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Consulting to the Air Pollution Control Industry

Analysis of PM and Hg Emissions and Controls from Coal-Fired Power Plants

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I. Executive Summary

The Mercury and Air Toxic Standards (MATS) established emission standards for mercury (Hg), non-Hg metal hazardous air pollutants (HAPs)[1], and acid gases from coal- and oil-fired power plants. It also established detailed rules and procedures to demonstrate compliance with those standards, including monitoring and reporting requirements. While EPA regulated non-Hg metal HAPs, it permitted compliance with the non-Hg metal HAPs standards by complying with a particulate matter (PM) emissions limitation as an alternative surrogate pollutant.[2] This is the most common way that power plants chose to comply with the non-Hg metal HAPs requirements of the MATS rule. This report provides the results of an analysis of PM and Hg emissions data from coal-fired power plants and a discussion of the primary technological methods to control those emissions. The objective of this effort was to assess the emissions performance currently being achieved by coal-fired power plants with different control configurations and potential for additional reductions. The industry has made significant technological advances since the MATS rule was finalized in 2011. This analysis evaluated:

- New technology developments, including changes in costs, that may have occurred since 2011.
- More widespread implementation of technologies that may have been available in 2011 but were not widely deployed, and the resulting improvements in emissions performance.
- Developments in best practices that may have occurred since 2011.

In addition, with the understanding of the above, the analysis also considered whether the emissions standards established by MATS could potentially be made more stringent, to what degree, and at what cost, consistent with the requirements of the Clean Air Act. Section 112 of the Clean Air Act states: "[t]he Administrator shall review, and revise as necessary (taking into account developments in practices, processes, and control technologies), emission standards promulgated under this section no less often than every 8 years."

This analysis utilized a comprehensive dataset published by the Natural Resources Defense Council (NRDC)[3] that includes company-reported data on Hg, SO_2, HCl, and PM emissions, as well as facility characteristics, pollution control equipment installed, equipment age, and other factors. The data were compiled from publicly available data sources: WebFire, Air Markets Program Data, and EIA 860.

A. Conclusions regarding PM emissions

MATS set a limit on emissions of non-mercury metals, which present in the form of PM and can be controlled by technologies that reduce PM generally. MATS allows coal units to demonstrate compliance with the non-mercury metals limit by remaining under a filterable PM limit of 0.03 lb/MMBTu, which serves as a surrogate for measuring emissions of non-mercury metals. Coal units have overwhelmingly chosen to comply with the non-mercury metals limit by adhering to the surrogate limit on filterable PM.

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[1] This report is focused on non-mercury metal HAP particulate matter but uses PM emissions as an alternative surrogate pollutant for the non-mercury metals which are regulated under MATS.

[2] PM from coal plants is comprised of non-Hg metal HAPs as well as other particulates. MATS established a filterable PM emissions limit of 0.03 lb/MMBtu as a surrogate for non-Hg metal HAPs.

[3] https://www.nrdc.org/resources/coal-fired-power-plant-hazardous-air-pollution-emissions-and-pollution-control-data

The PM control technologies discussed in this report help enable coal units to meet requirements for non-mercury metal emissions. The assessment of emissions data and analysis of methodologies for PM emissions control found that significant improvements in PM emissions rates since 2011 are largely the result of:

- Wider deployment today of technologies that may have existed in 2011, but were not widely deployed in 2011 (e.g., new filter bags, high frequency transformer rectifiers, continuous monitoring devices) and associated performance improvements based on greater experience.
- Improved practices. More attention paid by operators to keeping their PM emissions control equipment running well due to more regular and more robust monitoring.
- Technology improvements, including monitoring technology, filter bag technology, and electrostatic precipitator (ESP) technology.

Faced with a requirement to control PM emissions, industry found low-cost ways to achieve lower PM emissions that were not anticipated in 2011 or considered in EPA's 2011 assessment. Improvements in technology and operations since 2011, by technology type, include:

ESPs

- Correction of operational issues (e.g., leak repair, faulty electrodes, insulators, and plates); increases in treatment time (typically, $20/kW or less).
- High frequency transformer rectifiers (by far most common improvement approach (about $10/kW).
- Replacing or rebuilding internals (costs vary widely, likely in the range of $20-$50/kW).
- Adding fields or other approaches to increase treatment time (costs most likely over $50/kW).
- Fabric filter installed downstream of an ESP ($150-$200/kW to add FF, could be as much as $400/kW in the most challenging situations).

Fabric filters or baghouses[4]

- Correction of operational issues (e.g., casing and ductwork leak repair, typically, $20/kW or less).
- Improved maintenance and better management of bag cleaning processes.
- Bag and/or compartment leakage detectors to identify maintenance issues.
- Improved fabrics that are less prone to failure and clean more easily.
- Bag replacement (about $2-3/kW, roughly $1.15 million for 500 MW unit).

The impact of PM CEMS and "real-time" monitoring

- PM CEMS were considered a "new" or "emerging" technology in 2011, with limited application. Thus, many facilities did not install them. The technology is common today.
- More frequent monitoring allows facility operators to quickly identify and address potential problems.
- This is supported by the fact that PM CEMS are far more widely used among the best-performing versus worst-performing units.
- PM CEMS cost roughly $250,000 to install.

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[4] The terms "fabric filter" (FF) and "baghouse" (BH) are interchangeable for the purpose of this document, and both refer to the same device or control technology.

Evaluation of PM Data

The PM emissions rate data from EPA Clean Air Markets Division and Energy Information Administration's boiler-level database, as reflected in the NRDC spreadsheet,[5] was evaluated by ATP, to include division of units into deciles by PM emissions rate. Decile 1 includes the units with the lowest PM emission rate, and decile 10 the units with highest PM emission rate. The assessment of top and bottom performing units (PM emissions rate) shows:

- There is room for significant improvement:
  - There are technological improvements that have been deployed and, in some cases, could still be deployed.
  - The difference in PM emission rate between top and bottom deciles is very significant – roughly a factor of ten.
  - It appears that at some of the bottom performing units, are doing "just enough" to satisfy the MATS limits.
- Type of installed control has some impact on overall performance, but is not the sole factor in a unit's performance:
  - A significant portion of decile 1 had both ESP and BH.
  - A significant portion of the top deciles are unscrubbed with only an ESP for PM controls, indicating that this configuration – the most challenging configuration - is capable of low emissions.
  - Top deciles consistently had newer equipment.
  - Top performing deciles are likely employing best maintenance and management of existing controls, contributing to low PM emissions.
  - Scrubbers make a difference, but scrubbers are not the deciding factor:
    - Scrubbers were more common among top performing units, but removal by scrubbers cannot alone explain the large difference between top and bottom deciles.
    - Scrubbers are likely an indication of the overall investment in and importance of the unit. Because of their high cost, scrubbers are typically installed on facilities that are regarded as vital units.
- Top deciles are far more likely to be using PM CEMS.
  - PM CEMS were relatively novel when MATS was developed, used at a fairly limited number of facilities.
  - PM CEMS provide feedback that can be used to identify problems right away.

Impact of a reduced emissions rate standard

Based on analysis of the compliance data from NRDC's spreadsheet, the coal fleet is, for the most part, controlling to well below the MATS PM emission standard; only a small number of units reported emissions close to the level of the emission standard. Therefore, a reduction in the emission standard

[5] https://www.nrdc.org/resources/coal-fired-power-plant-hazardous-air-pollution-emissions-and-pollution-control-data

would be possible without a large impact on the coal fleet. Analysis suggests that very little cost impact would result from a reduction in the PM emissions standard to 0.007 lb/MMBtu. Most units with ESPs could comply with this standard with only modest improvements or maintenance costs and some units with older ESPs would require relatively modest upgrades. At 0.003 lbs/MMBtu, some units with ESPs would need to install baghouses but roughly half of units with ESPs would be able to meet this standard with modest upgrades or no additional costs. Reduction of a PM standard to 0.0015 lb/MMBtu would likely require baghouses on all coal units and fabric upgrades for those existing baghouses that are not operating well enough to meet such a revised standard. Table 1 provides a preliminary estimate of the impact of reduction of the PM standard to different levels. This is believed to be a conservative estimate.

Table 1. Estimated impact of reduction in PM emission rate standard[6]

PM Limit (lbs/MMBTU) *(Current standard is 0.03 lbs/MMBTU)*	**Implications for facilities with ESPs**	**Implications for facilities with baghouses**	**Implications for fleet as a whole** *(Preliminary estimates)*
0.007	• Most units can meet with modest improvements • Units with ESP built in last 20 years should be able to achieve with modest maintenance costs (~$20/kW or less) • A few units with significantly older ESPs may need to undergo ESP upgrades/rebuilds (~$50/kW)	• Virtually all units can easily meet this limit with no additional costs • A few units may require some maintenance or bag replacement ($2-5/kW)	• More than half of all units can achieve with little to no additional costs, 42% of fleet is above 0.007 lb/MMBtu • $268M annualized cost with >7,200 tons PM reduction (preliminary estimate)
0.003	• Many units may need to make upgrades but should be technically feasible for all units • Roughly half of units with ESPs would need to install baghouses, especially those with ESPs older than 30 years ($150-200/kW) • Remaining units could achieve with modest upgrades ($20-50/kW • Units with ESPs and wet scrubbers may not be able to fit baghouse before scrubber, but could install wet ESP after scrubber ($100-150/kW)	• Many units can still meet this with little to no costs • Some units may need modest upgrades. For instance, units may need to replace bag ($2-5/kW) and replace every 3 years rather than 5 years.	• About 25% of fleet can achieve with little to no additional costs • $1.29B annualized cost with >16,800 tons PM reduction (preliminary estimate)
0.0015-0.002	• Most units with ESPs would need to install baghouses, especially those with ESPs older than 30 years ($150-200/kW) • Remaining units could achieve with modest upgrades ($20-50/kW) • Some ESPs would still not require additional investments	• Many units can still meet this with little to no costs • Some units would need modest upgrades ($5/kW)	• 12-20% of the fleet can achieve with little to no additional costs • $2.4B annualized cost with >22,900 tons PM reduction (preliminary estimate)
Less than 0.0015	• Nearly all units with ESPs would need to make substantial upgrades, including installing baghouses	• Most units would need to make modest upgrades	• Most units would require modest to substantial improvements • $2.5B+ annualized cost (preliminary estimate)

[6] Estimated costs and PM reductions are approximate, and based upon an assumed BH upgrade cost of $5/kW for upgraded bags, $20/kW for a minor ESP upgrade, $50/kW for major upgrade, and $150/kW for installation of BH.

B. Conclusions regarding Hg emissions control

Methods for controlling mercury include scrubbers, baghouses, and ESPs – all of which are primarily used to control other pollutants – as well as Hg-specific control technologies, especially activated carbon injection (ACI).

All methods of Hg controls experienced large advances as MATS focused the attention of power plant owners and technology suppliers on the goal of capturing Hg efficiently and at the lowest possible cost.

ACI, which is the most commonly used Hg-specific control technology, is a "dial up" technology that is used to increase Hg capture beyond the inherent Hg capture of PM or SO_2 control devices. Lower emissions can be achieved with increased carbon injection rates.

