Examination of uncertainty in heat rate determinations

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ABSTRACT

Lowering heat rate is a key building block in US EPA's Clean Power Plan (CPP). The estimate for how much heat rate can be reduced under the CPP was determined from a statistical analysis of estimated gross heat rate using Air Markets Program Data (AMPD). Heat input as reported in AMPD is determined from the relationship that exists between exhaust flowrate and heat input that is commonly referred to as "F factor". Another public data source for estimating boiler heat input is plant fuel use data as found in EIA form 923. In this study these two sources of data were compared for several coal fired power plants. In addition, potential sources of variability in these methods are explored, including variability in the relationship between fuel heating value and exhaust gas flowrate, or F factor, and the degree to which it may impact variability in estimated gross heat rate using AMPD.

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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.

Heat rate is determined by dividing the heat input of the boiler by the megawatt hours of output. Fortunately, the output of the generator is measured directly in a reliable manner. Unfortunately, the heat input to the boiler must be inferred from other information. There are essentially three methods in use today.

1. Fuel Use Data – This methodology relies upon measuring the fuel consumed and multiplying that value by the heating value of the fuel (typically, the gross heating value or HHV). This is easy to do with liquid or gaseous fuels that are relatively homogeneous, such as distillate fuel oil or even natural gas. However, for coal this is more difficult because mass flow of coal is not as easily measured and because coal is not as uniform in composition as oil or gas. For power plants heat input over a month or over a year is published in EIA Form 923 fuel use data.
2. Exhaust Flow Monitoring Data – For any given fuel there is a relationship between the exhaust flowrate and the heat input. This relationship is captured in what is called the "flow factor" or the F factor. This can be determined from combustion calculations. EPA Method 19 also has a procedure for estimating the F factor. Most coal-fired boilers equipped with 40 CFR Part 75 CEMS utilize flow monitors and an F factor (as well as an adjustment for excess air) to estimate the heat input, and this is what is reported in US EPA's Air Markets Program Data (AMPD). The flow monitor must be regularly tested for accuracy and the F factor is input periodically based upon the fuel that is being used. Of course, coal is not a homogeneous fuel, and the F factor will not always capture the exact characteristics of the fuel.
3. Heat Balance – The method that many utilities rely upon is a heat balance. Based upon measured parameters and known relationships between temperature and pressure and the thermodynamic properties of water, steam, and furnace gases, it is possible to determine the heat input to the boiler at a point in time. This method is used to determine the boiler efficiency as well as the efficiency of the steam plant at a point in time under a set of conditions. Many plants have systems that continuously perform the heat balance and thereby can determine heat rate. The results of these heat balance studies are generally proprietary and are not made publically available. Some electric utilities report heat rate in their FERC Form 1 data; however, it is unclear if this data is the result of heat balances or other methods.

In this effort, we review previous work and then explore the first two means for determining heat input, how they compare and errors that may exist in hourly as well as annual heat rate data.

PREVIOUS WORK

Staudt and Macedonia

Staudt and Macedonia examined factors that contributed to heat rate using data from US EPA's National Electric Energy Database (NEEDS), to include facility size, capacity factor, emission controls, steam cycle (supercritical versus subcritical), coal type.[1] They determined that each of these factors played an important role on the heat rate of the unit. They also determined that there was a great deal of unexplained variability in the data.

Linn, et al.

An article by Linn, Mastrangelo and Burtraw[2] examined fuel use and generation data from 1985-2009. After controlling for firing type, capacity and fuel type, significant variability was found in the heat rate data. The authors concluded that the variability in the heat rates after controlling for these three technical features was evidence that there was room to improve heat rate by roughly 6% on average.

US EPA

Chapter 2 of the "GHG Mitigation Measures" Technical Support Document for the CPP Final Rule provides analysis that concludes that there is significant potential for heat rate improvement from the fleet of existing coal-fired EGUs. In both their initial CPP proposal and the final rule EPA conducted a statistical analysis of hourly heat rate from AMPD data for 884 coal fired units over that period. They examined hourly heat rate in relation to ambient temperature and hourly capacity factor. [3] For the final CPP, EPA used three different methods.

1. EPA examined the improvement based upon meeting the best one year gross heat or the best 2-year moving average gross heat rate over the period 2002-2012.
2. EPA examined the improvement possible if the unit met its best one year gross heat or the best 2-year moving average gross heat rate over the period 2002-2012 under similar conditions, accounting for hourly capacity factor and ambient temperature.
3. EPA examined the improvement possible if the unit met its best one year gross heat or the best 2-year moving average gross heat rate over the period 2002-2012 under similar conditions, accounting for hourly capacity factor and ambient temperature while also accounting for a consistency factor for that interconnection.

[1] Staudt J., Macedonia, J., "Evaluation of Heat Rates of Coal Fired Electric Power Boilers", presented at the MEGA Symposium, August 19-21, 2014

[2] Linn, J., Mastrangelo, E., Burtraw, D., "Regulating Greenhouse Gases from Coal Power Plants under the Clean Air Act", Journal of the Association of Environmental Resource Economics, Vol. 1., No. ½ (Spring/Summer 2014)., pp 97-134.

[3] 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, Docket ID No. EPA-HQ-OAR-2013-0602 Greenhouse Gas Mitigation Measures, August 3, 2015, pp 2-42 through 2-50

EPA determined that the most conservative approach estimated by EPA, which was the third approach,[4] yields average potential heat rate improvements of 2.1 percent in the Western Interconnection, 2.6 percent in the Texas Interconnection, and 4.3 percent in the Eastern Interconnection.

Cichanowicz and Hein

Cichanowicz and Hein examined EPA's statistical analysis provided in EPA's Clean Power Plan proposal by recreating the analysis and examining the results.[5] In the analysis that was incorporated into the proposal, EPA grouped facilities by quartile according to residual standard deviation (RSD) of heat rate variation, or a measure of how much heat rate improvement EPA believes is possible, with the first quartile being the lowest RSD (lowest opportunity for improvement) and the fourth quartile the highest (greatest opportunity for improvement). The RSD for the top quartile was 3.5% while the RSD for the bottom quartile was 9.8%, with the average RSD for all units 5.4%.

