Evaluation of Heat Rates of Coal Fired Electric Power Boilers

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ABSTRACT

Improvements in heat rate will reduce CO_2 emissions per unit output. The authors undertook a study to examine the factors that influence heat rates on existing coal fired power plant boilers. To this end, publicly available data of all operating power plants (US EPA's National Electric Energy Data System and EPA Title IV data) was analyzed for important trends. The data included historical heat rates and facility characteristics, to include fuel type, combustion system, unit size, steam cycle, operating data, and other characteristics that are collected by EPA and also by the Energy Information Administration (EIA). In this study a number of important factors that influence heat rate were isolated. This study also identified areas of uncertainty and important pieces of information that are missing from the publicly available data that, if available, would shed more light on the potential to improve heat rates on existing units.

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INTRODUCTION

Improvements to heat rate are one means to reduce the emissions of carbon dioxide (CO_2) from coal-fired power plants. Heat rate is the amount of heat input from fuel per unit of net power output. Because heat rate is the inverse of efficiency, a lower heat rate signifies a more efficient electric generating unit. Methods to improve (lower) a unit's heat rate generally fall into three categories:

- Improvements in boiler efficiency – increasing the efficiency of the boiler in converting the chemical energy in the fuel to energy stored in the form of high pressure steam;
- Improvements to steam cycle efficiency – increasing the efficiency of the steam plant in converting the energy stored in high pressure steam to power that drives an electric generator; and[1]
- Reductions in parasitic loads – reducing facility electric loads used to support the plant, which diminish the net electrical output of the power plant.[2]

In this study, rather than explore the specific approaches that might be used within these three general categories, we have examined unit specific data and trends regarding heat rates to determine which plant characteristics appear most influential on heat rate.

METHODOLOGY

Two databases of net heat rates were used, US EPA's National Electric Energy Database System (NEEDS) version 4.10 and NEEDS version 5.13. Needs version 5.13 is a more recent version of NEEDS than version 4.10. The NEEDS database includes data that describes the combustion system, the equipment installed at the facility for pollution control, the coal types, etc. NEEDS heat rate data is developed from the Energy Information Administration's (EIA's) Annual Energy Outlook (AEO). The heat rate data from NEEDS v5.13 is developed from the 2012 AEO while NEEDS v 4.10 used heat rate data from AEO 2008. . The AEO has heat rate data on a unit-by-unit basis. AEO 2012 used reported data from years 2008 through 2010 and it is expected that AEO 2008 used information from 2004-2006.[3] Table 1 summarizes the data sets used and what they were used for.

In addition to NEEDS versions 4.10 and 5.13, the analysis relies on EPA's Air Markets Program Data (AMPD) to determine estimates of capacity factor for the six years where fuel and generation data was used to develop heat rates. Capacity factor was determined by comparing the reported heat input against the rated hourly heat input times 8760 hours per year.[4] Capacity

[1] Electric generators tend to be very efficient at converting the power from the turbine to electrical energy. So, there is little opportunity at improving heat rate by improving the electric generator efficiency.
[2] These loads account for the difference between net and gross output, and net and gross heat rate.
[3] Email from Jeffrey Jones, EIA 4/22/14
[4] An alternative approach would be to compare the total output of the generator to the rated hourly generator output times 8760 hours per year. These should yield similar, if slightly lower, results. Notably, the AMPD

factors for coal units were expected to have dropped between the two periods, and as will be shown, the data generally confirmed that trend.

All heat rate data presented in this paper is net heat rate, not gross heat rate, unless specified otherwise.

Table 1. Data Sources Relevant to Analysis

Data	Database Version Used	Relevant Version of AEO	Relevant Years of Annual Data
Unit heat rate	NEEDS v 4.10	AEO 2008	2004 – 2006
	NEEDS v 5.13	AEO 2012	2008 – 2010
Unit capacity Factor	EPA AMPD		2004 – 2006 and 2008 - 2010

Segregation of the data

The data was also segregated to examine the effects of

- Unit capacity
- Combustion system (e.g., circulating fluidized bed (CFB) versus pulverized coal (PC));
- Fuel type; and
- Supercritical versus Subcritical steam cycle

The following units were not included in this analysis:

- Coal units smaller than 25 MW in size
- Stoker units, and
- Cogeneration units (because heat rate data may be unrepresentative when compared to power plants)

The NEEDS database lists fuels by Bituminous, Subbituminous, Lignite, Waste Coal, Petroleum Coke, and blends of bituminous and subbituminous and blends of lignite and subbituminous. For the purpose of simplicity for this analysis, blends were included in the category of the higher rank fuel, so that a) bituminous and subbituminous blends were treated as bituminous, and b) subbituminous and lignite blends were treated as subbituminous. This grouping of blended units affected 287 of 779 units in NEEDS v5.13, with 257 listed as bituminous/subbituminous (most were originally built to burn bituminous fuel and commenced blending some amount of subbituminous to reduce SO_2 emissions) and 30 listed as lignite/subbituminous (many having started burning subbituminous for SO_2 and other

data can also be used to develop estimates of gross heat rate, which will differ from net heat rate due to the effect of parasitic loads which are estimated in developing the unit net heat rates in the AEO.

reasons). Another simplification made for this analysis was the treatment of cyclone-fired boilers as pulverized coal.

The NEEDS database does not show whether or not the boiler has a supercritical or subcritical steam cycle. This data was also developed and used to segregate the pulverized coal units by steam cycle.

Factors Considered, and Previous Work by Others

Due to data limitations, it was not possible to examine every factor that may impact heat rate; however, the available data allowed for examination of some of the more critical factors that may play a role in affecting heat rate. Initially, we examined what others had determined.

A number of documents involving the potential for heat rate improvements were reviewed. In 2008, NETL did a study of key factors affecting heat rate as well as possible means to improve it. In 2010, NETL performed another analysis that broke the fleet into deciles, from top performers to bottom performers and also evaluated the effect of supercritical versus subcritical boilers and steam pressure. In that study, there were 112 supercritical boilers (about 10% of the total number of coal-fired electric generating units), but they averaged about 750 MW in size. As expected, the supercritical boilers averaged a lower heat rate than the subcritical boilers. In 2013, NRDC analyzed boiler heat rates and applied a modeling methodology that grouped the supercritical and subcritical boilers separately and divided each group into deciles from best performing to worst. It was assumed that the worst units (deciles five through ten) could achieve a heat rate improvement of 600 Btu/kWh and deciles one through four something less than that.

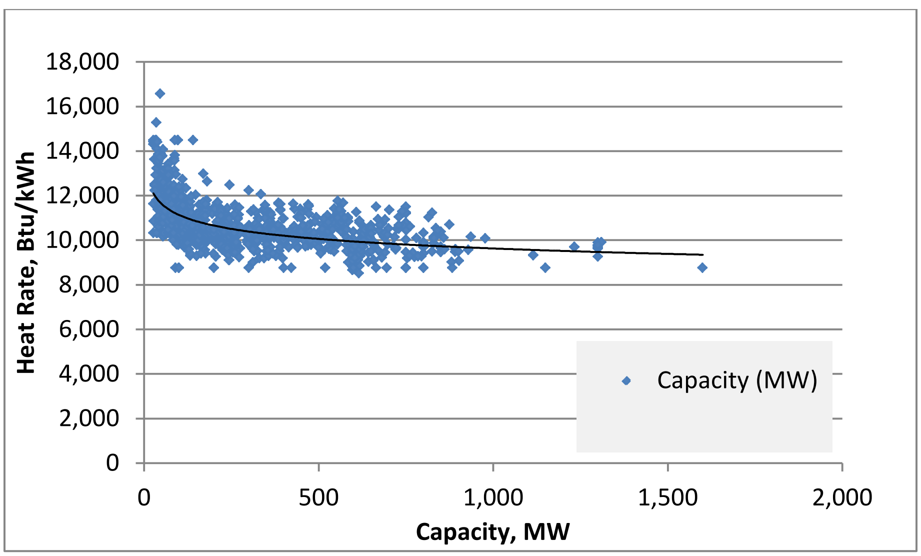
The 2010 NETL study found that, contrary to what one would expect, the addition of environmental controls did not appear to have a significant effect on heat rate. This may be because companies tend to invest in their best units. The 2008 NETL study also concluded that factors such as elevation, temperature and cooling system did not appear to have large affects either. This is not to say that these are not important in a specific situation, but the effects of these factors were not apparently significant in light of the variability of the data that is driven by a range of factors. NETL's 2010 study did show that both capacity and steam cycle (both discussed more later) have a significant effect on efficiency.

The approaches used by NRDC and NETL acknowledge that there are some facilities that are not likely to be able to improve their heat rate very much while others may present better opportunities for heat rate improvement. They also acknowledge that supercritical and subcritical facilities are not capable of the same heat rate – more on this later. Review of these previous approaches helped to identify some areas worthy of further exploration, including the following.

1. **Pollution controls.** We investigate the impact of environmental control equipment that increase parasitic loads, such as scrubbers.