Hg technology developments

There has been a large reduction in Hg emissions compared to 2011 ICR collected data. Improvements in Hg emissions since 2011 were the result of:

- Wider deployment of mercury control technologies that existed when the MATS regulations were finalized in 2011.
  - Broader use of ACI that had been deployed in states with Hg rules.
  - Use of PM and SO_2 controls to reduce Hg emissions.
- Advances in Hg control technologies that were motivated by the need to control Hg on all coal fired power plants in order to comply with MATS. These included:
  - More advanced activated carbons that required lower treatment rates or were much more effective in situations that had previously been very difficult (for example, the presence of high levels of SO_3 or NO_2). These carbons also had less adverse impact on fly ash marketability, particularly for cement applications, further reducing cost.
  - Chemicals and other technological advances developed since 2011 to improve Hg oxidation and capture in PM or SO_2 control equipment.
  - Improvements in continuous Hg monitoring that facilitated improved monitoring and use of controls, including the ability to quickly identify and correct for potential problems.
- Development of "best practices" that did not exist prior to the adoption of MATS and its requirement to control Hg.
  - Limited experience in 2011 meant that "best practices" had not yet been developed.

Evaluation of Hg emissions data

The database from NRDC's website shows that most of the coal fleet is operating well below the applicable standards. Hg capture was estimated from information in the IPM documentation, Chapter 9. For not low-rank coals, the data demonstrated that:

- There is substantial room for improvement, the top decile had an emissions rate nearly one tenth of the limit.
- The top six deciles are all controlling to over 90% removal, and the top two deciles well over 95% Hg capture.

- The top deciles are more likely to burn bituminous coal and more likely to be located in the East. The bottom deciles are more likely to burn subbituminous coal and more likely to be located in the West.
- The difference between top and bottom units was determined to be more a function of control equipment than coal type.
  - Top units are more likely to be scrubbed and also more likely to have a fabric filter.
  - Bottom decile units are more likely to have ACI controls installed; the data do not indicate the extent to which ACI controls are actually operating or the treatment rates being used.
  - Top decile units did include unscrubbed units with an ESP+ACI, demonstrating that high removal was possible for that configuration.

For low-rank coals it was demonstrated that:

- All units are complying with emissions below the 4 lb/TBtu standard.
- Only two of the units are unscrubbed, and these have BHs. These are also the lowest emitting units.
- Estimated Hg capture rates are generally well below 90% -- much lower than the capture rates that ACI is capable of. This is likely because the higher emission rate limit for these units does not require greater capture rates.
- The large majority of units utilize ACI; the four that don't are scrubbed and may use oxidizing agents or other chemicals to enhance Hg capture in the PM or SO_2 control device.

Impact of reduced emissions rate standards

The coal fleet is currently complying with the Hg emissions standard and in most cases is achieving emission rates that are well below the standard.

- For not low-rank coals, a lower Hg standard of 0.7 lb/TBtu could be complied with at a modest cost to some units, and no cost for most units.
- For not low-rank coals, a lower Hg standard of 0.3 lb/TBtu could be complied with at a modest cost to most units, and no cost for some units. The cost would not exceed 1 mill/kWh and would likely be much less. Units with fabric filters would have very little cost increase, if any.
- For low-rank coals, a lower standard could be complied with, as it appears that the estimated capture rate of these facilities is well below what is possible for available technologies. The highest estimated coal Hg content is 14.9 lbs/TBtu. These seven units are all units burning Texas Lignite, and they are equipped with scrubbers. Two have baghouses, and five have ESPs. Therefore, as scrubbed units, they are all capable of achieving higher capture rates (current capture rates are estimated at 80%-85% based upon 2019 data). About a third of all low rank coal units are already controlling to below 2 lbs/TBtu. A standard of 2 lbs/TBtu would necessitate modest increased cost that would likely be well below 1 mill/kWh, as this is consistent with under 90% removal in all cases. A control level of 1 lb/TBtu might also be justified, as this would require less than 95% capture in every case, and in most cases much less. Units with fabric filters would experience very little cost increase, if any. Wet-scrubbed units could enhance capture using scrubber chemicals at a modest cost, likely well below 1 mill/kWh.
- Table 2 summarizes the estimated impact of reducing the Hg emission limits.

Table 2. Estimated impact of reduction in Hg emission rate standard

Hg limit for not-low rank coal units (current standard 1.2 lb/TBtu)	Units with Electrostatic Precipitators	Units with Baghouses	Overall
0.7 lb/TBtu (equivalent to 90% Hg removal)	• Majority of units would have little to no additional cost • Roughly 25% of units would need to increase ACI treatment at additional cost of 1 mill/kWh or less	• Virtually all units can control to this level with little to no incremental cost	• Less than 50% of units are above 0.7 lb/TBtu
0.3 lb/TBtu (equivalent to 95% Hg removal)	• 75% of units with ESPs would need to increase ACI treatment at cost of 1 mill/kWh or less • If a unit installs a baghouse to meet the PM standard, it would not need any additional ACI	• Most units can control to this level with little or no incremental cost • Few units would incur 0.25 mill/kWh cost or less	• Roughly 50% of units are above 0.3 lb/Tbtu

Hg limit for low rank units (current standard is 4 lb/TBtu)	Scrubbed units	Unscrubbed units
2 lbs/TBtu (< 90% Hg removal)	• Low-Modest cost for most units, no cost for about a third of units	• No cost for one unit; modest cost well under 1 mill/kWh for other two
1 lbs/TBtu (< 95% Hg removal)	• Low-Modest cost of up to 1 mill/kWh for most units	• No cost for one unit; cost of up to 1 mill/kWh for other two

II. Methods of PM Control

Various methods of PM control were examined to identify how they work, how the technologies have been improved since 2011, and what may be possible going forward. This section of the report includes:

- A brief explanation of how these control devices work, to illustrate potential means to improve the performance of the devices and potential limitations on any performance improvements.
- A discussion of the type of improvements that can be performed for an existing control technology, the degree of performance improvement available, and what those improvements might cost.
- A discussion of the impacts of activated carbon injection and gas cofiring on PM control, as these are deployed on a fairly wide level in the industry.
- A comparison of operation of the technology pre-MATS and post-MATS.
- Conclusions regarding possibilities for more stringent emission limitations, and what their cost impact would be.

A. Electrostatic Precipitators (ESPs)

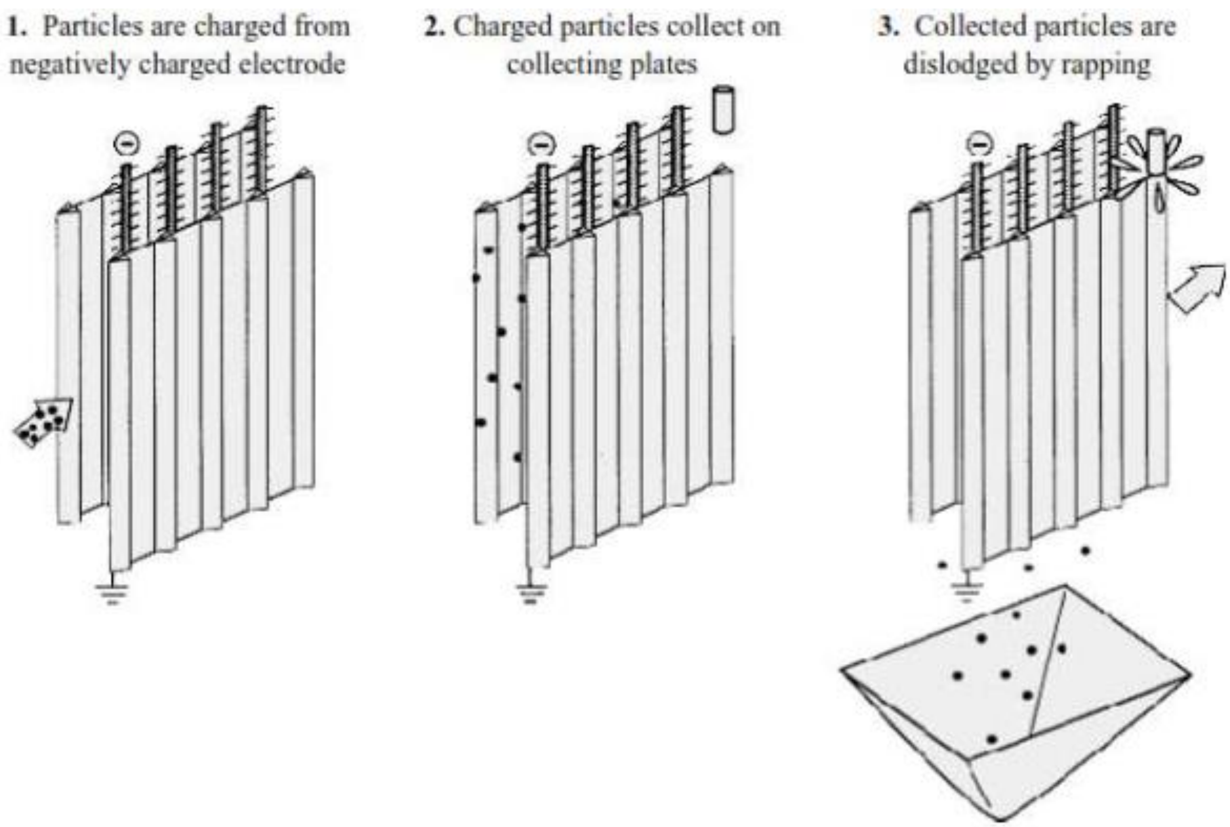
A large majority of coal power plants utilize ESPs for PM emissions control. The following section discusses the major factors that impact ESP performance, how ESPs were generally operated prior to MATS and what has changed since MATS.

How ESPs work

ESPs capture PM emissions by charging the PM electrically so that it is attracted to a collection plate. The untreated flue gas passes through parallel collection plates, between which are placed electrodes that charge the PM. The PM is knocked off of the collection plate by a "rapper," sonic horn, or other device that mechanically knocks off the collected PM (see Figure 1).