Cichanowicz and Hein determined that facility age, capacity factor, fuel type, steam cycle (subcritical or supercritical) and cooling system design (once through versus recirculating) exhibited trends with regard to the likeliness of a unit being in a particular quartile. Therefore, facilities with particular attributes or facilities that operate in a particular manner appeared to be more likely to consistently achieve near their best heat rate, while others were not. Units in the first quartile are likely to be lower in age, operate at higher capacity factors, less likely to burn bituminous fuel, more likely to be supercritical, and less likely to be once through cooling systems.

Quick

Although not an examination of heat rate, a related study is one by Quick that examined CO_2 emission estimates using US EPA's AMPD and EIA data.[6] The author found significant differences that he attributed to the CO_2 measurement and calibration methods and flow measurement methods used by EPA and limitations of the EIA fuel consumption data.

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[4] 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, Docket ID No. EPA-HQ-OAR-2013-0602 Greenhouse Gas Mitigation Measures, August 3, 2015, Pg. 2-50

[5] Cichanowicz and Hein, CRITIQUE OF EPA's STATISTICAL EVALUATION DEFINING FEASIBLE HEAT RATE IMPROVEMENTS, Prepared for the Utility Air Regulatory Group, December 1, 2014

[6] Quick, J., "Carbon dioxide emission tallies for 210 U.S. coal-fired power plants: A comparison of two accounting methods", *Journal of the Air and Waste Management Association*, 64(1)73-79, 2014

COMPARISON OF ANNUAL HEAT INPUT USING TWO METHODS

EIA Form 923 provides fuel use and fuel characteristic data on a monthly and total annual basis. Fuel use data from EIA Form 923 was used to estimate heat input for coal fired power plants that only use coal as the primary fuel. This eliminated plants that have a gas turbine or other unit that primarily fires another fuel. From this information it is possible to determine the heat input to the plant for a given year or for a given month in that year.

US EPA's AMPD data provides heat input data for each unit. The heat input is estimated using flow monitoring information and a fuel F factor.

For the 232 power plants that exclusively have coal as the primary fuel heat input was determined for the year 2014 in two ways - using EIA Form 923 data as well as AMPD data. Figure 1 shows a cumulative probability distribution for how annual total heat input compared for these plants using these two methods. As shown,

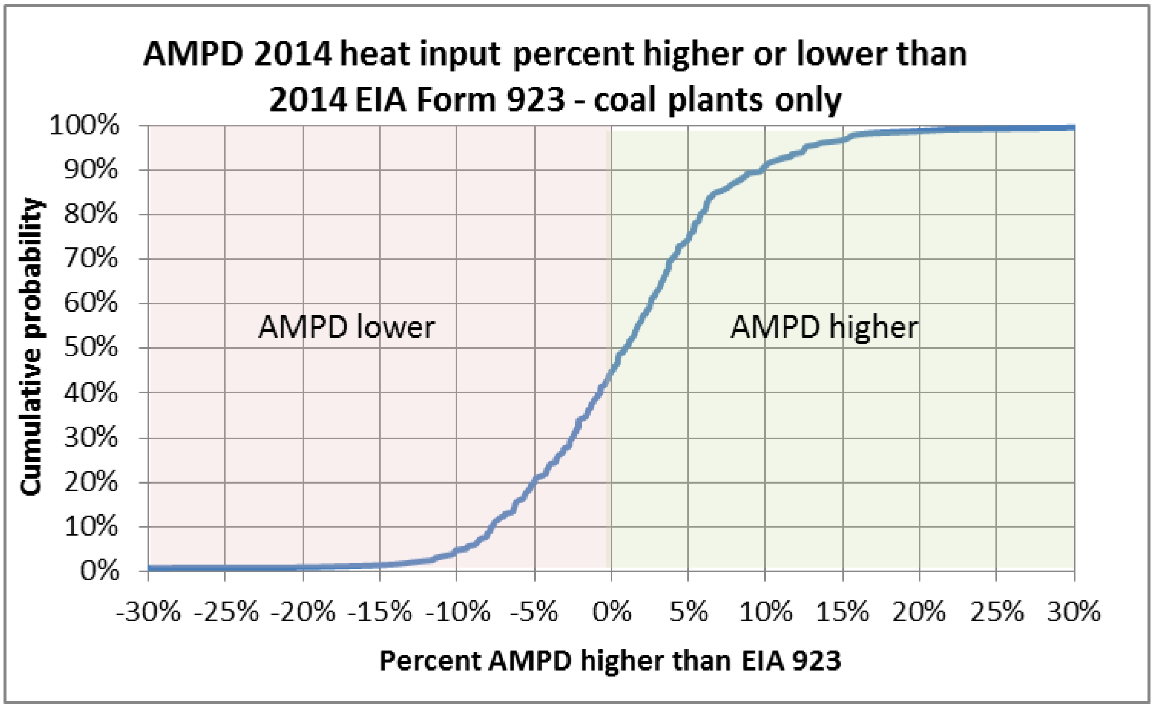
- AMPD heat input and heat input estimated from EIA Form 923 fuel use data are within 5% in only about 55% of the plants
- AMPD heat input and heat input estimated from EIA Form 923 fuel use data are within 10% in only about 85% of the plants
- The maximum amount that AMPD was lower than that determined by Form 923 was 100%.
- The maximum amount that AMPD was greater than that determined by EIA Form 923 was 34.3%

It is clear that these two approaches to determine heat rate can have substantial differences. The EIA Form 923 data is entered and submitted to EIA each year. Therefore there is the risk of data entry errors. Also, there may be inconsistencies in the approach to measuring heating value of the fuel.

