April 2006