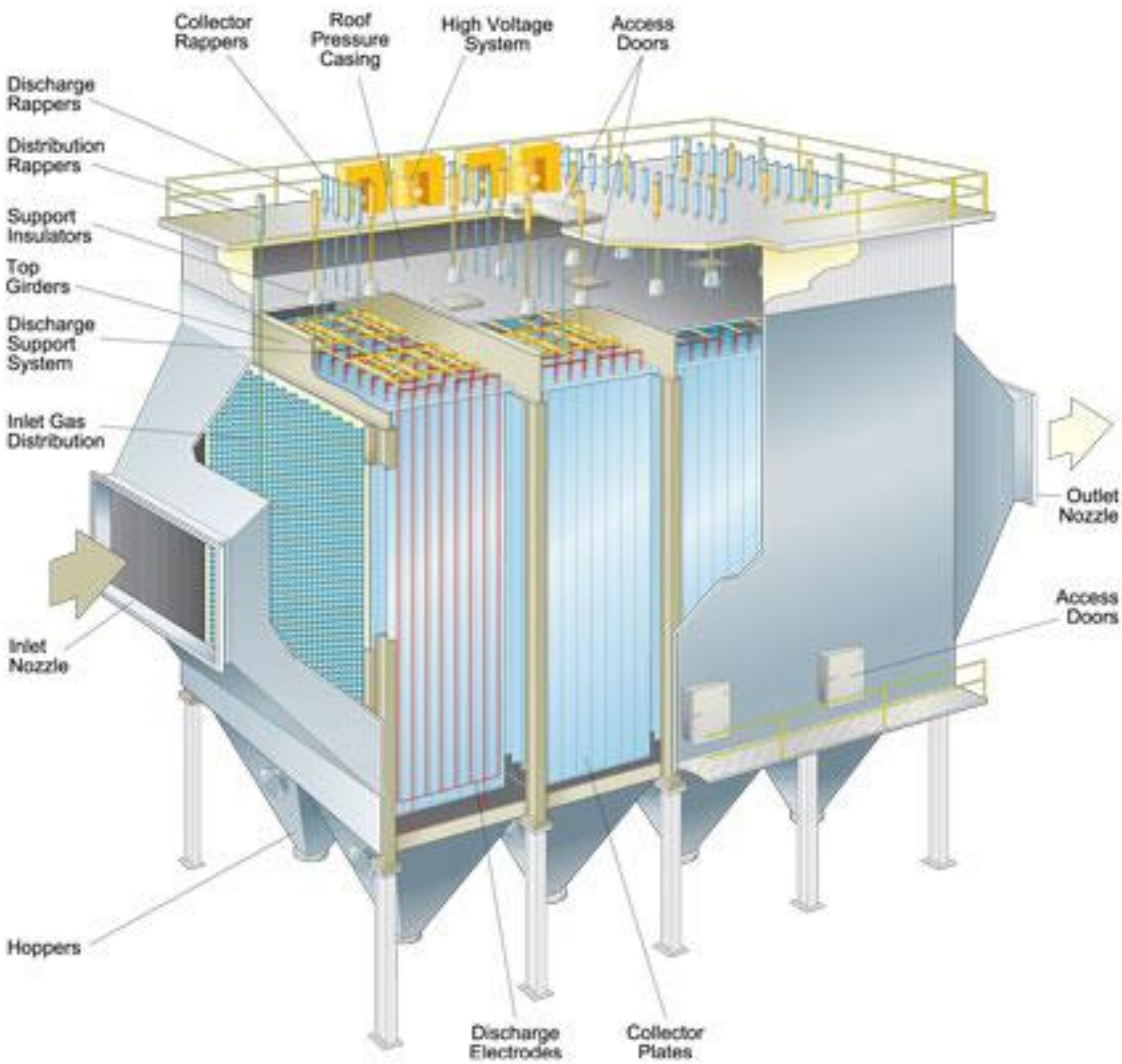
In an ESP, the boiler exhaust gas enters through ductwork, passes through a flow-balancing device in the form of a grid, and then passes through a series of electric fields used to capture the PM. Figure 2 shows an ESP. The gas flow enters from the left in this image. The image also shows the flow passing through several (typically, 3 or more) sequential fields with electrodes and collection plates. Finally, the treated gas exits the ESP to the right.

Figure 1. How an ESP works. [7]



[7] http://www.hamonusa.com/hamonresearchcottrell/products/esp_fundamentals

Figure 2. An electrostatic precipitator, (ESP). [8]



Factors that affect ESP performance

More factors affect ESP performance than FF performance, and the factors that affect ESP performance are often interrelated. Some of these factors and how they are addressed include:

- Treatment time (and flow balancing) – treatment time is the amount of time that the exhaust gas spends between collecting plates as it passes through the ESP. More treatment time improves PM capture. Unbalanced flow means that some parts of the gas have a lower treatment time. Methods to improve (increase) treatment time include:
  - Enlarge ESP, replace internals, improve/balance flow, fix leaks, add fields.
- Re-entrainment – this is re-release of PM when the field is rapped for cleaning, and it will increase outlet PM emissions. It is addressed by:

[8] https://www.babcock.com/resources/learning-center/basic-esp-operation

- Sectionalization – breaking the ESP into multiple, sequential fields so that the final field experiences lower inlet PM loading than the first field. ESPs typically have a minimum of 3 fields and newer ESPs frequently have 5 or more fields.
    - Re-entrainment can establish a threshold of emissions that cannot be lowered below. The degree of re-entrainment will depend upon the design of the ESP, the nature of the fly ash, and especially the number of fields.
- Power level – electrical power into the ESP captures the fly ash, but it may be limited by a number of things that can be addressed by:
    - Repair/replacement of failed electrodes and insulators that limit power input.
    - High frequency transformer rectifiers that improve power that can be input to the ESP.
    - Replacement of internals ("gut and stuff"), weighted wire to rigid discharge electrode (RDE) conversion (improves reliability).
- Resistivity – This relates to the electrical characteristics of the PM being captured. It must be in a proper range – not too high and not too low.
    - Most often a problem of too high rather than too low - often a problem with lower sulfur coals because the presence of SO_3 lowers resistivity to near the ideal level and insufficient SO_3 will increase resistivity to above the ideal level.
    - High resistivity is often addressed through flue gas conditioning – injecting SO_3 or another chemical that improves fly ash resistivity.

As PM emission standards have been reduced over the years, utility ESP treatment times have also become longer, which means that ESPs have become larger for any given coal type and gas flowrate, as shown in Figure 3. Longer treatment times for a given outlet emission rate would generally be associated with lower sulfur coals and shorter treatment times are associated with higher sulfur coals. Lower sulfur coals typically have higher resistivity fly ash that is more difficult to capture and requires longer treatment times or flue gas conditioning by injection of SO_3.

Figure 3. ESP treatment time, required particulate emissions and typical treatment times. [9]

Date	Required Particulate Emissions, LB/MMBTU	Typical Utility ESP Treatment Time, Seconds
1970s	0.10	5-13
1980s	0.03	7-20
1990s	0.03	8-25
2000s	0.015-0.03	10-25

Longer treatment time means a larger ESP

[9] R. Mastropietro, "Electrostatic Precipitator Rebuild Strategies For Improved Particulate Emissions"

ESP operation prior to MATS and improvements since 2011

Prior to MATS, most ESPs did not receive significant attention, unless a significant problem arose. This is because PM was not monitored or reported with the regularity of pollutants such as NOx or SO_2. Continuous PM emissions monitoring was only installed on units that had installed these devices in response to Consent Decrees or other state requirements. Prior to MATS, for most coal units the only continuous monitoring device intended for PM was an opacity monitor, which is a far less reliable indicator for PM because it monitors a surrogate for PM. Stack tests were performed on perhaps a yearly basis as determined by the state requirements. As a result, problems could go unnoticed for a while, or would not be noticed until they were significant enough to get attention, and this inattention resulted in higher PM emission rates over time.

MATS emission rate requirements and monitoring requirements (continuous PM monitor or, alternatively, quarterly stack tests), and especially the need to report the results, made operators of coal-fired power plants much more attentive to the PM control devices, including ESPs.

Prior to MATS, many of the coal units had substantial room for improved PM emissions performance simply because the limited monitoring and reporting requirements had often left problems unidentified or unaddressed. These problems included ductwork and casing leaks that resulted in more than design gas flow through the ESP (lowering treatment time), damaged or out of service fields or electrodes, etc., correction of uneven flow, and other factors.

Fundamental ESP technology has not experienced revolutionary changes since 2011; however, since 2011 various technology improvements have been deployed across the population of ESPs. Furthermore, as will be shown, there are numerous ESP improvement methods that were available in 2011 which may have been deployed since then and in some cases could still be deployed. Not all of these methods were considered in EPA’s 2011 assessment and/or the costs of these methods are lower than what EPA assumed in 2011. Moreover, after years of minimizing the attention given to ESPs, industry has learned and started to adopt “best practices” associated with monitoring ESP operation more carefully and maintaining the ESP regardless of whether or not they have made any modifications to the ESP.

There is no universal type of ESP rebuild or other improvement. Across the fleet of ESPs, the improvements, if any, were tailored to the particular situation. As a result, some units have deployed more intensive ESP improvements than others. In many cases, more could be done, often at costs of between $20-$50/kW. Furthermore, depending upon the treatment time, coal characteristics and degree of sectionalization of the ESP, there is a limit to the outlet emission rate that is possible due to the phenomenon of re-entrainment in the final ESP field. As a result, some ESPs will reach a practical limit to what is achievable with the existing ESP without adding more fields or adding a baghouse. These types of projects could cost over $50/kW for adding more fields and on the order of $150/kW-$200/kW for addition of a baghouse. The specific costs of these methods are addressed in the following section. The degree to which these retrofits would be necessary would depend on the specific emission limit of a future standard, because there are less expensive means to reduce PM emissions from the ESP at higher emissions limits. This is discussed in more depth below.

Methods for improving ESP performance

There are many ways to improve ESP performance. Cost and performance improvement estimates for each method are approximate and will vary depending on site specific factors. In its IPM v4.10 documentation, US EPA estimated the cost of three methods for improving ESP performance.[10] It is notable that, at the time, EPA was evaluating a proposed PM limit that included condensable PM, which was changed in the final MATS rule. This is partly why the filterable PM trigger points for the three options are all below the filterable PM limit in the final rule. The three methods for upgrading ESP performance included:

- Option 1: High frequency transformer rectifier (HFTR) sets, at an estimated capital cost of $55/kW to be installed for PM emissions up to 0.005 lb/MMBtu.
- Option 2: HFTR and replacement of ESP internals, at an estimated capital cost of $80/kW at PM trigger points over 0.005 up to 0.01 lb/MMBtu.
- Option 3: HFTR, replacement of ESP internals, and addition of an ESP field, at an estimated capital cost of $100/kW at PM trigger points over 0.01 up to 0.02 lb/MMBtu.

In effect, in this methodology every unit with an ESP would incur a cost of at least $55/kW. EPA also included a fourth option of installing a fabric filter in the event filterable PM emissions were over 0.02 lb/MMBtu. Costs of installing a fabric filter will be discussed later. The discussion that follows will demonstrate that there are additional means to improve ESP performance and that the cost and performance improvement estimates in the IPM v4.10 documentation are higher than what has been found in this effort.

The various ways to improve ESP performance, along with the associated approximate costs, include the following: [11]

Repair casing leaks and/or improve flow balancing

- Boiler casing, duct and air preheater leaks increase the flowrate through the ESP, reducing treatment time and adversely impacting performance.
- Imbalanced flow will also result in portions of the gas having low treatment time, which adversely impacts performance.
- Many coal plant operators have learned to live with air preheater leakage of over 20%, which is a large waste of energy.[12] A more reasonable level of leakage is 10% or less.

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[10] Table 5-25 of the 4.10_MATS IPM documentation: https://www.epa.gov/sites/production/files/2015-07/documents/suppdoc410mats.pdf. Three methods of improving ESP performance are shown along with the cost of a fabric filter retrofit.

[11] Costs discussed here are approximate. Data taken from electric utility projects to support these costs will be discussed later.

[12] https://www.power-eng.com/emissions/air-heater-improvement-small-investment-quick-payback/#gref; the vast majority of air preheaters are of the regenerative type, which have an intrinsic amount of air leakage that ideally is minimized.

- Usually, this is a relatively inexpensive improvement. This is not expected to cost much more than about $20/kW.
- A 20% reduction in flow will yield a 25% increase in treatment time – equating to roughly a 40% reduction in PM emission rates.[13]
- A benefit of this is an improvement in boiler heat rate thus reducing the net cost of the improvement because of lower fuel costs. Replacement of air preheater seals (not the entire air preheater) is a relatively inexpensive improvement that provides a good payback.[14]

Repairing the ESP – with in-kind equipment

- Damaged fields can result from wear and tear and leave a portion of the gas untreated – effectively, shortening treatment time.
- Repair or replacement of failed insulators, electrodes or even plates can restore performance – yield perhaps up to 20% - 30% improvement or more, depending upon the defect being corrected.
- Cost depends upon nature of repair, but generally are about $20/kW or less.