The AMPD heat input estimate has other sources of error that relate to flow measurement errors as well as assumptions in the F factor that are explored later in this document.

Figure 2a shows the calculated 2014 CO_2 emission rate in lb/MWh gross based upon US EPA's AMPD for those coal-fired units with CO_2 emission rates during that year that were at or below 1800 lb/MWh gross. The results indicate that over 10 units reported emission rates under 1700 lb/MWhr, some well below that value. This suggests that several facilities were cofiring natural gas. On the other hand, Figure 2b shows the percent of heat input from coal versus other fuels for those same units, as determined from EIA Form 923 data. As shown, only units #1 and #21 are cofiring a significant amount of natural gas, at least according to the Form 923 data.

Figure 1. Comparison of 2014 annual heat input using AMPD and EIA Form 923 for plants with only coal as primary fuel



The apparently very low CO_2 emissions of those units that are not cofiring significant amounts of natural gas suggest that the heat rates of those units are very low. Several of those units, however, are fairly old units that would not be expected to achieve such low emission rates. Figure 2c shows a comparison of the heat input using EIA Form 923 data and US EPA AMPD for each of the units shown in Figures 2a and 2b. For the EIA Form 923 heat input data the reported heat input for all fuels was totaled. As shown, for most of the units the difference between heat input developed from Form EIA 923 data and the heat input reported in US EPA's AMPD is significant. Figure 2d shows how gross heat rate compares for these units when using EIA Form 923 data versus US EPA's AMPD. Again, there is a large difference in most cases. In fact, the heat rates determined from US EPA's AMPD in many cases were unexpectedly low, given the age of the units. For those units, EIA Form 923 generally resulted in higher heat rates that were more consistent with what would have been expected for those units. Therefore, at least for these units the annual heat input estimated from EIA Form 923 data appears to be more reliable than the annual heat input from AMPD.