2. **Boiler capacity.** Boiler capacity has a large impact on heat rate because certain parasitic losses do not increase in proportion to size and smaller boilers are more likely to have lower pressure (thus, less efficient) steam cycles. In 2010 NETL examined this effect especially with regard to steam pressure for small units. Not As a result, larger boilers have inherently lower heat rates than smaller boilers. Figure 1 shows a plot developed in this effort from data in NEEDS v4.10 of boiler heat rate versus capacity for all pulverized coal or cyclone boilers. As shown, heat rate is highest for small boilers and lowest for large boilers, and this is worth examining further.
3. **Facility age.**[5] Even within a cycle type (i.e., supercritical versus subcritical), there have been advances in boiler plant design over the decades. One such effect is with respect to steam cycle, with older low pressure (LP) subcritical units and newer high pressure (HP) subcritical units. This may also be captured to a degree in the facility capacity since the oldest facilities tend to be smaller. Other advances include more efficient fans and auxiliary equipment. Also, as will be demonstrated, the vintage of the boiler results in some unexpected results when comparing supercritical and subcritical units.
4. **Capacity factor.** Boilers designed for base load are expected to have an inherently higher heat rate if they are operated at a much lower capacity factor than they are designed for, and many coal boilers are being operated well below their originally intended capacity factors. The effect of capacity factor is explored in this paper.
5. **Other site-specific factors**. There are also other factors that are site specific that will impact the ability to improve heat rate (for example, slagging tendency of coal), but these are not captured in the available database and, therefore, cannot be used to guide us.

Figure 1. Heat Rate versus Unit Capacity (NEEDS v4.10)

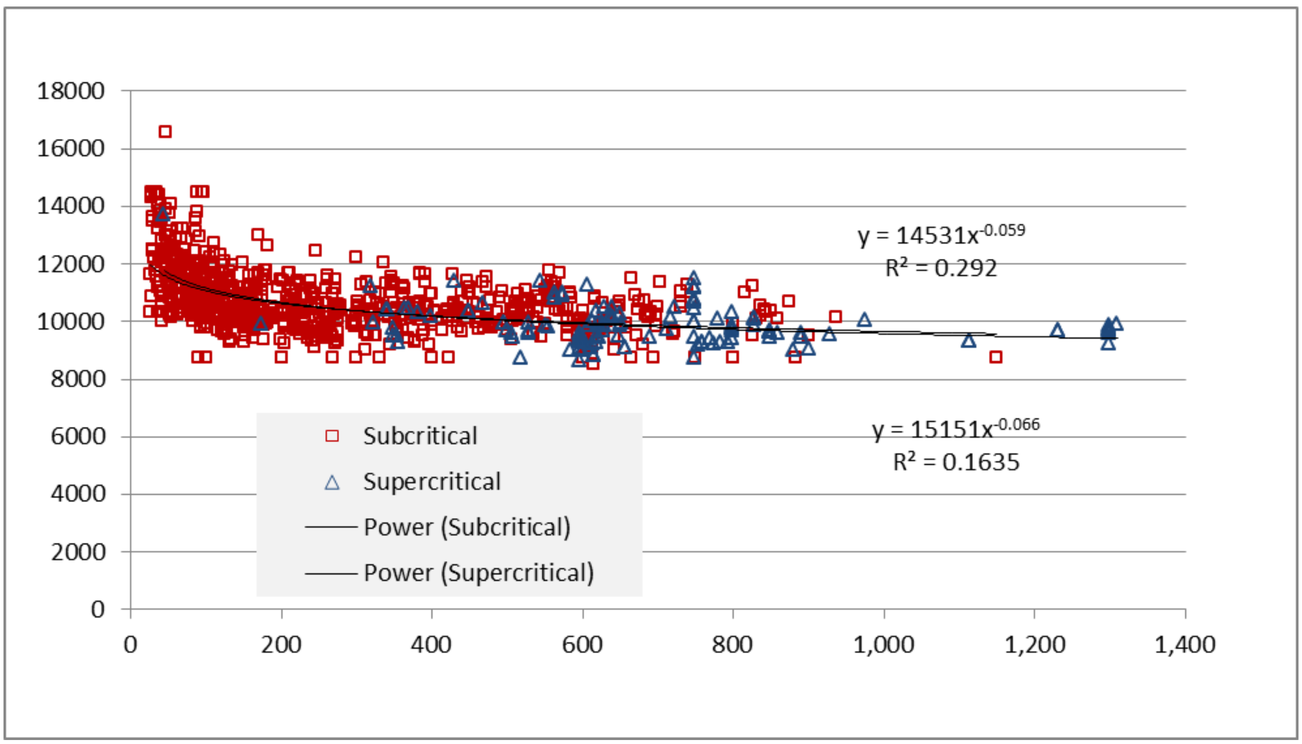


[5] Although the memo ICF International prepared for NRDC says that they looked at facility age, as confirmed by discussions with ICF, the approach they adopted did not appear to make any distinction based upon facility age, but did for fuel type and steam cycle.

Subcritical versus Supercritical and HP versus LP Subcritical

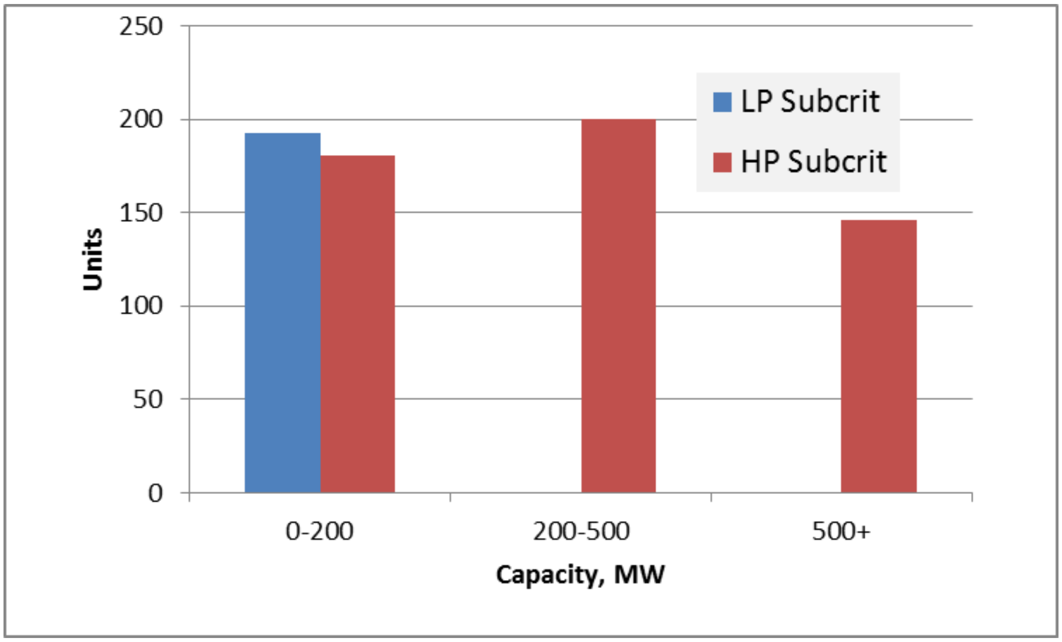
Some of the prior work compared subcritical versus supercritical heat rates while comparing the total population of boilers without looking at the impact of capacity. As background, NEEDS v4.10 lists 120 odd supercritical units that are mostly very large units – less than 15% of the total boiler units. The balance of the boiler population is comprised of subcritical units, many well under 200 MW. Figure 2 is a plot of subcritical unit heat rates as a function of capacity and a plot of supercritical unit heat rates as a function of capacity. As shown the supercritical heat rates fall within the range of data for subcritical unit heat rates. The trend lines are almost indistinguishable. Although the median heat rate at any given capacity is somewhat higher for subcritical units, the lowest heat rate units are subcritical. So, when examining the entire population using the NEEDS data, it appears that other factors can play a greater role than steam cycle in impacting heat rate. This is not to say that a supercritical unit should not have a lower heat rate than a subcritical unit if all other things were equal (on average, for any given capacity they do), but the NEEDS v4.10 (and the NEEDS v5.13) data appears to suggest that all other things are not equal.