Install High Frequency Transformer Rectifier Sets (HFTR) (equivalent to Option 1 of EPA's three options from IPM v4.10, where EPA estimated the capital cost at $55/kW)

- HFTR sets do the following:
  - Change electrical controls to increase the frequency of charging the electrodes.
  - Increases the amount of power put into the ESP and used to charge particles.
- An inexpensive means to achieve moderate improvements in PM emissions.
- Few ESPs had this upgrade prior to MATS
- On the order of 20%-30% improvement or more at a cost of about $10/kW or frequently less.
- This is at a low cost and provides a good benefit. Therefore, HFTR was deployed in response to MATS at many locations.

Improving ESP Reliability – upgrade to newer or more reliable components, even if not damaged

- Replacement of electrodes and insulators.
- Replacement of damaged plates.
- Replacement of weighted wire electrodes with rigid discharge electrodes.
- Cost and performance improvement will vary depending upon what is done.

Complete rebuild within existing casing (aka, "gut and stuff") (equivalent to Option 2 of EPA's three options from IPM v4.10, where EPA estimated the capital cost at $80/kW)

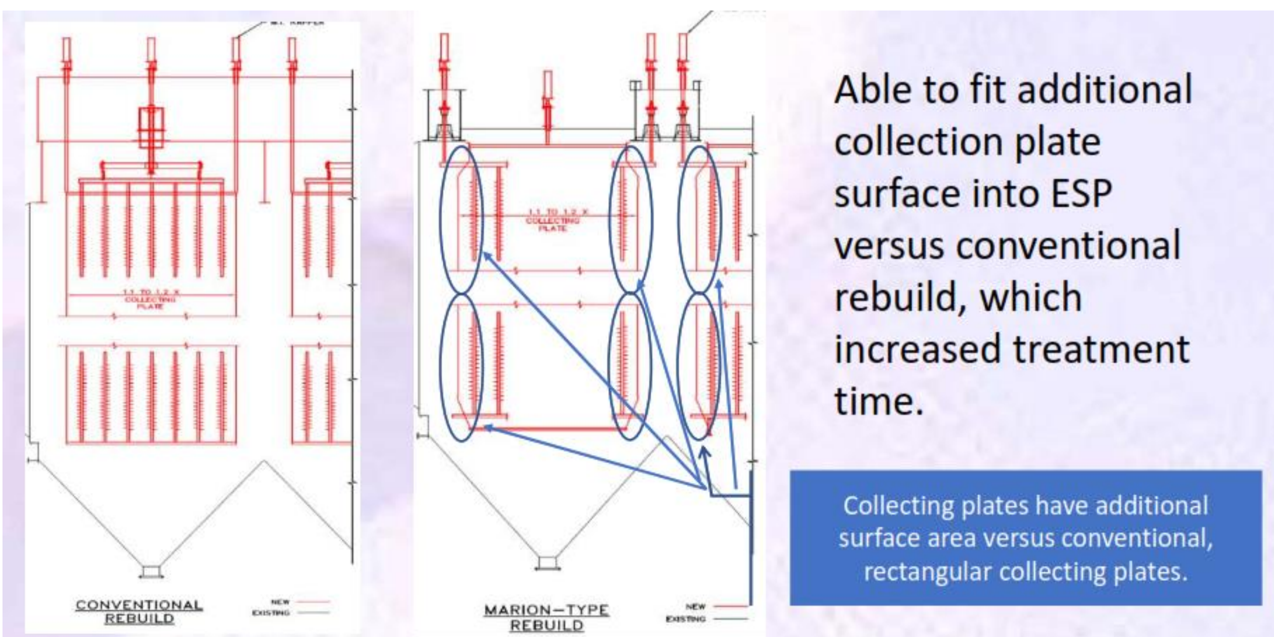
- This entails replacing all of the internals within the existing ESP casing and normally the associated ESP control and power electronics as well. Although there may be casing or ductwork repairs, it

[13] See R. Mastropietro, "Electrostatic Precipitator Rebuild Strategies For Improved Particulate Emissions" for information that shows the relationship between treatment time and emission rate
[14] https://www.power-eng.com/emissions/air-heater-improvement-small-investment-quick-payback/#gref

generally does not require significant changes to the ESP casing or support structure or ductwork because it works within the existing casing and ductwork. This rebuilds the ESP to original performance, or perhaps better since components and controls have improved. This would typically include HFTR upgrade since the cost of including it is relatively small and electrical controls are normally being replaced in any event.

- This is less of a major upgrade as much as a restoration of the ESP to "like-new" condition, or better. It should be done periodically because of routine wear and tear and associated deterioration of performance – perhaps every 25 years or so - simply to restore the performance of the ESP. The level of wear and tear will be determined by the specific application, with some more challenging than others. Although this sort of upgrade is recommended, these are not universally performed on old or degraded ESPs if emissions are within the limit. If performed more frequently, this type of upgrade would make PM emissions lower and more consistent than what is experienced with historical practice.
- Benefits include higher power input and greater reliability, and typically can improve treatment time as well by optimizing the treatment volume within the existing ESP casing. An example is the rebuild at Southern Illinois Power Company's Marion unit #4, as shown in Figure 4. 2011 EIA Form 923 shows typical PM emissions of 0.04 lb/MMBtu for this unit, while the reported PM emissions in 2019 for it averaged 0.00343 lb/MMBtu,[15] or a roughly 91% reduction in PM emissions, achieving an emission rate roughly one ninth the MATS PM emissions limit.
- Cost would be about $50/kW – and will vary depending upon the specifics of the ESP.

Figure 4. Rebuild at Southern Illinois Power Company's Marion unit #4. [16]



[15] See NRDC database

[16] R. Mastropietro, "Electrostatic Precipitator Rebuild Strategies For Improved Particulate Emissions"

Increasing the casing volume to increase treatment time (Equivalent to Option 3 of EPA's three options from IPM v4.10, where EPA estimated the capital cost at $100/kW)

- This entails rebuilding the ESP in a manner that increases treatment time beyond what is possible within the existing ESP casing – raising height, adding fields, or other work outside of the existing ESP casing, along with improvement of existing equipment.
- This can be done by adding fields, adding a parallel chamber, or increasing height of the ESP, as shown in examples in Figure 5, Figure 6, and Figure 7, respectively.
- This is the most expensive option relative to other measures detailed above and therefore this is a fairly rare retrofit. The cost is normally between $50/kW and $80/kW, perhaps higher in some cases. Additional fields for an ESP have been estimated to be in the range of $65/kW for some projects. It will often include HFTR upgrade.
- This also requires having adequate space, which is a major limitation on this type of improvement.

According to data presented by Mastropietro,[17] a roughly one-third increase in treatment time will reduce emissions by about 50% and a roughly two-thirds increase in treatment time will reduce PM emissions by about 70%. There is a threshold where further PM emission reductions will not be possible. This is because of the effect of re-entrainment emissions from the final field of the ESP. The impact of re-entrainment on outlet emissions will be determined by the particulars of the ESP, especially, the number of fields, but also inlet loading, condition and treatment time of upstream fields, and resistivity of the fly ash. As a result, some ESPs may not be able to achieve an adequate reduction in emission rate without addition of fields in a major ESP upgrade or addition of a fabric filter.

Because major ESP upgrades that add fields or expand the ESP casing become costly and may be limited by space, such upgrades are rare, and a utility will seriously consider the alternative of a BH. A BH retrofit will cost significantly more than a major ESP retrofit, but it offers several advantages for control of mercury and acid gases as well as PM, as will be discussed later.

[17] Mastropietro, "Electrostatic Precipitator Rebuild Strategies For Improved Particulate Emissions"

Figure 5. ESP rebuild that adds an additional field [18]