Figure 2a. Lowest CO_2 emitters in 2014, per US EPA AMPD

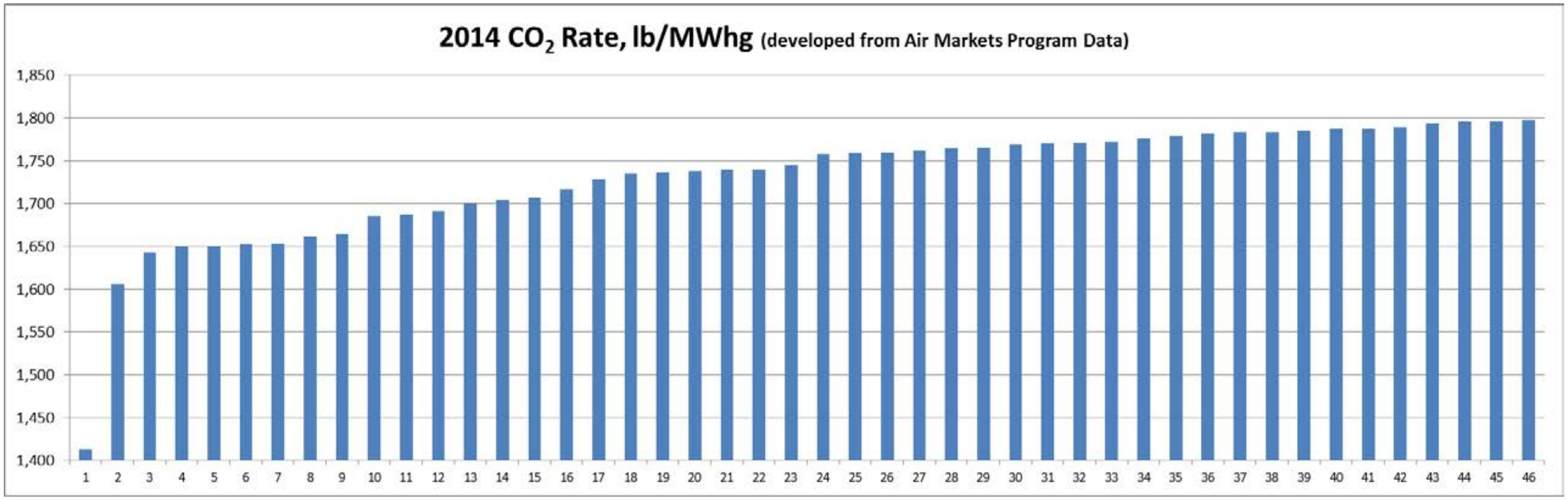


Figure 2b. Fuel Mix of Lowest CO_2 emitters in 2014, per EIA Form 923

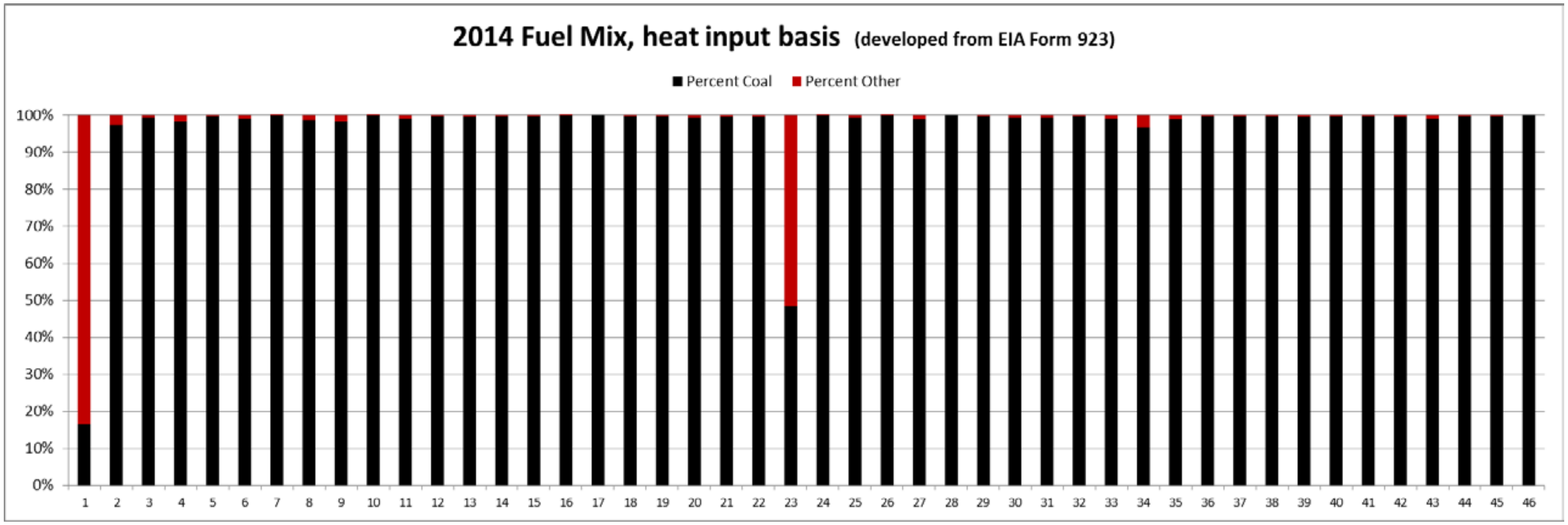


Figure 2c. Comparison of 2014 heat input calculated from EIA Form 923 versus reported in US EPA AMPD

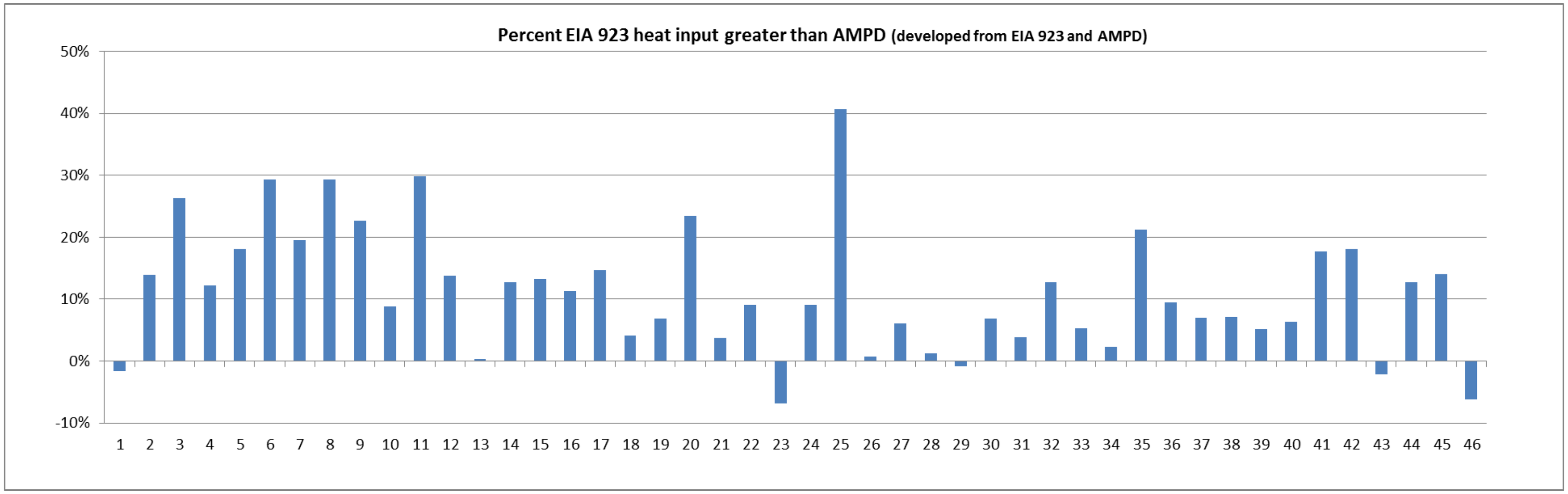
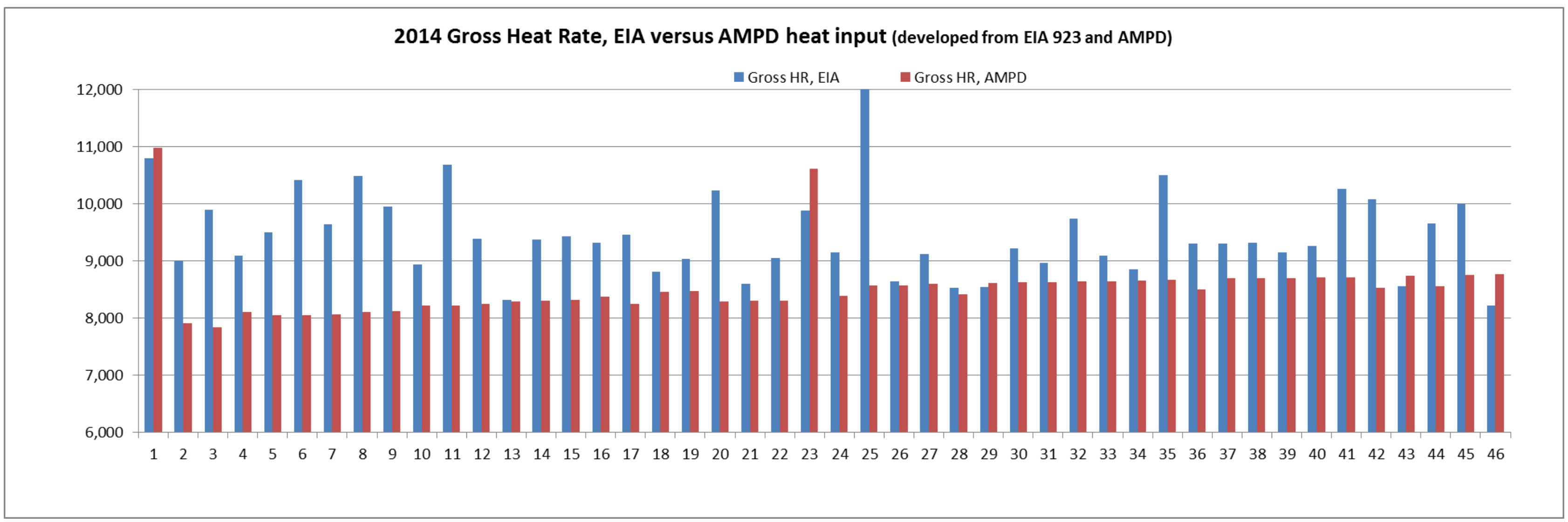