Figure 2. Plot of heat rate versus capacity for Subcritical and Supercritical boilers (NEEDS v4.10)



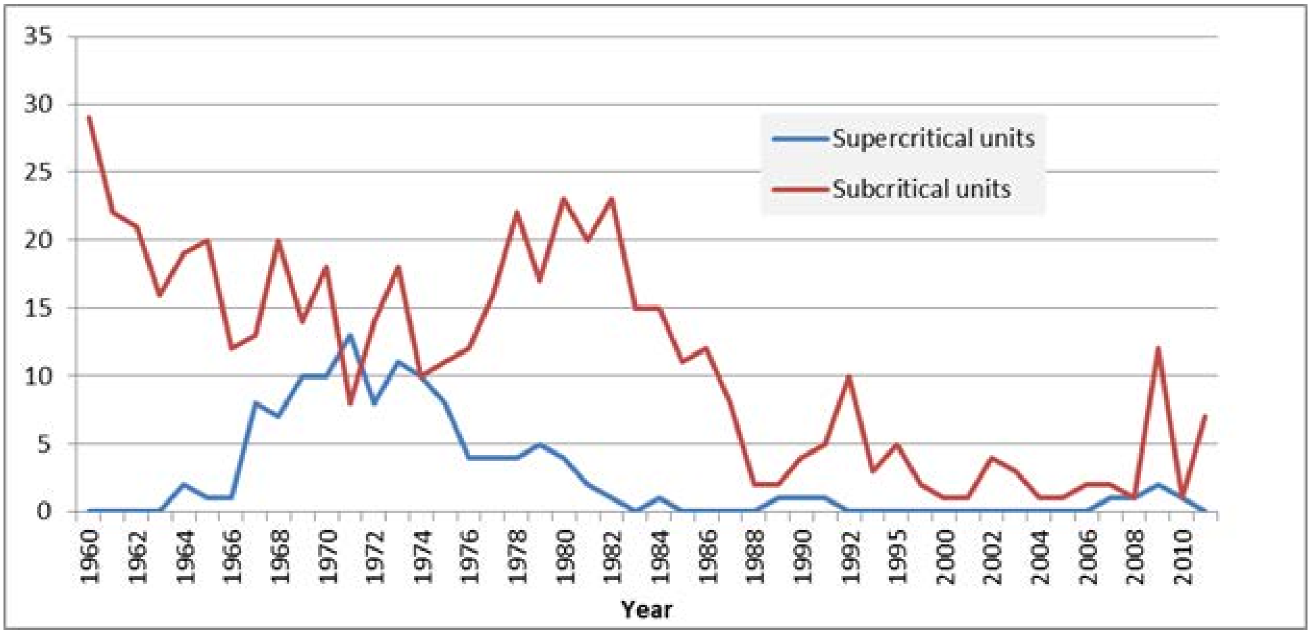
It is also apparent from Figure 2 that when you leave out the effect of capacity, on average, subcritical heat rates are in fact significantly higher than supercritical heat rates, which is consistent with previous studies. This is because all of the small, inefficient, subcritical units get averaged in while there are virtually no small, inefficient supercritical units. The 2010 NETL study showed that low pressure (600-1600 psig) steam cycles are concentrated in the under 200 MW plants. High pressure subcritical steam cycles (1800-2600 psig) were used across the full range of sizes and all units greater than 200 MW used high pressure steam cycles. Figure 3 shows data taken from that report and represented graphically.

Figure 3. Frequency of subcritical steam cycle versus capacity (data from NETL 2010)



In principal, a supercritical unit should be more efficient than a subcritical unit – all other things being equal. Figure 4, a plot of the number of supercritical and subcritical boilers that commenced service in a given year, may help explain why supercritical units in practice are not always the *most* efficient ones out there. As shown in this plot, supercritical units were very popular in the period around 1970, but they fell out of favor in the late 1970's and very few were built in the 1980's and 1990's. In fact, around 1976-1978 you can see a big drop off in supercritical boilers and a big pick up in subcritical boilers. This is mainly because the supercritical units were very expensive, they also were more expensive to maintain and operate, and they have less operational flexibility. As a result, most of the more recently built plants are subcritical and they are built with more up to date technology throughout the plant than the older supercritical units. This suggests that there may be opportunities to improve the supercritical units further.

Figure 4. Plot of Supercritical and Subcritical installations (units) by year in service (NEEDS v4.10)



The Effects of Age and Fuel

As will be shown, age plays a role, but it is also very closely tied to capacity. To remove the role of capacity, Figure 5 shows a plot of heat rate versus year in service for three groups of boilers over 500 MW – supercritical units, bituminous subcritical units and subbituminous subcritical units.[6] Although there are a few units of 2010 vintage that appear to have low heat rates (there are also some with higher heat rates), most of the rest of the data is very scattered, with weak trends that are in the direction expected – somewhat lower heat rates for newer units. The subbituminous units include many older boilers in the Midwest that were originally built for Illinois Basin coal but now use Powder River Basin (PRB) coal, and are not as efficient as those newer units built for PRB. For supercritical units, the trend toward lower heat rate for newer units is weakest. Figure 6 shows the average heat rate versus average year in service for supercritical units larger than 500 MW, subcritical subbituminous units larger than 500 MW and bituminous units larger than 500 MW (the averages of the data in Figure 5). This demonstrates that when narrowing down to units larger than 500 MW, the supercritical units, *on average*, have

[6] For this analysis where bituminous and subbituminous are shown as a blend, we assumed bituminous, because these boilers were originally designed to burn bituminous and generally burn mostly bituminous fuel with a small amount of PRB to reduce SO_2 emissions. When both lignite and subbituminous are shown, the unit was treated as lignite.

lower heat rates, even though they are, *on average*, older in age. Similarly, as expected, bituminous units over 500 MW, *on average*, have lower heat rates although, *on average*, they are older than subbituminous units over 500 MW. But, what is also important is that the most efficient unit is a subcritical bituminous unit built in the 1980s although on average supercritical units are more efficient. This is true whether using the NEEDS v4.10 or NEEDS v5.13 database.

Examining the effects of age and size, Figure 7 shows a scatter plot of heat rate versus year in service for four groups organized by capacity: in 1) up to 99 MW; 2) 100-199 MW; 3) 200-499 MW; and 4) ≥ 500 MW. Except possibly for Group 1 (the smallest boilers) year in service has almost no effect on the heat rate within the group. The scatter plot shows a general trend from the upper left to the lower right as you go from group 1 to group 4. Figure 8 shows the average year and average heat rate for the data points in Figure 7. This clearly shows a trend of decreasing heat rate and later year in service as the boiler sizes are increased. This should not be too surprising. Many of the under 100 MW units have low pressure subcritical steam cycles and are generally older.

Environmental Equipment

Flue gas desulfurization (FGD) systems, also known as scrubbers, and other environmental equipment add parasitic load. So, one would expect that scrubbed units would be less efficient than un-scrubbed units. NETL previously found no discernible difference in heat rate as a result of environmental equipment. Figure 9 shows heat rate versus capacity for scrubbed units by fuel. As you can see, except possibly for lignite, everything is in the same range. Lignite on average is higher heat rate, but if you look closely some of the lignite units are also among the lowest heat rates. Lignite units are also a very small part of the total boiler population.

Figure 10 shows a similar plot for un-scrubbed units. Again, heat rates are slightly higher for lignite – but these are only 5 units in total.

Figure 11 shows the heat rates of all scrubbed versus all un-scrubbed units. Ironically, the lowest HR units are scrubbed – this is probably because companies tend to scrub the best units rather than the worst. But, the difference between scrubbed versus unscrubbed was found to be small.

Figure 5. Heat Rate versus year in service for over 500 MW units. (NEEDS v4.10)

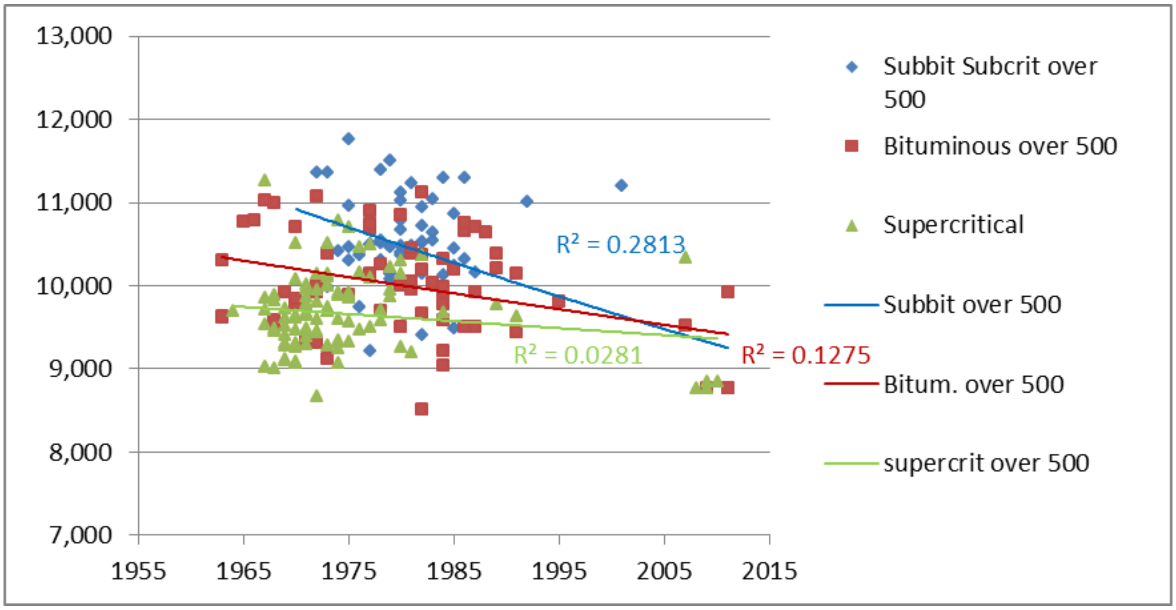


Figure 6. Average heat rate versus average year in service for over 500 MW units (NEEDS v4.10)