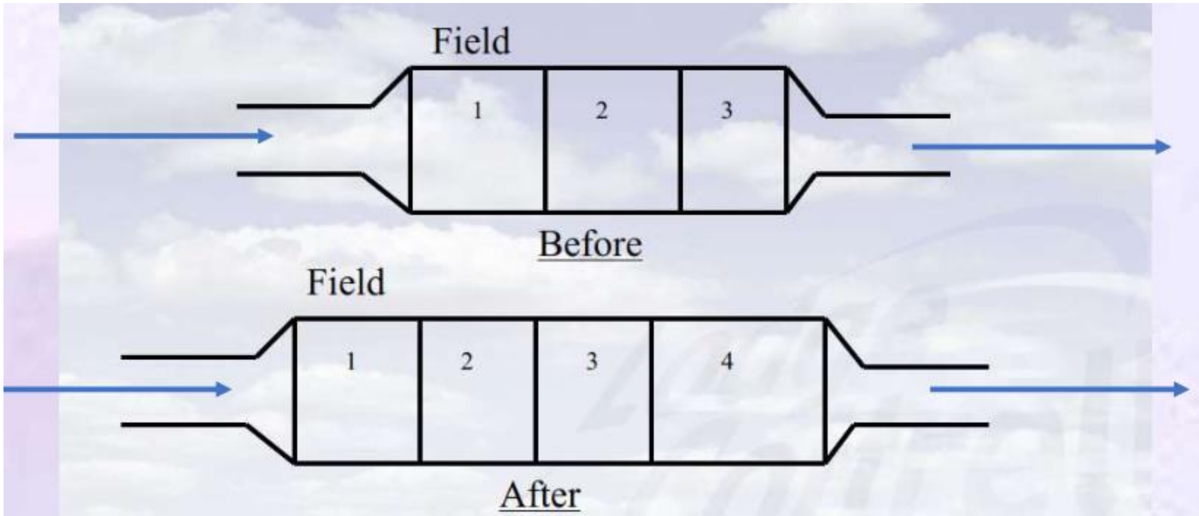
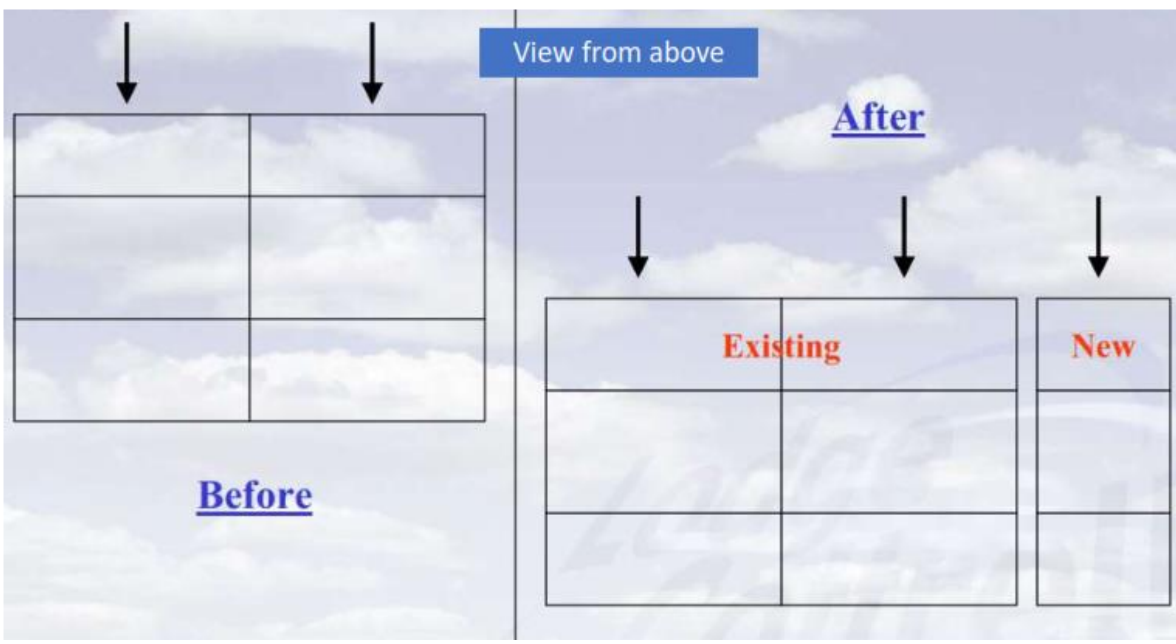
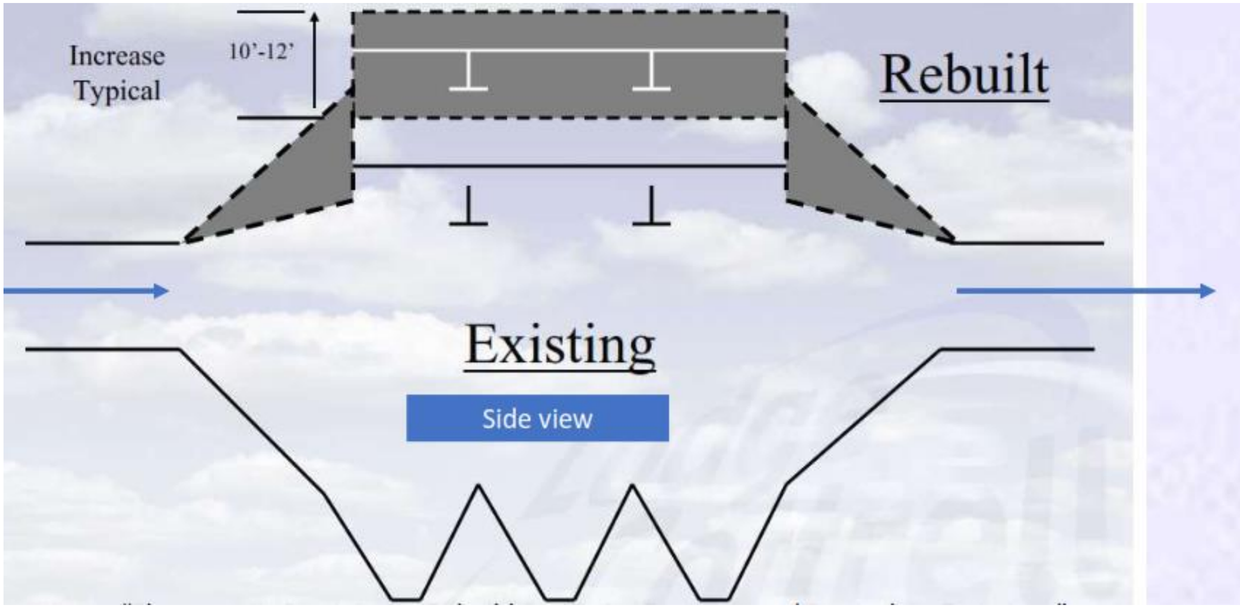


Figure 6. ESP rebuild that adds a parallel chamber[19]



[18] Ibid.
[19] Ibid.

Figure 7. ESP rebuild that increases the height of the ESP [20]



Data on cost of ESP upgrades

ATP has assembled data collected from utility capital budgets that it has reviewed in the normal course of its business. The data, that is presented in Table 3, has been normalized to a $/kW (2012 $) basis and any information that could be used to identify the plant or unit is not provided. In some cases, the details of what was included in the budget was not available. The costs range from a low of $4/kW for HFTR upgrades on one unit to over $80/kW for ESP changes that included increased volume. Additional fields for an ESP were in the range of $65/kW. Duct repairs cost in the range of about $6-$18/kW. In some cases, this includes repair of expansion joints that are used to connect ductwork and allow for thermal expansion. The expansion joints are frequently the locations of leaks. The large number of HFTR project budgets is an indication of the attractiveness of this approach. Every project is unique. For any other situation, these costs should be regarded as indicative of rough cost estimates, recognizing that there might be some significant differences. Some applications that included HFTR sets also included other ESP improvements, including repair or replacement of some ESP components, such as electrodes, insulators, and plates. Some of these projects did not proceed because the unit was ultimately retired, but that is not believed to impact the validity of these utility estimates. The data on installation of a wet ESP is shown, and this data will be discussed later.

[20] Ibid.

Table 3. Costs for ESP upgrades or modifications.[21]

Row Labels	Average of $/kW	Max of $/kW	Min of $/kW	Count of projects
Add Field to ESP	$65	$65	$64	2
Additional ESP	$52	$52	$52	1
Duct Repairs/expansion joint	$14	$18	$6	4
ESP (HFTR)	$8	$25	$3	32
ESP Changes (incl enlargement)*	$22	$82	$3	22
ESP Tune-Up	$4	$6	$2	2
WESP	$175	$180	$160	7
* The wide range of costs and large number of projects is indicative of a wide range of project types – from minor ESP changes to far more major ones. For these projects, the project description either did not have adequate detail to clearly put it into another project category, or it included several project characteristics.				

Impact of activated carbon on ESPs

As described by Mastropietro,[22] activated carbon will slightly reduce the resistivity of the fly ash. This small positive impact on PM capture generally offsets the small increase in inlet PM loading. So, for well-designed and functioning ESPs, ACI generally does not increase outlet PM emissions. As Staudt has described, experience has shown that ACI has had no measurable adverse impact on outlet emissions of the ESP.[23]

Effect of cofiring natural gas on ESP operation

The cofiring of natural gas with coal will reduce exhaust gas SO_3 concentration somewhat, increasing fly ash resistivity and adversely impacting PM capture. Cofiring natural gas will also reduce PM inlet loading. The impact of resistivity on reduced capture will usually be greater than the impact of reduced inlet PM loading on outlet PM emissions. However, reducing fly ash resistivity is easily performed at a very low cost with flue gas conditioning, which is widely used for ESPs on boilers that have changed fuels to lower sulfur coal.

B. Fabric filters (aka baghouses)

The terms fabric filter and baghouse will be used interchangeably in this report. They refer to the same device and these terms are commonly used interchangeably in industry.

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[21] These are reported in 2012 $ and can be escalated to 2020 $ using the CEPCI. The 2012 CEPCI was 584.6 and the 2020 CEPCI was 596.2, or roughly 2% increase in cost. Additional data is in the appendices.

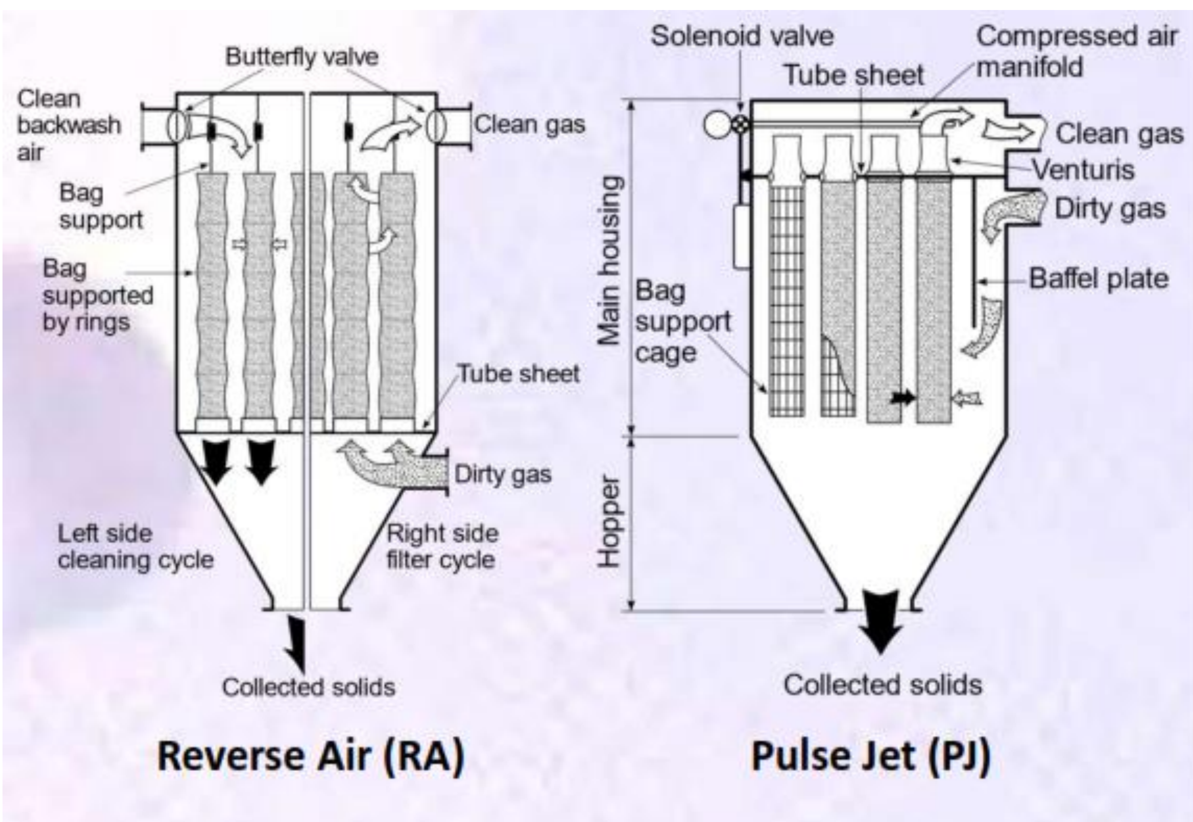
[22] Mastropietro, R., "Fly Ash Resistivity with Injected Reagents and Predicted Impacts on Electrostatic Precipitators," http://www.carmeusena.com/sites/default/files/brochures/flue-gas-treatment/tp-LCI-NOL-TEC-Systems-inj-reagents-fly-ash-resistivity-ESP-perf.pdf

[23] Staudt, J., "Does ESP Size Really Matter", at https://www.andovertechnology.com/wp-content/uploads/2021/06/Does-ESP-size-really-matter.pdf.

How they work

Fabric filters used in coal fired power plant applications are predominantly of two types: reverse air (RA) or pulse jet (PJ), pictured in Figure 8. In both cases, untreated flue gas enters the baghouse and passes through a fabric filter that is in the shape of a long cylinder (which for PJ baghouses is closed at the bottom and for RA baghouses is often closed at the top – thus, the term filter "bag" or "baghouse"). The fabric filter separates the particulate matter from the gas, and the treated flue gas then leaves the baghouse. In the case of RA baghouses, the gas typically passes from the inside of the cloth cylinder to the outside of the cylinder. For PJ baghouses the gas passes from the outside of the fabric cylinder to the inside of the cylinder (the cylinder is closed at the bottom and sealed to a tube sheet at the top). An internal wire cage prevents collapse of the filter bag during operation. The treated flue gas leaves the fabric filter through the top. The filters must be periodically cleaned. For RA baghouses, a portion of the baghouse called a compartment is shut off from the untreated gas flow, and treated air is passed through in a reverse direction that causes the collected PM to fall to the bottom of the baghouse. Rings prevent collapse of the filter bag during cleaning. For PJ baghouses the filter bags are periodically cleaned by a jet of pulsed air introduced to the open top of the bag, flexing the bag fabric outward, and causing collected PM to drop to the bottom of the baghouse. For both baghouse types, the solids collect in the bottom hopper of the baghouse and are discharged to the ash collection system.