Figure 2d. 2014 Gross Heat Rate – calculated from EIA Form 923 versus US EPA AMPD



EXAMINATION OF VARIABILTIY IN HOURLY HEAT RATE

As noted earlier in this document, heat rate variability has been identified by some as an indication of the ability to improve heat rate. Specifically, heat rate variability for a given load and ambient temperature condition have been identified by EPA as an indication that heat rate can be improved. EPA calculated hourly heat rates for different load and ambient conditions using data from AMPD for hourly heat input and load to determine variability of heat rate at a given condition. Based upon the variability EPA made estimates of what heat rate improvements they believed was possible.

For coal fired power plants heat input as reported in AMPD is inferred from measured exhaust flowrate and the F factor for the fuel. It may also be determined from CO_2. The F factor is an estimate of the flowrate of gas per unit of heat input that is manually input to the CEMS software. F factor is estimated using EPA Method 19. Figure 3 shows the general idea. Total measured flowrate is adjusted for excess air and gas conditions (temperature and pressure) to arrive at the stoichiometric flowrate in scfm. The stoichiometric flowrate is then divided by the F factor to arrive at the heat input rate for the measured flowrate.

For example, according to EPA Method 19, when using total flowrate (including moisture), the following equation is used for estimating the F factor.

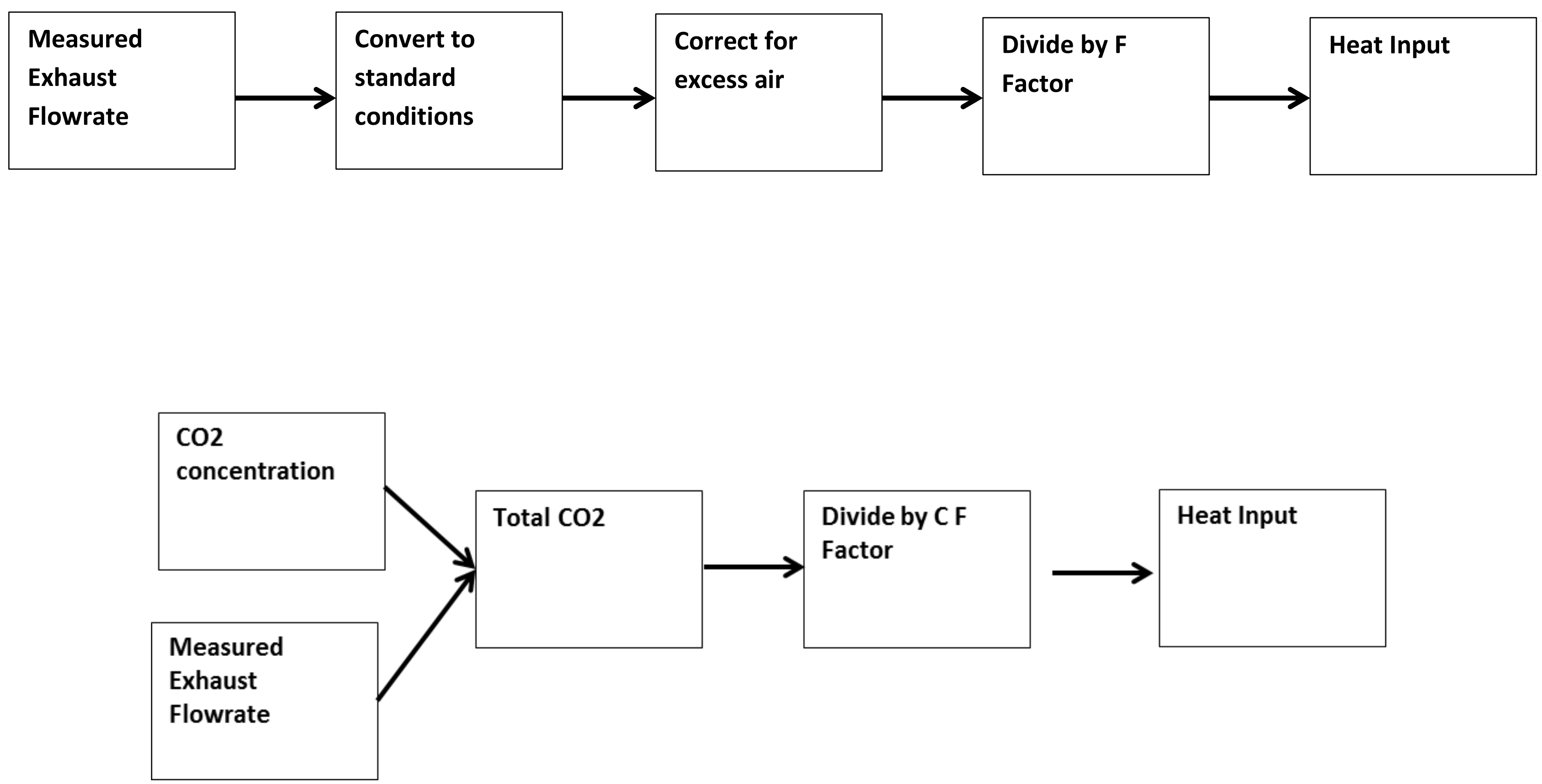
$$F_w = \frac{K\left[K_{hw}\%H + K_c\%C + K_s\%S + K_n\%N - K_o\%O + K_w\%H_2O\right]}{GCV_w}$$