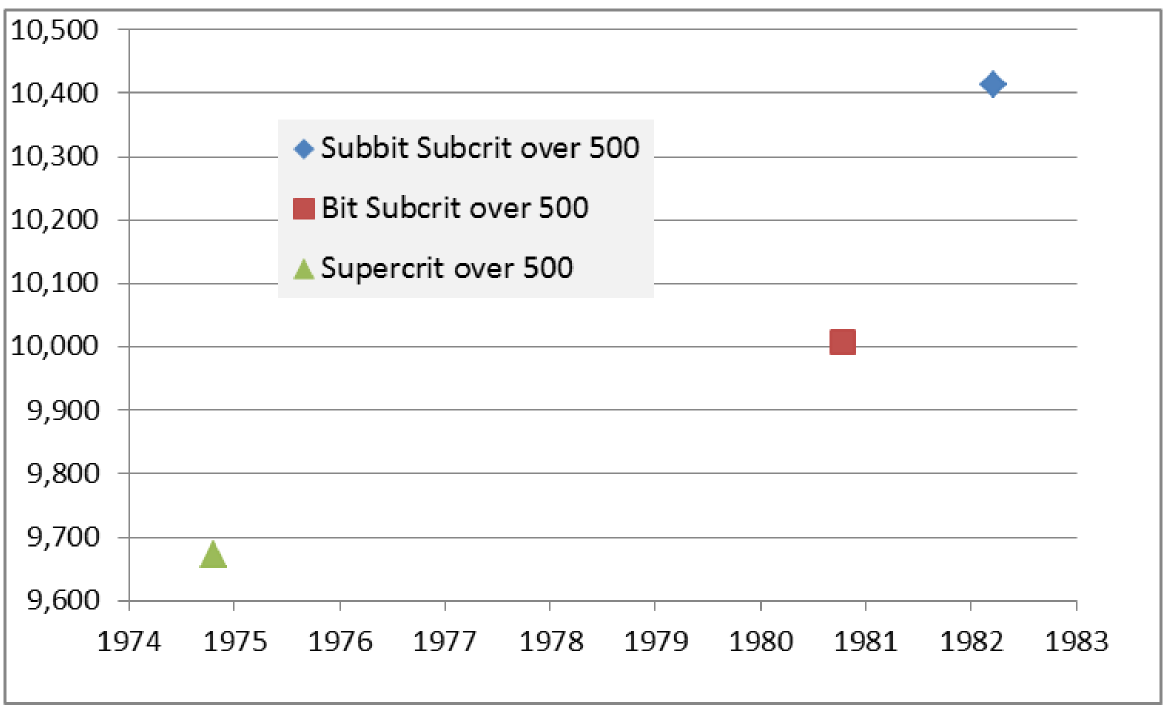


Figure 7. Heat rate versus year in service for units organized in four groups:
1) under 100 MW; 2) 100 to under 200 MW; 3) 200 to under 500 MW; and 4) 500 MW or greater.

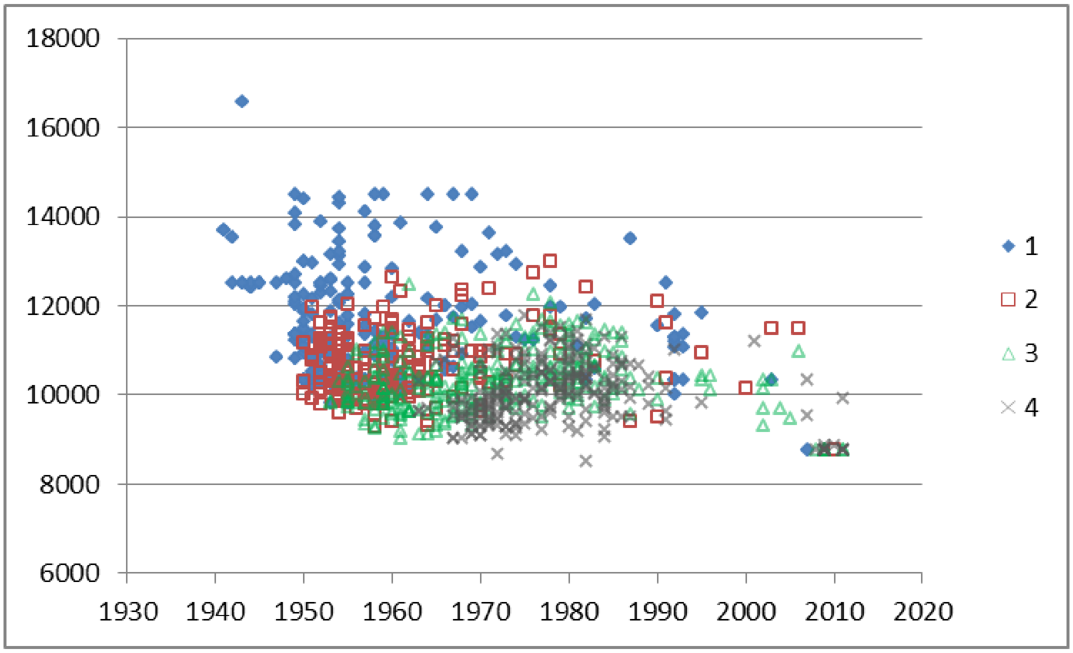


Figure 8. Average heat rate versus average year in service for groups in Figure 7
1) under 100 MW; 2) 100-under 200 MW; 3) 200 to under 500 MW; and 4) 500 MW or greater.

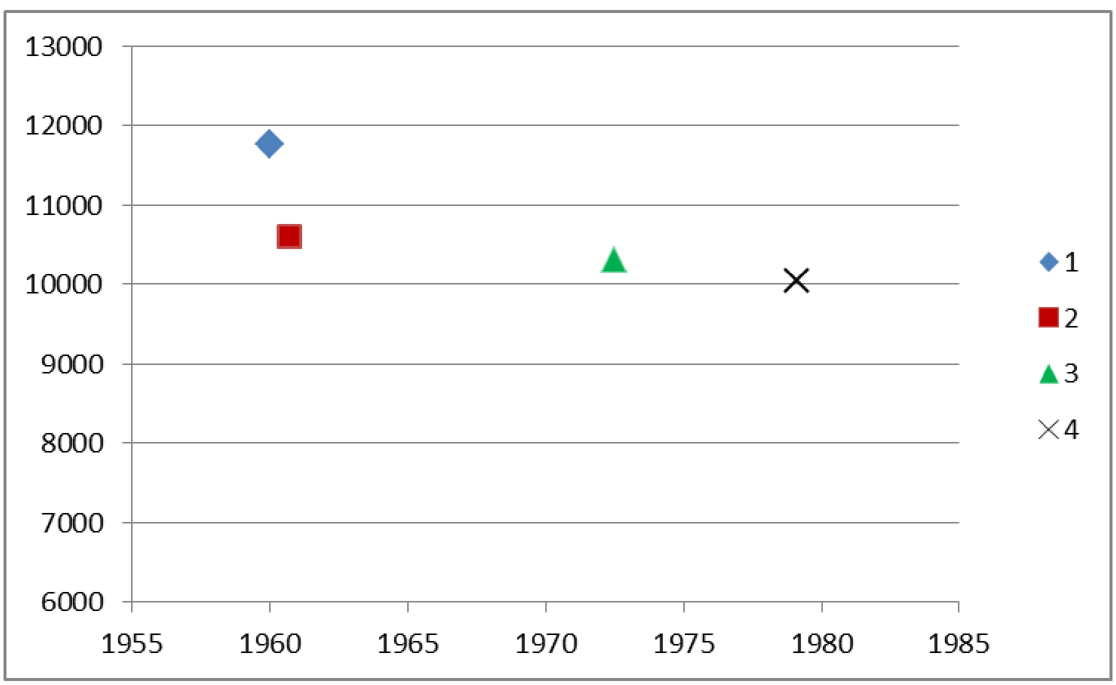


Figure 9. Heat Rate (Btu/kWh) versus Capacity (MW) for scrubbed units (NEEDS v4.10)