Figure 8. Reverse Air and Pulse Jet baghouses

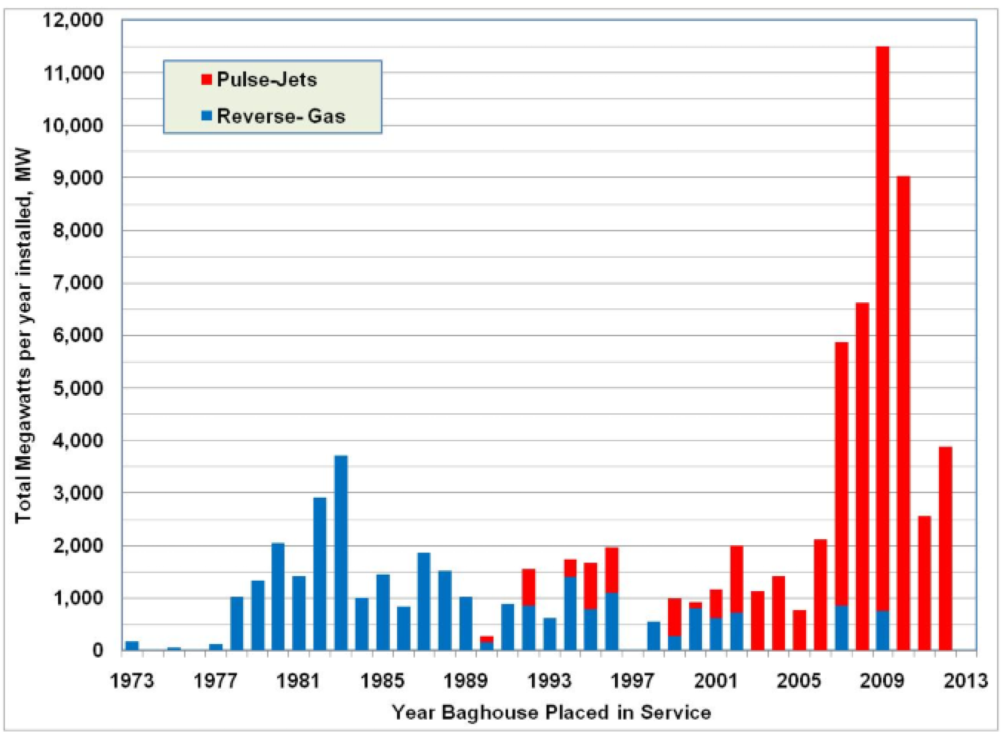


Newer baghouses tend to be PJ type since they are frequently less expensive to build[24] and more compact in size because they can handle a higher gas flowrate for a given square footage of filter fabric (see Figure 9). A PJ baghouse does not have to shut down a compartment in order to clean but they require more durable fabrics because the cleaning is more energetic. More reliable and durable fabrics have made PJ baghouses more attractive today.

The cost of a fabric filter retrofit will be dependent upon the size of the unit and the complexity of the site. Sites that require long duct runs to accommodate locating the baghouse will be much more expensive than others. Figure 10 shows reported costs of fabric filter retrofits. As shown, most retrofits are in the range of about \$100/kW to \$250/kW. However, some may be more expensive due to site space limitations that would make it necessary to have long duct runs.

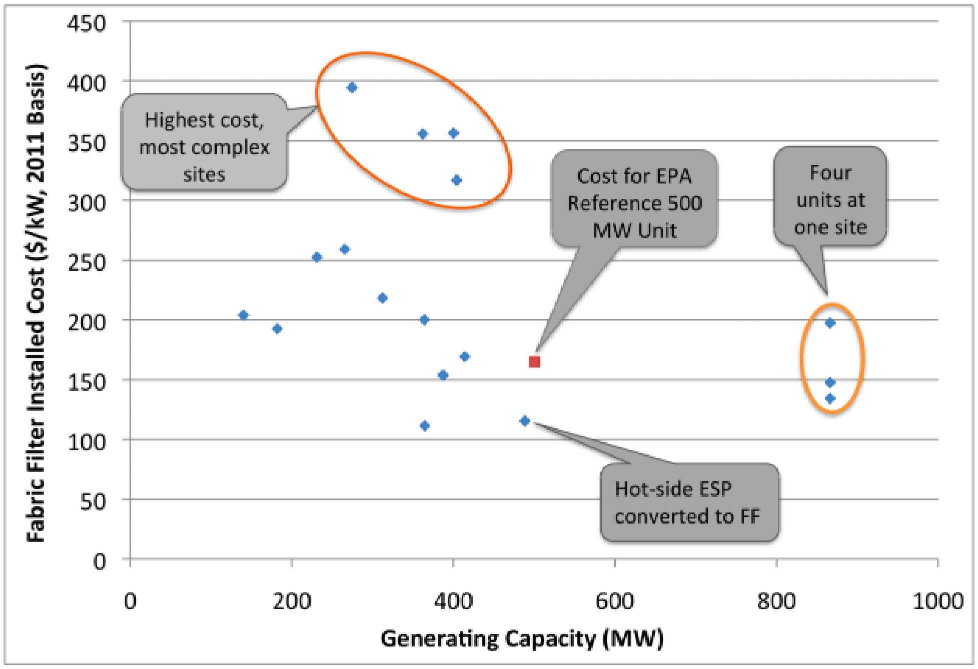
An important design parameter for baghouses is air-to-cloth ratio, or AC. AC is equal to the actual cubic feet per minute of gas flowrate through the baghouse divided by the square footage of filter material in the baghouse. There is an advantage to operating at a lower AC because fabrics last longer; however, that requires a more expensive baghouse that must be larger to accommodate more filter fabric for a given, treated gas flowrate. PJ baghouses have a somewhat higher AC than RA baghouses designed for the same gas volume flow rate.

Figure 9. Installation history of RA and PJ baghouses by US Power Plants[25]



[24] How much less expensive will depend upon a number of factors, to include coal type, the selection of fabric, and other factors.
[25] EPRI Power Plant Baghouse Survey, 1019729. 2010

Figure 10. Reported costs of baghouse retrofits (2011 $)[26]



Factors that affect fabric filter performance

PM emissions from a baghouse will increase as filter material fails through one of three means: (1) mechanical failure, such as abrasion or excessive flexing; (2) thermal degradation, or overheating of material; and (3) chemical degradation from acids or other harsh chemicals in the exhaust gas. The other ways that PM emissions from a baghouse can increase include leakage that bypasses the bag filter from tubesheet seal leakage or corrosion of the tubesheet or other parts. Coal operators can reduce abrasion and wear and tear through lower bag cleaning frequency because each bag cleaning event stresses the filter bags. Blinding of bags can occur when the flow of flue gas through portions of the filter bag is reduced or cut off due to deposits on the bags that are not readily cleaned off by regular cleaning events. Blinding can be due to moisture or other effects, and it will adversely impact filter bag life because more air must be forced through the unblinded portions of the bags, which stresses the bags. To extend bag life and reduce PM emissions over time, operators should optimize bag-cleaning frequency to reduce blinding but avoid stress from overcleaning.

Baghouse operation prior to MATS and advancements since 2011

Prior to MATS, most baghouses did not receive attention until there was a significant problem. PM was not monitored or reported with the same regularity of pollutants such as NOx or SO_2. Continuous PM emissions monitoring was only installed on units that had installed these devices in response to consent decrees or other state requirements. For most operating coal plants, the only continuous monitoring

[26] Cichanowicz, J.E., "Current Capital Cost and Cost-Effectiveness of Power Plant Emission Control Technologies", prepared for Utility Air Regulatory Group, July 2013; Costs are in 2011 $. They can be approximately escalated to 2020 $ using the Chemical Engineering Plant Cost Index (CEPCI). The 2011 CEPCI was 585.7 and the 2020 CEPCI was 596.2, or roughly a 1.8% increase

device intended for PM was an opacity monitor, which is a far less reliable indicator for PM performance than a CEMS device. Stack tests were performed on perhaps a yearly basis as determined by the state requirements. As a result, problems could go unnoticed for a significant period of time or would not be noticed until they were significant enough to get attention.

MATS emission rate requirements and monitoring requirements (continuous PM monitor or, alternatively, quarterly stack tests) made operators of coal-fired power plants much more attentive to the operations and performance of their PM control devices.

Because a baghouse can achieve very low PM emissions, to comply with MATS, units that already had baghouses in place frequently improved their performance by simply addressing pre-existing problems. These problems that often did not get addressed in a timely manner included ductwork and casing leaks that resulted in more than design gas flow. This leakage increased bag cleaning frequency and fabric filter pressure drop, contributing to greater stress on fabrics. Other problems included failure of filter bags, blinding of bags, and leakage of plenum seals, which all contributed to increased PM emissions.

Apart from improvements in fabric technology, discussed in the following section, most of the underlying engineering associated with baghouse technology has only experienced minor changes over the past decade. However, MATS forced companies to deploy improved fabric materials and improved operating practices described above. For example, there is more widespread use of membrane and P84 felted bags than before MATS. Efforts to reduce leakage and take measures to minimize risk of bag failure have been deployed. All fabric filters are capable of very low filterable PM emission rates; the substantial variation in emissions among fabric filter-equipped units is the result of the degree to which improved fabrics and operating practices have been deployed.

Because fabric filter failure creates risks of high PM emissions, more durable materials have been developed over the years, and this development has continued since 2011. Table 4 shows a list of some fabrics that are used. For example, fiberglass, once the most widely used material (and one that heavily relied upon filter cake for high filtration), has largely been replaced by other materials, such as NOMEX and PPS (Ryton), P84 and Teflon-coated bags that are more durable and clean more easily. The newer fabrics are more expensive, but also more reliable. PPS felt was found in a 2010 EPRI survey to be the most common fabric for pulse-jet fabric filters.[27] As these bag materials have evolved, durability against flexing, abrasion, high temperatures and harsh chemistry have improved reliability, having a positive impact on emissions performance. Felted and coated fabrics are also less reliant on a base particulate layer for filtration. This is helpful for performance because when a cleaning event removes a base layer of PM from a fabric that relies upon that base layer for filtration of the finer fractions of PM, some finer PM fractions may pass through the fabric filter. Coated fabrics, such as Teflon or Goretex or P84 felt, also clean more easily than other fabrics, which means that less energetic and less frequent cleaning may be possible. The benefit of less frequent cleaning is that this reduces the wear and tear that could damage filter bags and lessen the effectiveness of the baghouse in capturing PM. Some fabrics, such as P84, are intrinsically more effective as filters but are also more expensive. Therefore, they may be used in a

[27] EPRI Power Plant Baghouse Survey, 1019729. 2010

composite form in combination with a less expensive material. P84 fabric, for example, which is often used as a needle felt on a less expensive substrate (such as fiberglass), has irregularly, multi-lobe shaped fabric (not cylindrical) that has interlocking fibers that offer finer filtration in a manner similar to a membrane.