Where K_{hw}, K_c, K_s, K_N, K_o *and* K_w are constants that are, respectively, multiplied by the concentrations of hydrogen, carbon, sulfur, nitrogen, oxygen and moisture in the fuel and GCV is the gross calorific value (Btu/lb) of the fuel. This equation is based upon balances of combustion reactions

Of course, coal is not a homogenous material. Carbon, hydrogen, sulfur, nitrogen, oxygen and moisture content will vary for any given coal or coal type, and therefore the relationship between gas flowrate and heat input is not a stable one. It will vary as the coal varies. On the other hand, F factor in the CEMS is not continuously varied as the coal characteristics change. It is typically entered into the software perhaps once a year or during a RATA.

Therefore, the heat input rate to the boiler that is determined as a result of the measured flowrate and use of the F factor will differ from the actual heat input rate to the boiler any time that the actual coal characteristics differ from the assumed coal characteristics when estimating the F factor used in the CEMS.

Figure 3. Inference of Heat Input from Measured Flowrate and/or CO_2



Examination of instability in the relationship between exhaust gas flowrate and heat input

Exhaust gas flowrate for a given coal can be determined by combustion calculations or, alternatively, calculations of F factor per Method 19. In this effort combustion calculations were made for three different types of coal while assuming 15% excess air in every case. The six different coals were:

- Montana PRB
- Wyoming PRB
- Northern Appalachian Coal (NAP)
- Central Appalachian (KY)
- Central Appalachian (VA)
- Central Appalachian (WV)

Coal analysis data was taken from the USGS Coal Quality Database. Calculations were made of the scf per million Btu of heat input for each analysis for each of the above coals. There were no fewer than 171 samples available per coal type and in several cases well over 300. Therefore, these are likely to be statistically significant sample sizes. Figures 4a and 4b graphically demonstrate for PRB and NAP the cumulative distributions of the calculated scf per million Btu at 15% excess air (that is, the values calculated here should be higher than the F factor because excess air is included) and in Figure 4b the lbmol CO_2 per million Btu. As shown, the two PRB coals have a higher average and a wider range of flowrates per million Btu than the NAP coal. The two PRB coals have standard deviations of roughly 3% of the average compared to about 1.5% of their average for the NAP. Combining the WY PRB and the NAP data, it was also possible to develop a simulated combination of PRB and NAP. The simulated blend had the widest standard deviation of 3.78% of the average.

The CAP coal relationships are shown in Figures 4c and 4d. The central Appalachian coals were very similar to one another, each with flowrates in the range of 11,815-11,840 scf/million Btu with 15% excess air. Standard deviation ranged from 0.75% to 1.05% of the average values.

The implications for these results are that the relationship between exhaust flowrate or CO_2 and heat input for any coal is not constant, and can vary by significant amounts, especially for the PRB coals. For facilities that blend or change coals – especially those that blend PRB with bituminous coals or may change between PRB and bituminous coals, as is common for many smaller, unscrubbed boilers in the east, the relationship between measured flowrate and heat input will be more unstable than if a single fuel type was used.

Figure 4a. Cumulative probability of exhaust flow to heat input at 15% excess air for Montana PRB, Wyoming PRB, Northern Appalachian (NAP) coals and 50/50 blend of WY PRB and NAP

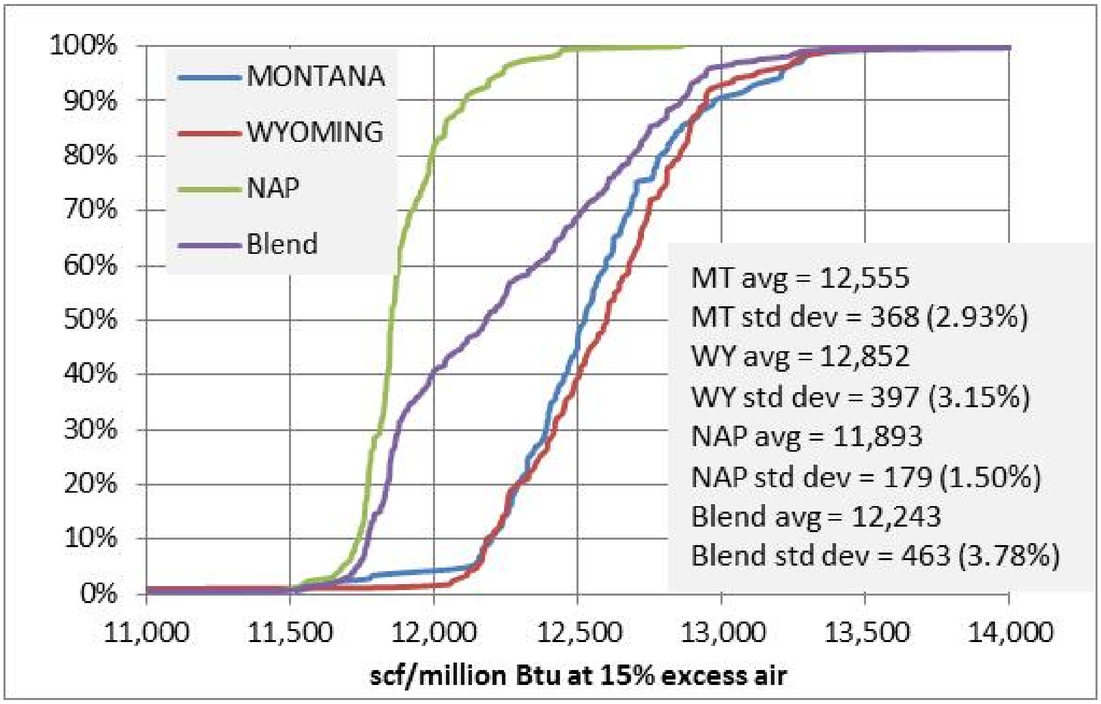


Figure 4b. Cumulative probability of lbmol CO_2 to heat input for Montana PRB and Wyoming PRB and NAP