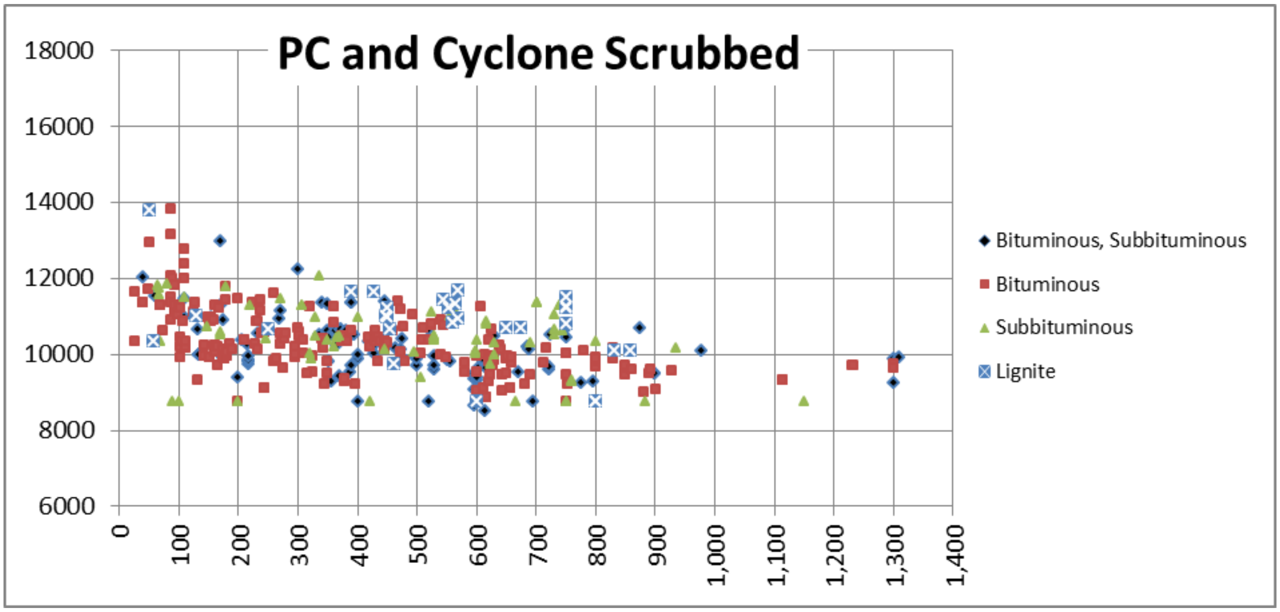


Figure 10. Heat Rate (Btu/kWh) versus Capacity (MW) for unscrubbed units

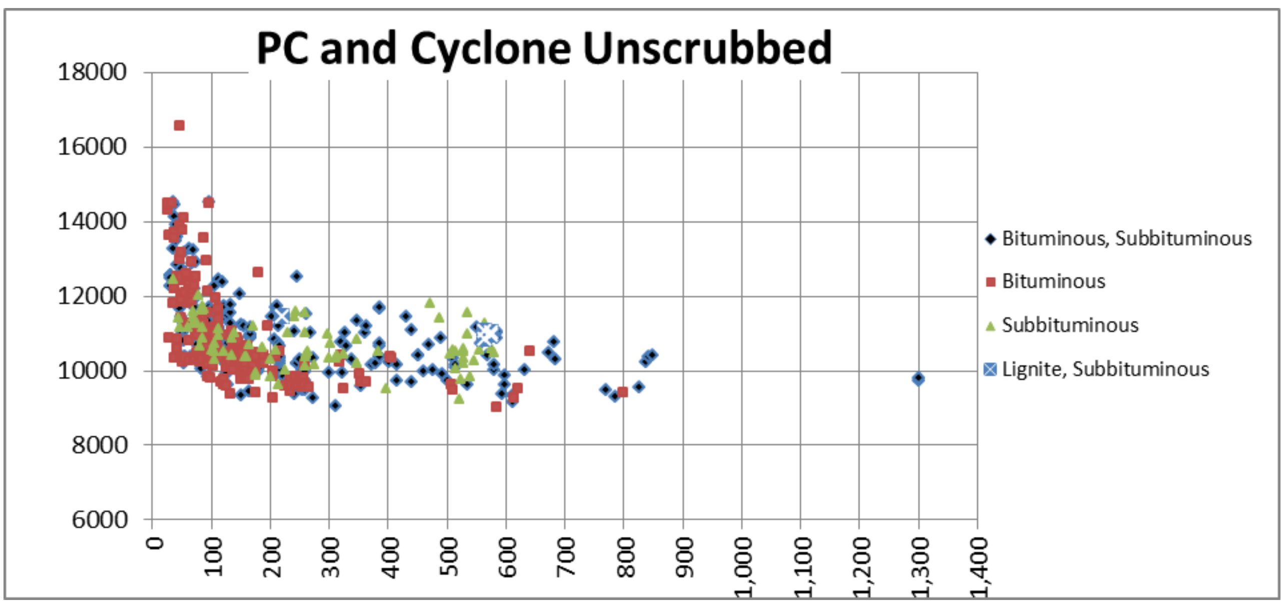
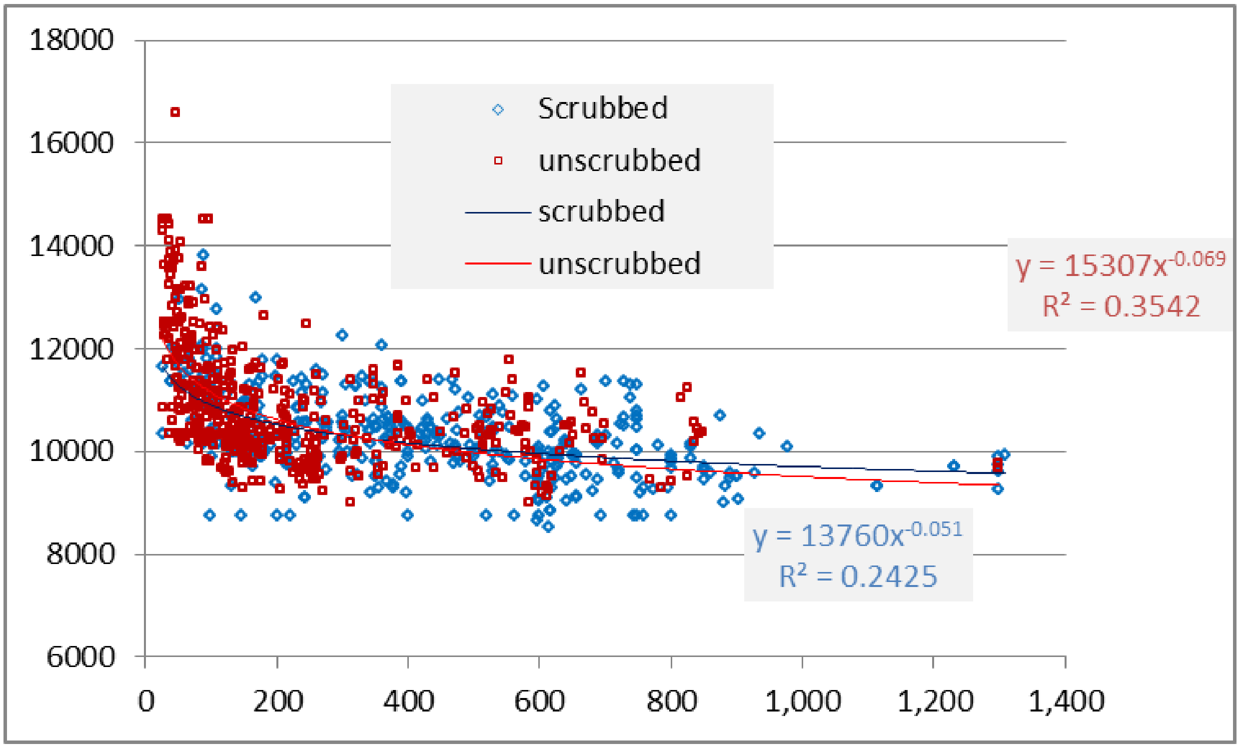


Figure 11. Heat Rate (Btu/kWh) versus Capacity (MW) – scrubbed versus un-scrubbed



The addition of a scrubber, however, does increase heat rate. Heat rate and capacity factor data were compared for units that were scrubbed in the NEEDS v5.13 database and un-scrubbed in the NEEDS v4.10 database. For units that installed wet scrubbers, the data is plotted in Figure 12, and for dry scrubbers the data is plotted in Figure 13. For wet scrubbers not all units showed an increase in heat rate between periods, but there is a slight correlation between the change in heat rate and the change in estimated capacity factor for these units, with negative changes in capacity factor resulting in heat rate increases. For units that added dry scrubbers, there was fairly consistently an increase in heat rate (if not a consistent amount of heat rate increase) that appeared to have no correlation with the change in capacity factor of these units.

The contrast in behavior for the effect of wet versus dry scrubber addition on heat rate *may* be explained by a change in fuel that is likely to occur for a unit adding a wet scrubber but is less likely to occur for a unit adding a dry scrubber. But, this is speculation and requires further examination of the data to gain more insight.