Table 4. Fabrics used in utility coal-fired applications [28]

Standard Fabrics Used in Utility Coal-Fired Boiler Applications 1

	Acrylic	PPS	Aramid	Fiberglass	P84	Pleated elements
Max Operating Temp	265 F	375 F	400 F	500 F	500 F	Dependent on base fabric
	130 C	190 C	204 C	260 C	260 C	
Concerns in coal fired boiler applications	Lowest maximum operating temperature.	Susceptible to degradation at elevated temperatures coupled with oxygen levels over 12%.	Not as capable as PPS in chemically active gas stream environment.	Woven style fabric that is more fragile than other options. Requires tight tolerance to be maintained on bag-to-cage fit in pulse jet applications.	Dimensional stability at higher temps over 400 F. Requires oversizing of filter to maintain proper bag-to-cage fit.	Air to cloth ratio must be below 3.5 to 1. Applicable only when additional cloth area is needed to lower air to cloth ratio and eliminate inlet abrasion.
Relative Cost	$	$$$	$$$	$$	$$$$	$$$$$
Fabric treatments to improve performance	**ePTFE Membrane:** Laminated to collection surface-most efficient option, enables fabric to handle system upsets reviewed in paper at more consistent airflow/less cleaning frequency.					
	Micro-denier fibers/Tri-lobal fibers: Creates improved efficiency over standard fibers by increasing total fiber surface area. Limited improvement over ability to handle upset conditions reviewed.					
	PTFE Coating: Non-membrane surface coating used to improve dust cake release-sacrifices ability to maintain consistent airflow leading to increased cleaning frequency/high differential pressure.					
	Singe: Removes some of the fabric surface area, creating an improved ability of the fabric to release dust cake. Limited improvement over ability to handle upset conditions reviewed.					

According to Sargent & Lundy, the cost of filter bags has increased between 2012 and 2017, largely a result of improvement in filter bag materials. For this reason, they incorporated an escalation factor for bags in their cost estimating algorithm, but they did not provide guidance on the factors to use.[29]

Methods to improve baghouse performance

There are several ways to improve fabric filter performance, including the following:

- **Reducing boiler casing and ductwork leakage will reduce the amount of gas that must be pulled through a fabric filter, which effectively reduces air to cloth ratio**
    - Lower pressure drop means less frequent cleaning and longer bag life, which makes filter bags less prone to failure and high PM emissions.

[28] https://www.power-eng.com/emissions/air-pollution-control-equipment-services/real-world-performance-results/#gref

[29] https://www.epa.gov/sites/production/files/2018-05/documents/attachment_5-7_pm_control_cost_development_methodology.pdf, page 9

    - Less dilution from leakage means higher temperatures, less condensation and blinding, lower pressure drop, less frequent cleaning, and longer bag life, which means that filter bags are less prone to failure and high PM emissions.
    - Lower gas flow means less risk of leakage around bag seals.
    - This also offers the benefit of lower induced draft fan load, which has the benefit of lowering cost because of lower parasitic load.
- **Installation of bag leak detectors and greater attention to baghouse maintenance**
    - Leak detectors are PM measuring devices installed on a baghouse that can identify leakage in a baghouse compartment to help make an early diagnosis of a bag failure. They are different from CEMS, which are used for compliance measurements and are installed farther downstream. Having a leak detector on a compartment will help identify the offending bags and can potentially be more sensitive in identifying a failure than a PM CEMS that senses the total gas flow rather than just one compartment. PM CEMS are independently useful in detecting problems with baghouses, such as damaged bags.
- **Regular inspection to detect damaged bags, corrosion of fabric filter plenum and bypass of filter bags**
- **Optimizing bag cleaning frequency**
    - This is something that should always be pursued to minimize risk of filter bag failure.
    - Frequent cleaning can prematurely wear out bags and can cause higher PM emission rates.
    - Bag cleaning schedules should be based on the differential pressure across the baghouse. Ignoring differential pressure can result in cleaning that is either too frequent or too infrequent.
- **Use of more reliable and better filtering fabrics**
    - A wide variety of fabrics are available, as previously addressed.
    - Improved fabrics are less likely to fail due to chemical, thermal or abrasion failure (longer life in harsher environments).
    - Improved fabrics offer more effective cleaning (especially, for membrane-coated bags), which reduces cleaning frequency and extends bag life.
    - PTFE membrane-coated bags and felt bags are less reliant upon establishing a filter cake for achieving high filtration effectiveness.
    - More durable materials, such as NOMEX and PPS (Ryton), P84 and Teflon-coated bags; also less reliant upon filter cake
    - To realize the benefits of more expensive fabrics (like P84) at a more modest cost, they are often used in combination with less expensive fabrics in composite filter media.

- **More frequent bag replacement, costs are estimated as follows:**
    - Operating costs associated with bag replacement are roughly $0.069/MWh of operation for air-to-cloth ratio of 4, and about $0.073/MWh of operation for air-to-cloth ratio of 6 based upon Sargent & Lundy study for EPA.[30]
    - For example, a 500 MW coal plant that operates at a 75% capacity factor, would spend about $230,000 per year or $1.15 million over five years. Five years would be a typical bag life.[31]
    - This translates to $2.3/kW for a complete bag replacement. Conservatively accounting for the potential for higher cost fabrics means that a cost in the range of $2/kW to $5/kW may result every 3-5 years. Better bag materials will increase the cost of the replacement but will also generally result in better filtration and longer bag life. So, more frequent bag replacement combined with better materials will have the best result for PM emissions but may be more than necessary for a particular PM emission level.
    - How much of an improvement in PM emissions will result from bag replacement depends heavily upon the condition of the bags that are being replaced – but new bags in a well-functioning baghouse are capable of providing PM emissions under 0.0015 lbs/MMBTU based on current performance data discussed in a later section.
- **Reduce air-to-cloth ratio though addition of bag compartments.**
    - Adding additional compartments can lower cleaning and lower pressure drop – resulting in longer bag life.
    - This is more expensive than other approaches, but less expensive than a new baghouse. This is generally only done if other approaches prove to be inadequate, and it is determined that current air-to-cloth ratio is too high.

Impact of activated carbon on baghouse operation

In a normal, full-burden baghouse (no upstream ESP), ACI will increase the inlet PM burden to a baghouse, but this is typically much less than one percent of the normal fly ash loading – essentially, less than normal fly ash variability. For example, fly ash into a PM control device typically averages between about 5 and 10 lbs/million Btu of heat input. If ACI is used at a treatment rate of under 1 lb/million ACF and a boiler has about 4000 ACFM per MW and a heat rate of 10,500 Btu/kWhr,[32] the result is about 0.02 lb of activated carbon/MMBtu, or only about 0.3% of the fly ash input to the fabric filter – well below the typical variability of ash loading. In fact, ACI treatment rates for fabric filters are typically well below 1 lb/million ACF and would therefore have much less impact than 0.3% of fly ash loading. So, the impact of ACI on downstream fabric filter operation is negligible.

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[30] https://www.epa.gov/sites/production/files/2018-05/documents/attachment_5-7_pm_control_cost_development_methodology.pdf. This is calculated using the equation for VOMB on pages 10-13 and using a gross heat rate of 10,500 Btu/kWh and assuming subbituminous coal.

[31] Ibid.

[32] These are common estimates of gas flowrate and heat rate

Impact of natural gas cofiring on baghouse operation

Natural gas cofiring will reduce the PM burden to the baghouse in proportion to the percentage of coal that is replaced. Reduced PM loading will reduce bag cleaning frequency, which will improve filter bag life and improve emissions. It will also increase moisture while reducing SO_3 content of the flue gas. SO_3 increases the acid dew point and moisture reduces it. Therefore, these two effects offset one another. MATS also resulted in reduced SO_3 emissions in many cases, which is beneficial with this regard. Moisture can contribute to blinding of filter bags and sulfuric acid can chemically harm some filter bag materials. Because the effects offset one another, cofiring of natural gas should not have a significant impact on blinding and it may reduce chemical attack on filter bag material. By reducing acids in the flue gas and reducing bag cleaning frequency, cofiring will have a beneficial impact on filter bag reliability. Therefore, the overall impact of natural gas cofiring will generally be positive.

C. TOXECON, OR COHPAC

TOXECON is an acronym for TOXic Emissions CONtrol device. COHPAC is an acronym for COmpact Hybrid PArticle Collector. A COHPAC system is a PM collection system that combines an ESP followed by a downstream baghouse. A TOXECON system differs from a COHPAC system only in that between the ESP and the downstream baghouse is a device that injects a reagent or sorbent to capture an air toxic, such as injection of activated carbon after the ESP but before the baghouse. For the purpose of PM emissions control, COHPAC and TOXECON can be considered equivalent. A baghouse that does not have an upstream ESP may be regarded as a full-burden baghouse because PM is not removed upstream of the baghouse, as occurs for a COHPAC or TOXECON. Some coal power plants equipped with ESPs were incapable of meeting one or more of the MATS emissions control requirements with only the ESP and therefore had to add controls. In some of these cases, owners/operators added a baghouse downstream of the ESP. For example, coal power plants equipped with only a hot-side ESP[33] for air pollution control (no scrubber or fabric filter) were incapable of achieving adequate Hg capture with ACI to meet the MATS requirement without addition of a fabric filter. Therefore, coal units with hot-side ESPs either converted the hot-side ESP to a cold-side ESP or added a baghouse.

As shown in Figure 10, the cost of a fabric filter retrofit will vary, but is generally in the range of about $150/kW. A TOXECON baghouse is, in principle, slightly less expensive than a full-burden baghouse due to slightly higher air-to-cloth ratio possible in a TOXECON arrangement, but the actual cost will be very dependent upon the difficulty of the retrofit.

In 2010, the Electric Power Research Institute (EPRI) conducted a survey of baghouses and found that slightly over 20% of the PJ baghouses installed were in a TOXECON or COHPAC arrangement. As shown in Figure 11, the largest fraction of baghouses were full burden baghouses that did not include ACI. This, of course, was prior to MATS. In many states there was no requirement to control mercury.