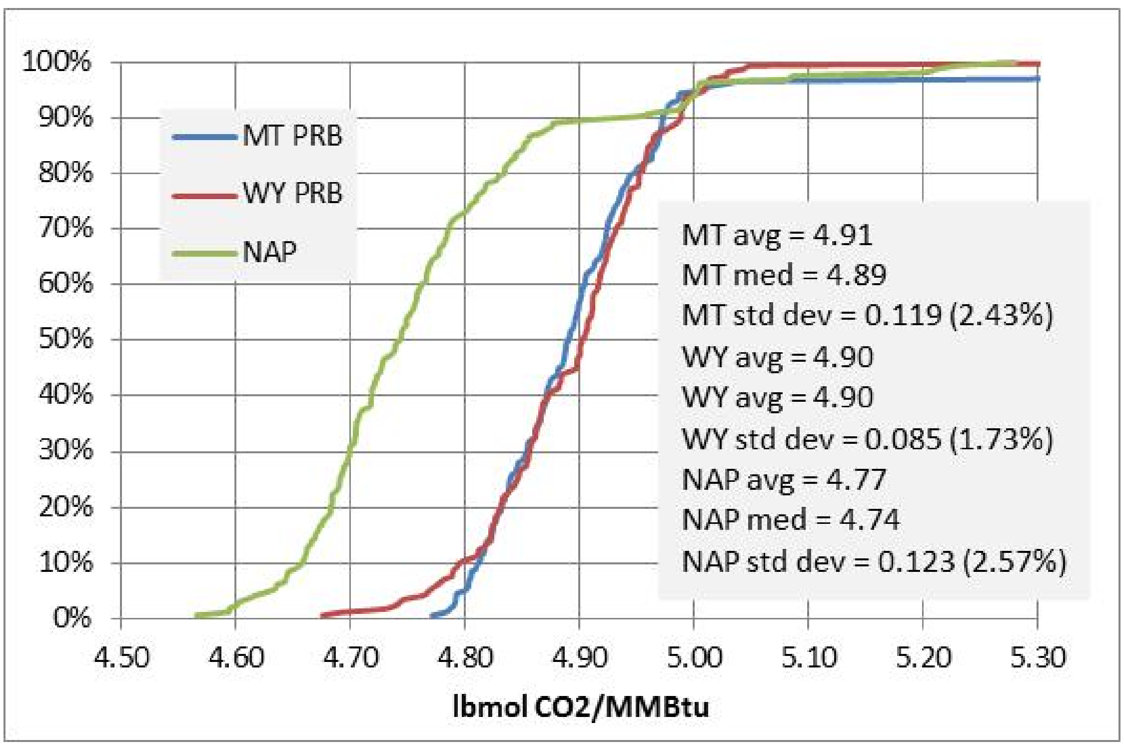


Figure 4c: Cumulative probability of exhaust flow to heat input at 15% excess air for Kentucky, Virginia and West Virginia Central Appalachian coals

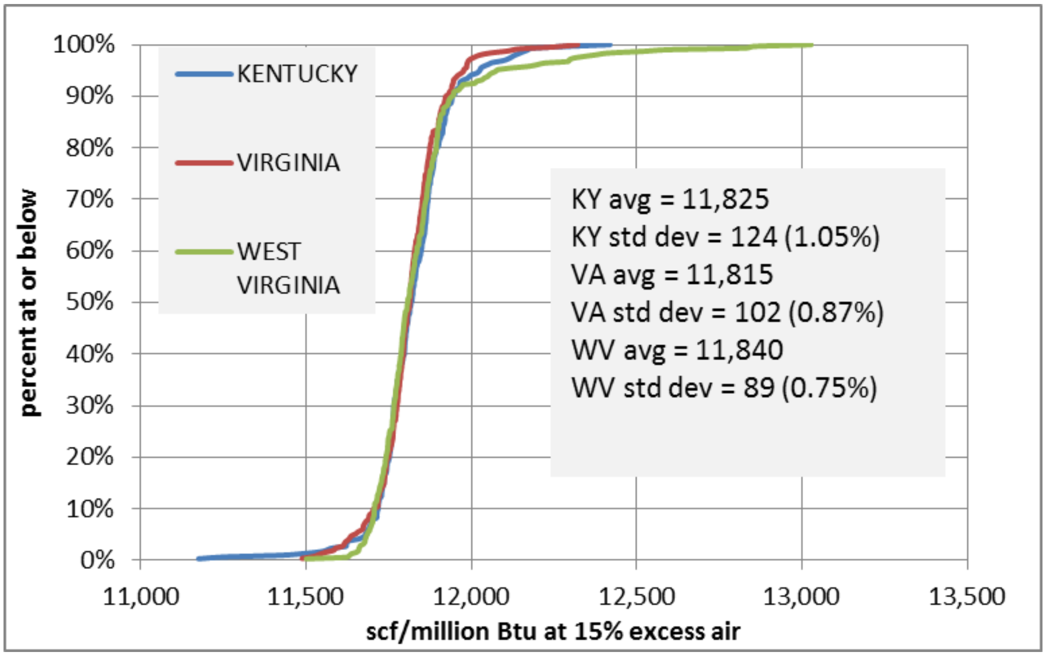
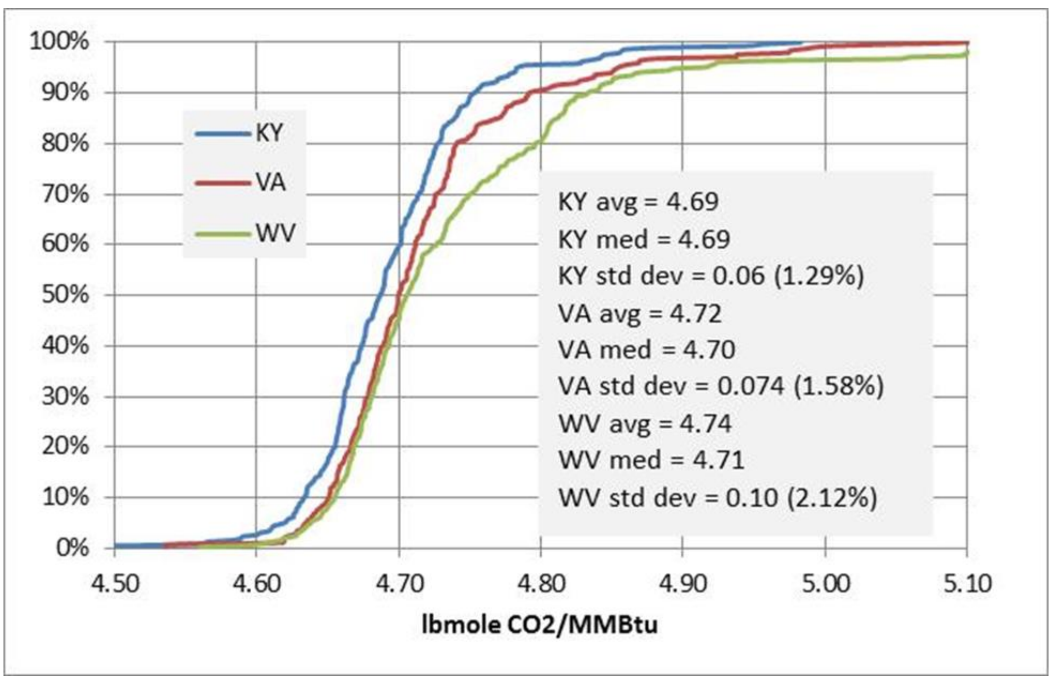