Figure 12. Change in Heat Rate versus Change in Capacity factor for units that added a wet FGD

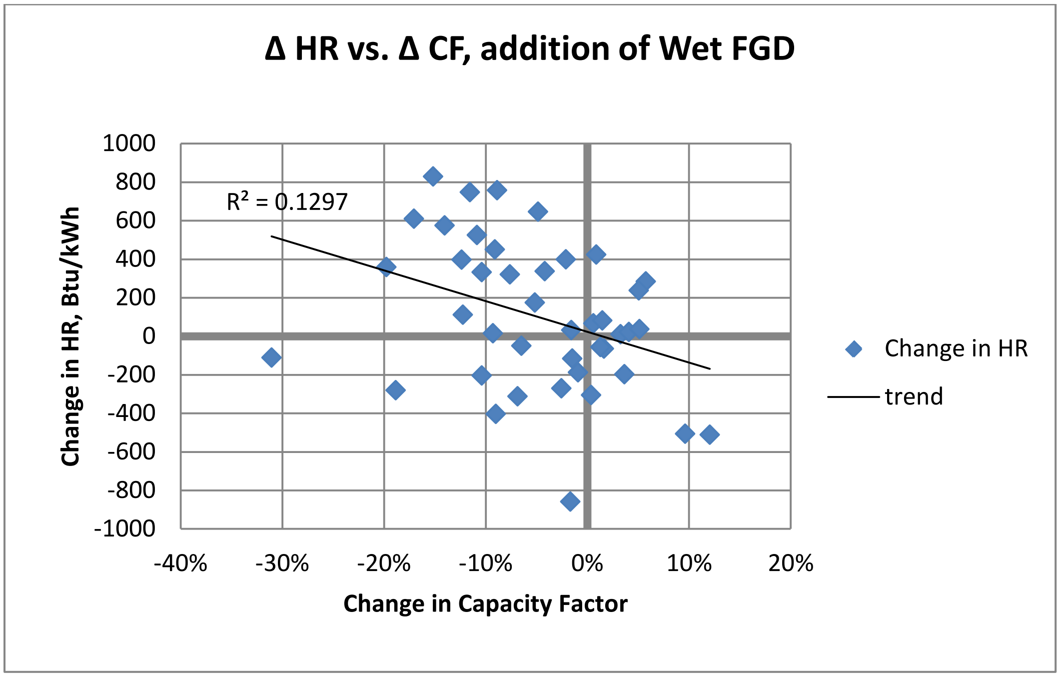
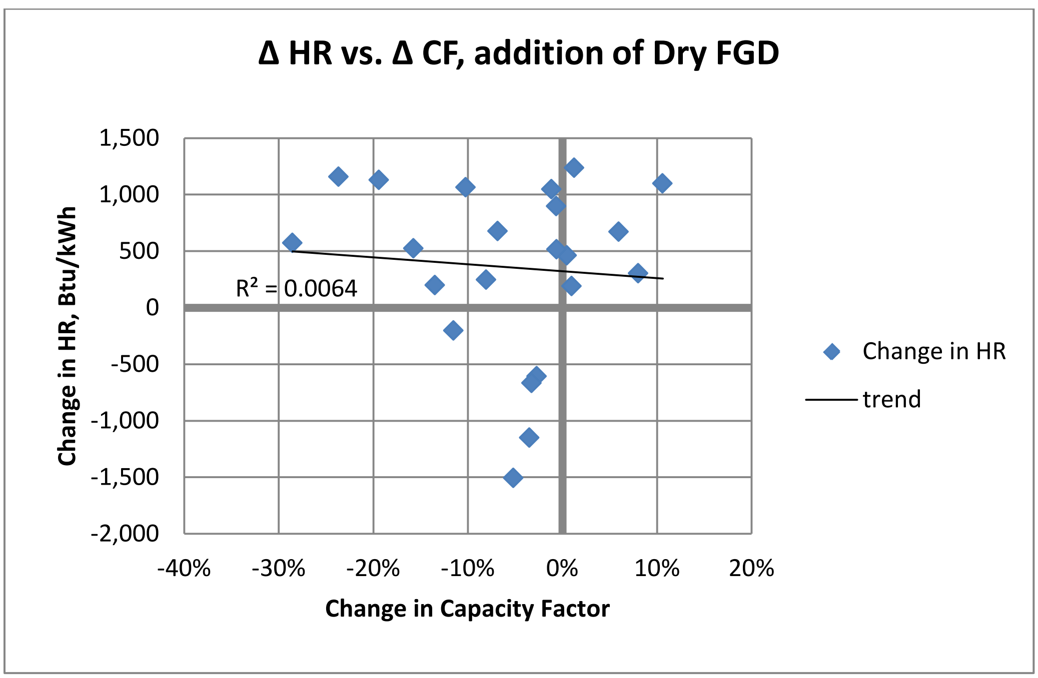


Figure 13. Change in Heat Rate versus Change in Capacity factor for units that added a dry FGD



Effect of Capacity Factor – all units

The change in heat rate was plotted versus the change in capacity factor for all units that were in both the NEEDS v5.13 and v 4.10 database, and this is shown in Figure 14. It was expected that an increase in capacity factor would result in a reduction in heat rate. As shown in Figure 14, there appears to be no trend regardless of fuel, which, when this figure was developed, was an unexpected result. Figure 15, which is from the Technology Support Document to EPA's recently proposed Existing Plant Performance Standard may help explain this. EPA looked at hourly data. As expected, capacity factor is shown in this figure to change over the course of the year, demonstrating a high correlation with the ambient temperature – especially during the summer months. Higher ambient temperatures have a well-known adverse impact on Rankine Cycle efficiency. As a result, ambient temperature may be a confounding effect that makes it difficult to extract a good relationship from the yearly data sets that we were working with. If a year had a hotter than usual summer, capacity factors would be high, but heat rate would also suffer from the high temperatures. The effects will also vary by location. In the south, where summers are very hot, but winters mild, high capacity factor periods will coincide with high heat rate periods. For locations where summers are typically mild but winters are much colder, the temperature effect will be different than in the south. *As a result, to examine the relationship between capacity factor and heat rate, it is necessary to take a different approach than used here.*

Figure 14. Change in HR versus Change in Capacity Factor – all units

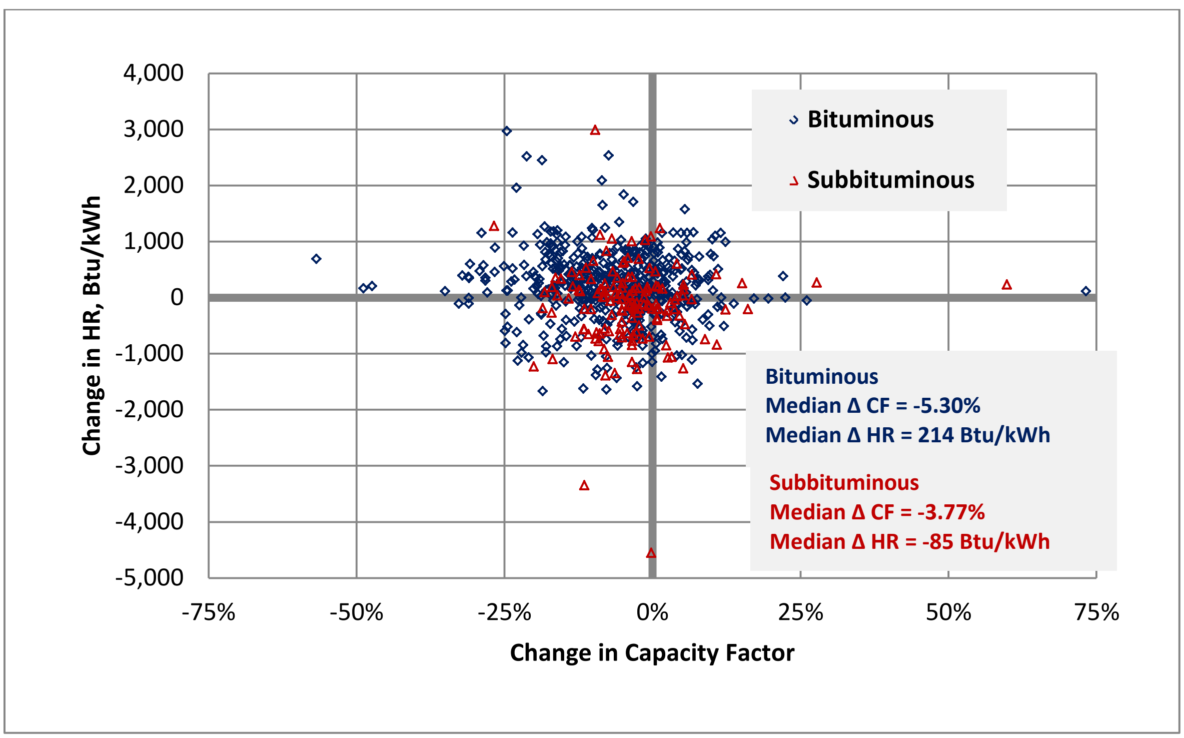
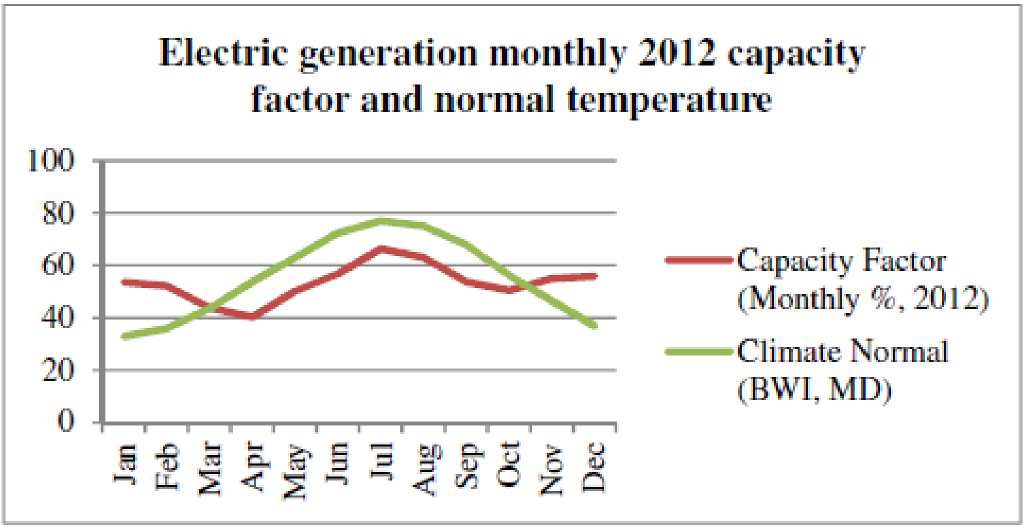


Figure 15. Average monthly capacity factor in 2012 and the normal monthly temperature [7]



[7] U.S. Environmental Protection Agency, Office of Air and Radiation, Technical Support Document (TSD) for Carbon Pollution Guidelines for Existing Power Plants: Emission Guidelines for Greenhouse Gas Emissions from Existing Stationary Sources: Electric Utility Generating Units, GHG Abatement Measures, June 2014. Page 2-24

SUMMARY OF KEY EFFECTS AND SUBCATEGORIES

It is clear that capacity plays a major role in the heat rate of boilers and needs to be factored into the analysis. The role of steam pressure on subcritical units likely has a significant role for the smaller units of 200 MW or less. Other effects to consider include fuel, steam cycle (subcritical versus supercritical) and combustion system (CFB versus PC), and these characteristics are used to form groupings. Tables 2a through 2d show the heat rates, change in heat rates, capacity factor, and change in capacity factor for subcategories grouped by fuel, steam cycle, capacity, firing system with the 30 subbituminous/lignite units grouped with subbituminous and Tables 3a through 3d are similar tables with the 30 subbituminous/lignite units grouped with lignite. Examining the data in this manner allows heat rate and capacity factor changes to be examined. Examining the data from the two periods it is apparent that:

- For the subcritical bituminous units, median and average heat rate increased for all capacity subcategories while capacity factor decreased.
- Capacity factor dropped across the board for nearly all subcategories over the two periods.
- Supercritical units have lower average and median heat rates than subcritical units of the same fuel and similar size; however, the lowest heat rate units were subcritical.
- For subcritical subbituminous units, median and average heat rate dropped for all capacity categories except 200-500 MW. Note that there are 30 units that are included in the subbituminous population that are listed as burning subbituminous and lignite in NEEDS v5.13. If these are moved to the lignite categories, the reduction in heat rate remains similar for these subbituminous groups.
- Due to the small number of units left in the lignite subcategories, there are some situations where mean and average are equal.
- For the most part, there was a large increase in CFB heat rates between the two periods. It is unclear why this occurred. Unfortunately, good capacity factor estimates could not be made for many of the CFBs due to data limitations.
- In general for subcritical bituminous units, smaller units have lower capacity factors, which is expected. For the subbituminous units, capacity factors appear to be less affected by facility size. This likely is due to these units tending to be physically located in different power markets.

Table 2a. Heat Rate (with 30 Sub/Lignite included in Subbituminous)

	Subcritical PC						Supercritical PC						CFB (all capacities and fuels)	
	Bituminous		Subbituminous		Lignite		Bituminous		Subbituminous		Lignite			
	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13
MW≤100, except CFB														
Average	11,776	12,105	11,746	11,434									10,689	12,326
Median	11,407	11,886	11,596	11,435									10,331	11,766
Min	9,792	10,212	10,331	9,945									8,763	10,948
Max	14,500	14,500	14,500	12,656									13,500	10,575
100<MW≤200														
Average	10,448	10,663	10,677	11,051										
Median	10,251	10,618	10,661	10,786										
Min	9,308	9,434	9,604	10,262										
Max	12,985	12,364	12,068	13,732										
200<MW≤500														
Average	10,285	10,470	10,677	10,642	11,631	11,811	10,190	10,364						
Median	10,245	10,437	10,661	10,572	11,631	11,811	10,087	10,279						
Min	8,763	9,445	9,604	8,800	11,623	11,276	9,296	9,891						
Max	12,246	11,994	12,068	11,669	11,639	12,345	11,405	11,256						
MW>500														
Average	10,055	10,121	10,534	10,374			9,713	9,868	10,697	10,587	11,426	10,929		
Median	10,018	10,216	10,484	10,345			9,694	9,850	10,804	10,501	11,426	10,896		
Min	8,518	8,800	8,763	8,800			8,663	9,064	8,763	9,746	11,426	10,475		
Max	11,124	11,539	11,762	11,422			11,262	10,753	13,719	11,398	11,426	11,417		

Table 2b. Change in Heat Rate (with 30 Sub/Lignite included in Subbituminous)							
	Subcritical PC			Supercritical PC			CFB (all capacities/fuels)
	Bituminous	Subbituminous	Lignite	Bituminous	Subbituminous	Lignite	
MW≤100, except CFB							
Average	334	(322)					1406
Median	278	(183)					1156
Min	(1671)	(4555)					(1156)
Max	4169	1395					3639
100<MW≤200							
Average	207	(164)					
Median	355	(443)					
Min	(1622)	(1232)					
Max	1704	2992					
200<MW≤500							
Average	177	18	180	174			
Median	184	170	(363)	252			
Min	(1581)	(1387)		(404)			
Max	2091	1238		923			
MW>500							
Average	153	(110)		165	(76)	(9)	
Median	96	(60)		179	47	(9)	
Min	(1114)	(1506)		(705)	(3349)	(9)	
Max	1648	1280		1181	983	(9)	

Note: Above values were calculated by first determining the change in HR for each unit within the subcategory and then calculating the average, median, max, or min of the changes in HR for that subcategory of units. They were *not* determined by simply comparing the average of HRs, median of HRs, etc. for the subcategory.

Table 2c. Capacity Factor (with 30 Sub/Lignite included in Subbituminous)														
	Subcritical PC						**Supercritical PC**						**CFB (all capacities and fuels)**	
	Bituminous		**Subbituminous**		**Lignite**		**Bituminous**		**Subbituminous**		**Lignite**			
	NEEDS v4.10	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**
MW≤100, except CFB														
Average	57.34%	44.16%	70.62%	65.79%									72.77%	64.94%
Median	58.09%	44.01%	73.96%	70.79%									80.80%	77.37%
100<MW≤200														
Average	62.43%	53.41%	69.08%	62.40%										
Median	62.62%	53.46%	69.29%	61.26%										
200<MW≤500														
Average	64.80%	59.46%	68.11%	66.26%	75.49%	74.69%	68.10%	59.62%						
Median	67.60%	61.15%	66.81%	64.74%	75.49%	74.69%	71.81%	59.47%						
MW>500														
Average	70.94%	68.91%	72.84%	68.99%			66.30%	64.44%	69.34%	66.94%	73.48%	43.73%		
Median	72.60%	68.12%	72.91%	68.26%			68.12%	66.04%	68.52%	66.54%	73.48%	48.61%		

Table 2d. Change in Capacity Factor (Average and Median of unit changes in capacity factor – not the difference in above values)														
	Avg.	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**
MW≤100, except CFB														
	-13.17%	-12.58%	-4.83%	-2.58%									2.70%	-2.50%
100<MW≤200														
	-9.02%	-8.87%	-6.68%	-5.72%										
200<MW≤500														
	-5.35%	-3.28%	-1.85%	-2.77%	-0.80%	-0.80%	-8.47%	-5.62%						
MW>500														
	-2.03%	-1.87%	-3.85%	-3.93%			-1.86%	-1.55%	-2.41%	-1.98%	-24.87%	-24.87%		

Table 3a. Heat Rate (with 30 Sub/Lignite included in Lignite)														
	Subcritical PC						Supercritical PC						CFB (all capacities and fuels)	
	Bituminous		Subbituminous		Lignite		Bituminous		Subbituminous		Lignite			
	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13	NEEDS v4.10	NEEDS v5.13
MW≤100, except CFB														
Average	11,776	12,105	11,714	11,422	11,703	11,239							10,689	12,326
Median	11,407	11,886	11,596	9,945	10,990	10,547							10,331	11,766
Min	9,792	10,212	10,331	9,945	10,331	10,547							8,763	10,948
Max	14,500	14,500	14,500	12,656	13,787	12,622							13,500	10,575
100<MW≤200														
Average	10,448	10,663	11,204	11,074										
Median	10,251	10,618	11,251	10,847										
Min	9,308	9,434	10,203	10,262										
Max	12,985	12,364	12,334	13,732										
200<MW≤500														
Average	10,285	10,470	10,633	10,573	11,150	11,337	10,190	10,364	10,462	10,468				
Median	10,245	10,437	10,489	10,517	11,114	11,226	10,087	10,279	10,462	10,468				
Min	8,763	9,445	9,604	8,800	10,661	11,071	9,296	9,891	10,453	10,434				
Max	12,246	11,994	12,068	11,669	11,639	12,345	11,405	11,256	10,470	10,501				
MW>500														
Average	10,055	10,121	10,534	10,374	10,840	10,618	9,713	9,868	9,597	9,958	11,105	11,162		
Median	10,018	10,216	10,484	10,345	10,818	10,366	9,694	9,850	9,311	9,959	11,023	11,156		
Min	8,518	8,800	8,763	8,800	10,102	10,180	8,663	9,064	8,763	9,746	10,784	10,977		
Max	11,124	11,539	11,762	11,422	11,686	11,422	11,262	10,753	10,331	10,094	11,512	11,417		