Figure 4d. Cumulative probability of lbmol CO_2 to heat input for Central Appalachian coal



Because the relationship between exhaust flowrate and heat input is not stable an increase in exhaust flowrate observed at a coal fired boiler may not always be the result of an increase in heat input. It is therefore possible that heat inputs determined from measured flowrate and F factor - as is estimated with the AMPD – may be in error and demonstrate variation that is not representative of the actual heat input. This may explain some of the apparent variability in heat rate that was observed by EPA.

Using the data represented in Figures 4a and 4b, it is possible to estimate how large this error might be for the particular coals and coal data represented in the Coal Quality database. The calculated scf/million Btu values for each coal were sorted from lowest value of scf per million Btu to highest and then divided into deciles – 0 to 10% for the lowest values and on to 90% to 100%. Each value of scf/MMBtu that was higher in value than the 10% data point was compared to the 10% data point and a percent reduction was determined. The average reduction is shown in Table 1 for each of the coals evaluated.

As Table 1 demonstrates, PRB fuels exhibit enough variability in the relationship between flowrate and heat input that a 3%-4% "apparent" improvement in heat rate appears to be possible. "Apparent" is in parentheses because this is not truly a possible improvement in heat rate, but what might mistakenly be concluded when using heat input estimates determined from exhaust flowrate and F factor. For the bituminous coals the "apparent" improvement in heat rate is lower, but still significant. And, for those units that change or blend PRB with bituminous coals the apparent improvement in heat rate would be greater than any of the coals individually because of the much wider range between the two coals.

Table 1. "Apparent" improvement in heat rate resulting from instability in the relationship between flowrate and heat input.

MT PRB	WY PRB	NAP	WY PRB-NAP Blend	KY CAP	VA CAP	WV CAP
3.53%	3.95%	1.56%	4.43%	1.09%	1.11%	1.28%

CONCLUSIONS

Heat rate improvements are an important means of reducing the CO_2 emissions from coal fired power plants. Heat rate determinations rely upon accurate and reliable measurement of the heat input to the boiler, and this paper examined some of the means that are used and compared the results. In this effort, the following conclusions were reached.

- There is a significant disparity between heat inputs reported in US EPA's AMPD and in EIA Form 923 data. For the 2014 total plant heat input data examined, there does not appear to be a bias to the difference. That is, one is not consistently higher than the other.
- For the 46 coal units that, according to the AMPD data, had the lowest CO_2 emission rates, there were some results that seemed unusually low in both emission rate and heat rate when considering the facility age and fuels used. Upon further examination, for these units heat input when using EIA Form 923 data was significantly higher than for AMPD, and heat rate calculated using EIA Form 923 data was more consistent with expectations. This suggests that there is an error in the AMPD heat input determinations for these units.
- The relationship between exhaust gas flowrate and heat input was determined to be unstable for several coals, which could contribute to errors in the "apparent" heat input using the F factor method. These errors may contribute to apparent variability in heat input, which may be mistaken as an opportunity to improve heat rate for a given unit. The effect was found to be significant for all coals, but greatest for PRB fuels and situations where fuels are blended. Of course, the analysis here was performed using data from the Coal Quality database. Results might differ for the specific coals that a given plant might use.

RECOMMENDATIONS

The data in the AMPD as well as EIA Form 923 are potentially useful tools in providing insights to potential heat rate improvements and reducing CO_2 emissions from coal-fired power plants. However, at this point in time there appear to be significant inconsistencies in the data that raise questions about how it should be utilized. Also, proper use of the data needs to factor in how the actual measurements and data are produced and what other effects could influence the data. Otherwise, the data could be misinterpreted. A significant technical effort should be expended to fully understand the inconsistencies that are observed in the data and find methodologies to address these inconsistencies. Heat input estimates using the F factor method also need to be examined for ways to improve them or to at least better understand how this information should be applied in an effort to reduce boiler heat rates.