Table 3b. Change in Heat Rate (with 30 Sub/Lignite included in Lignite)							
	Subcritical PC			Supercritical PC			CFB (all capacities/fuels)
	Bituminous	Subbituminous	Lignite	Bituminous	Subbituminous	Lignite	
MW≤100, except CFB							
Average	334	(307)					1406
Median	278	(183)					1156
Min	(1,671)	(4,555)					(1156)
Max	4,169	1,395					3639
100<MW≤200							
Average	334	(307)					1406
Median	278	(183)					1156
Min	(1,671)	(4,555)					(1156)
Max	4,169	1,395					3639
200<MW≤500							
Average	207	(150)	(464)				
Median	355	(271)	(443)				
Min	(1,622)	(1,232)	(1,165)				
Max	1,704	2,992	216				
MW>500							
Average	177	(2)	187	174	6		
Median	184	149	239	252	6		
Min	(1,581)	(1,387)	(363)	(404)	(36)		
Max	2,091	1,280	722	923	48		

Note: Above values were calculated by first determining the change in HR for each unit within the subcategory and then calculating the average, median, max, or min of the changes in HR for that subcategory of units. They were *not* determined by simply comparing the average of HRs, median of HRs, etc. for the subcategory.

Table 3c. Capacity Factor (with 30 Sub/Lignite included in Lignite)														
	Subcritical PC						**Supercritical PC**						**CFB (all capacities and fuels)**	
	Bituminous		**Subbituminous**		**Lignite**		**Bituminous**		**Subbituminous**		**Lignite**			
	NEEDS v4.10	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**	**NEEDS v4.10**	**NEEDS v5.13**
MW≤100, except CFB														
Average	57.34%	44.16%	73.39%	69.41%	62.59%	67.19%							72.77%	64.94%
Median	58.09%	44.01%	77.50%	70.79%	62.59%	67.19%							80.80%	77.37%
100<MW≤200														
Average	62.43%	53.41%	69.64%	62.63%	57.42%	57.54%								
Median	62.62%	53.46%	70.38%	61.27%	57.42%	57.54%								
200<MW≤500														
Average	64.80%	59.46%	67.34%	65.82%	74.00%	70.68%	68.10%	59.62%	84.21%	84.17%				
Median	67.60%	61.15%	66.42%	64.74%	71.82%	68.78%	71.81%	59.47%	84.21%	84.17%				
MW>500														
Average	70.94%	68.91%	71.78%	68.31%	79.67%	74.04%	66.30%	64.44%	75.46%	58.67%	65.29%	58.43%		
Median	72.60%	68.12%	72.24%	67.90%	79.75%	73.37%	68.12%	66.04%	74.79%	67.39%	66.95%	61.78%		

Table 3d. Change in Capacity Factor (Average and Median of unit changes in capacity factor – not the difference in above values)														
	Avg.	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**	**Avg.**	**Medn.**
MW≤100, except CFB														
	-13.17%	-12.58%	-3.61%	-2.58%	4.60%	4.60%							2.70%	-2.50%
100<MW≤200														
	-9.02%	-8.87%	-7.01%	-5.93%	0.12%	0.12%								
200<MW≤500														
	-5.35%	-3.28%	-1.52%	-2.49%	-3.32%	-3.59%	-8.47%	-5.62%	-0.04%	-0.04%				
MW>500														
	-2.03%	-1.87%	-3.58%	-3.48%	-5.63%	-5.17%	-1.86%	-1.55%	-6.49%	-4.96%	-3.05%	-0.86%		

MISSING DATA

There are a number of key effects that we simply don't have the data on (at least for now) and would need to be factored in to any site specific analysis of heat rate. These include:

- Pressure of steam system – except for supercritical versus subcritical, we don't have data on the plant steam pressure. Supercritical boilers have steam pressures in excess of 3,000 psi; however, subcritical boilers come in a range of pressures well below 3000 psi. Older and smaller boilers are more likely to have low pressure subcritical steam systems (say, 1600 psi or less) while newer or larger subcritical boilers will tend to have higher pressure steam systems (say, 1800 psi or more). The pressure of the cycle will have a big impact on the heat rate, with higher pressure steam cycles having lower heat rates. Raising the steam pressure for a low pressure steam cycle will in theory raise the cycle efficiency, but it is not likely to be a realistic retrofit option because it will require recertifying the boiler[8] and probably substantial modifications to the steam turbine, piping, valves and auxiliaries. It would have been helpful in this effort had it been possible to further classify boilers by steam pressure, but the data was not available at the time.[9]
- General condition of plant – Each power plant may have had different owners with different maintenance or operating philosophies. Some plants may have been recently sold, which means that the previous owners may have been less inclined to invest in improvements and general maintenance. As a result, these site specific factors will impact the heat rate of the unit.
- The relationship between capacity factor and heat rate that was expected was not found, and this may be due to the confounding effect of ambient temperature which is correlated with capacity factor, and the impact of ambient temperature on heat rate.

[8] All boilers and pressure vessels require an ASME stamp that certifies the steam pressure/temperature of the steam generator. This certification is for the purpose of assuring that the boiler can be safely operated at those conditions.

[9] Neither NEEDS, EPA's Air Markets Reporting Data, EIA form 860 nor EIA form 923 have boiler steam pressure data. The steam pressure data used by NETL in its 2010 study was from a Platts database, and therefore is not publicly available. From a discussion with NETL, the data on steam pressure itself was somewhat spotty/incomplete. NETL said that they have requested that EIA collect this information in the future.

CONCLUSIONS AND RECOMMENDATIONS

This effort was intended to identify important characteristics that impact the heat rate of coal fired electric utility boilers. The following are some general conclusions from the data. It should be noted that for any particular unit, the circumstances for that unit may be such that these conclusions – that apply for most units - may not apply.

- Capacity (in MW) appears to play a major role in heat rate. This is believed to be at least partly explained by the pressure of the steam cycle because low pressure steam cycles tend to be more concentrated in smaller boilers.
- On average, supercritical boilers have the lowest heat rates, but the lowest heat rate units are not supercritical. This is at least partly explained by the age of most supercritical units – most having been built in the 1960s and 1970s. This raises the possibility for improving supercritical unit heat rates through modernization.
- As expected, for a given capacity level, bituminous units tend to have lower heat rates than subbituminous, and subbituminous lower heats than lignite.
- It was expected that a lower capacity factor would result in higher heat rate. For bituminous units this trend was confirmed, but not so for subbituminous units. It is unclear from the data what other factors may be contributing to this unexpected result. A confounding effect is likely to be ambient temperature. In much of the country higher ambient temperature coincides with periods of high capacity factor, and ambient temperature has an impact on steam cycle efficiency. This effect was examined by EPA in the TSD to their proposed rule.
- After addition of a wet scrubber heat rate tended to increase in most cases but in some cases heat rate was lower and this generally coincided with a higher capacity factor. It is unclear why this was observed. One possible explanation for this that use of a wet scrubber may have permitted use of higher sulfur bituminous coal which may have impacted both the economics of the dispatch as well as the heat rate, but this is only speculation as to why this was observed.
- After addition of a dry scrubber heat rate generally (but not in all cases) increased and this was generally independent of the change in capacity factor. Installation of a dry scrubber is less likely to coincide with a change to high sulfur bituminous coal than installation of a wet scrubber, which may explain the difference between the observed change in heat rate and capacity factor for wet versus dry scrubbers.
- Although addition of a scrubber will usually correspond to an increase in heat rate, when examining the full population of scrubbed and unscrubbed units, no significant difference was observed. This is likely an artifact of the fact that the addition of FGD is typically made to the most economically viable – and most efficient – units.

DATA SOURCES

NEEDS v4.10 and v5.13 heat rate data was used. Removed from the NEEDS data

- Units smaller than 25 MW
- Units that did not show a firing type (these were mostly small units under the 25 MW threshold)
- Cogeneration or Combined Heat and Power
- Integrated Coal Gasification Combined Cycle (IGCC) units
- Stoker units (these are generally small, anyhow).
- Fluidized-bed combustion (FBC) were evaluated separately from PC or cyclone firing

EIA form 860 data was used to determine supercritical versus subcritical boilers

US EPA Air Markets Program Data, years 2004-2006 and 2008-2010 was used to develop capacity factors

DOCUMENTS REVIEWED

- Natural Resources Defense Council, “Closing the Power Plant Carbon Pollution Loophole: Smart Ways the Clean Air Act Can Clean Up America’s Biggest Climate Polluters”, March 2013
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- US Department of Energy, National Energy Technology Laboratory, “Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity”, Revision 2, November 2010 DOE/NETL-2010/1397
- US EPA, NEEDS v.4.10 and v5.13 User Guide