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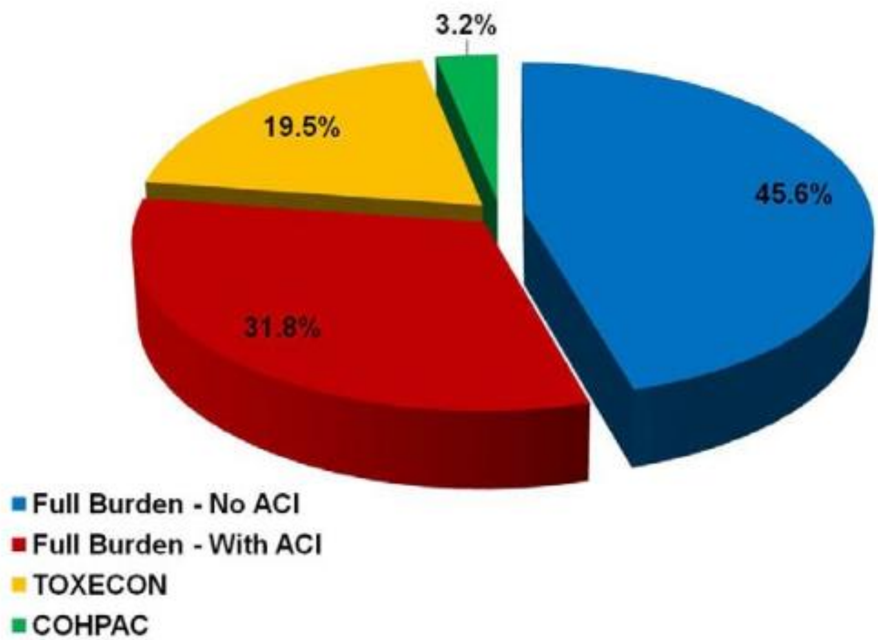
[33] A hot-side ESP is installed upstream of the air preheater at a point where the exhaust gas temperature is in the range of about 600ºF, while cold-side ESPs are installed downstream of the air at a point where the exhaust gas temperature is in the range of about 300ºF.

Figure 11. Configurations of Pulse-Jet baghouses in the Power Generation Industry [34]



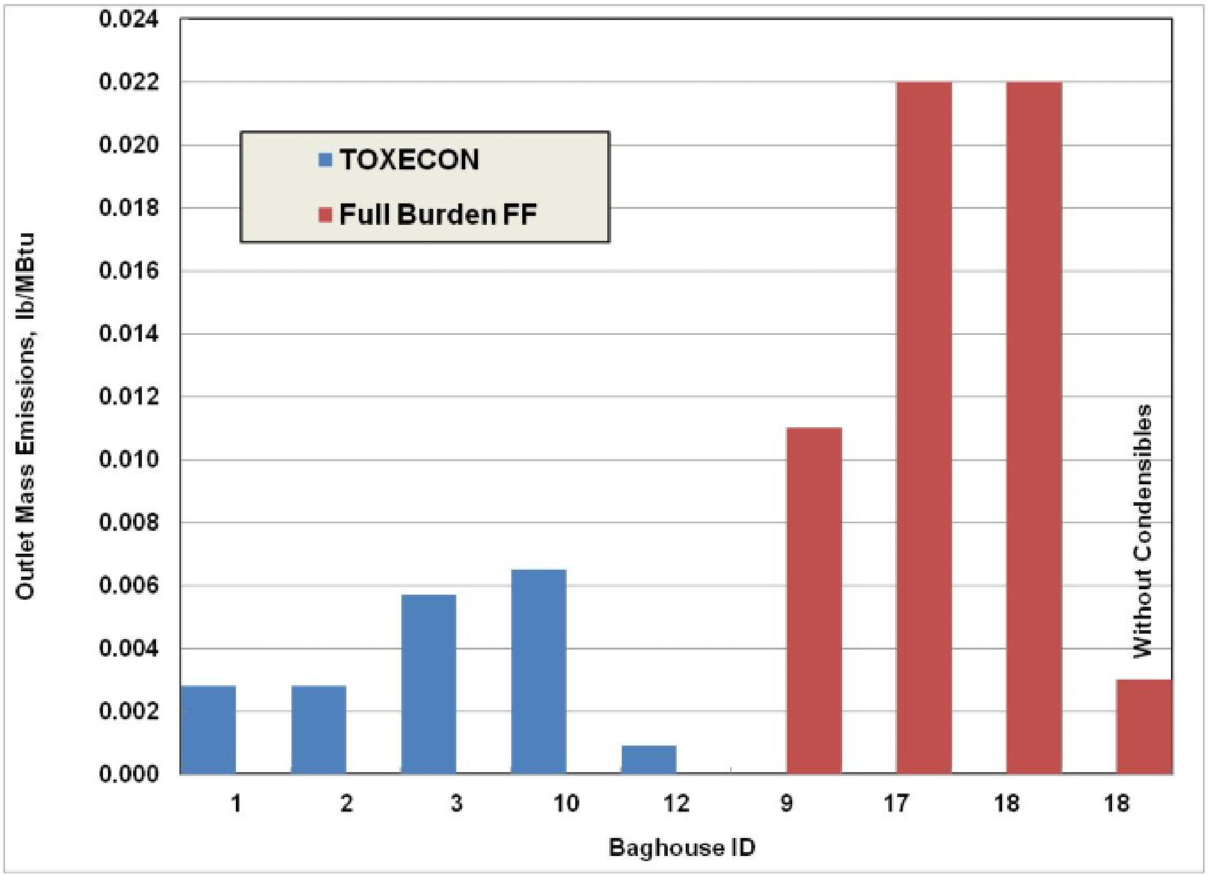
The impact of TOXECON on PM and other emissions

The addition of a fabric filter to meet one requirement, such as PM, will be beneficial to meeting other MATS requirements, such as mercury. In the case of a hot-side ESP, the addition of a baghouse to help with meeting the Hg limit with ACI also helps to reduce PM emissions. The addition of a baghouse for PM control will also improve the cost of Hg emissions control because the activated carbon is used much more effectively, reducing the activated carbon that is required for any given removal rate. A fabric filter will also make collection of acid gases with dry sorbent injection (DSI) more effective. Thus, there are substantial synergies possible through the addition of a fabric filter.

An EPRI baghouse survey found that a TOXECON system most often had lower outlet PM mass emissions than a full-burden baghouse. These results are shown in Figure 12. It was later determined that several of the full-burden baghouses were experiencing bag leaks. This illustrates some important points. First, bag leakage is the principal reason for high emissions for any BH. Second, the combination of an upstream ESP with a downstream baghouse reduces the risk of high emissions when a filter bag leaks, or another leak occurs, because the inlet loading to the baghouse is much less in the TOXECON arrangement. So, it is possible that the TOXECON baghouses in the EPRI study also had bag leaks, but the impact of the leaks would be much less than for a full-burden baghouse. That is why a TOXECON configuration reduces the risk of high PM emissions in the event of a filter bag failure.

[34] EPRI Power Plant Baghouse Survey, 2010, 1019729, fig 1-4

Figure 12. Comparison of full-burden baghouse emissions to TOXECON emissions[35]



D. Wet ESPs

Wet ESPs are not widely used on coal power plants because most coal plants utilize either a dry ESP or a baghouse. Wet ESPs differ from dry ESPs in that the collection plates are cleaned with a stream of water. This offers two benefits: 1) re-entrainment of fly ash does not occur to a significant extent, which improves PM capture, and: 2) higher power levels are possible. Wet ESPs can be installed downstream of a wet FGD system and used to capture mist. It is not possible to install a fabric filter downstream of a wet scrubber due to the presence of moisture that would plug the baghouse. A wet ESP might be an option for a scrubbed unit that needed to increase ESP treatment time but did not have adequate space to make ESP modifications. Utility budgetary data provided in Table 3 suggest that a wet ESP costs in the range of about $150-200/kW.[36]

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[35] Ibid.

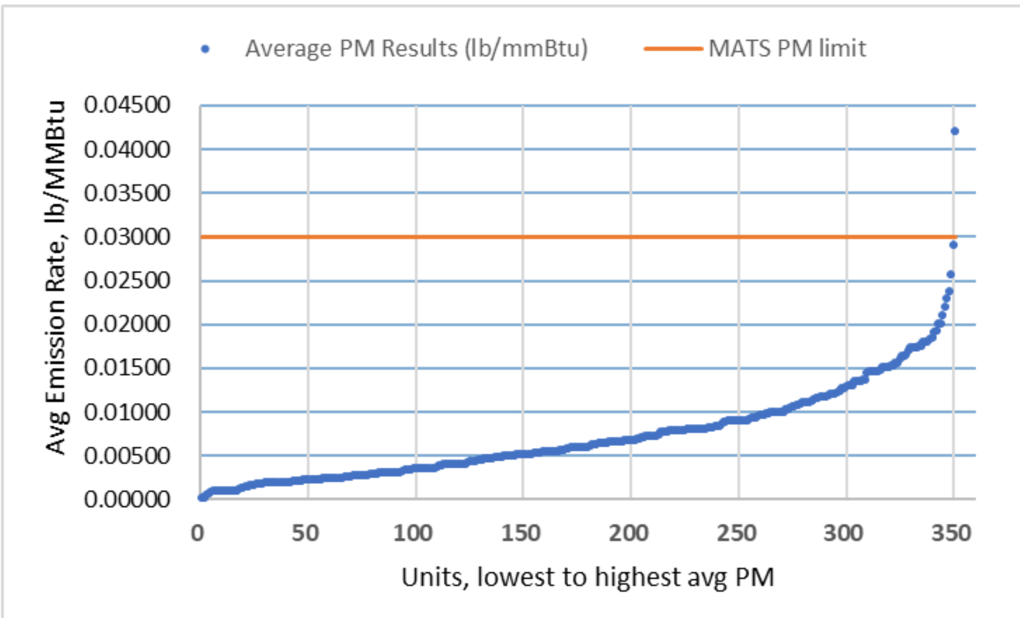
[36] See Table 3

E. Assessment of PM Emissions Data

The database published by NRDC includes the average, minimum and maximum reported PM emissions from EPA's 2019 Air Markets Program Data as well as facility characteristics from EIA Form 860 data. ATP further examined this data to look for relationships that could be used to explain performance.[37]

Figure 13 shows that over 99% of all the units in the database were under the PM emissions limit of 0.03 lb/mmBtu, based on the average emission rates calculated for each unit (i.e., average of 2019 PM CEMS data or 2019 PM stack test data). Those units that had emission rates above 0.03 lb/mmBtu may have still complied with the rule based on a facility-wide averaging plan.[38] The average emission rate was 0.0072 lb/mmBtu and median emission rate was 0.0060 lb/mmBtu. The best performing 25% of units had an average emission rate of 0.002 lb/mmBtu and a maximum average emission rate of 0.003 lb/mmBtu.

Figure 13. Overview of PM emissions data.



Given the range of data, ATP examined the full population of units by breaking the population into deciles to examine if there were any trends. Decile 1 was the decile with those units that had the lowest PM emissions, and so on. Figure 14 shows the average PM emissions for each decile. As shown, the PM

[37] ATP analyzed the data for 351 sources in the Unit Level PM Analysis worksheet of the NRDC database where an average unit PM emissions rate was provided for the unit in the Webfire data. The Unit Level PM Analysis was calculated from the Webfire data where that data showed an emission level for a specific unit. For a small number of common-stack units the Webfire data did not provide a unit-level PM emission rate. Those units are are included in the analysis as reported in Webfire. In the "Master Data all combined" worksheet of the NRDC database, each common stack is broken out to a unit level estimate, even if it was reported at the common stack level from the Webfire report. For example, Marion 916-123 is in the Unit Level Analysis spreadsheet once (as a common stack represting units 1, 2, and 3), while Marion 976-123 is listed 3 separate times to represent data on a unit level in the Master Database all combined worksheet. Due to the small number of affected units, this is not expected to make a large difference in the results of the decile analysis.

[38] It is acknowledged that the limit is a 30-day average, which is somewhat more stringent than an annual average.

emissions rate for the top deciles were on the order of one fifteenth those of the bottom decile. The impact of coal was examined in Figure 15. As shown, there was no apparent trend in PM performance with respect to the type of coal being used at the facility.

Figure 14. Average PM emissions rate per decile

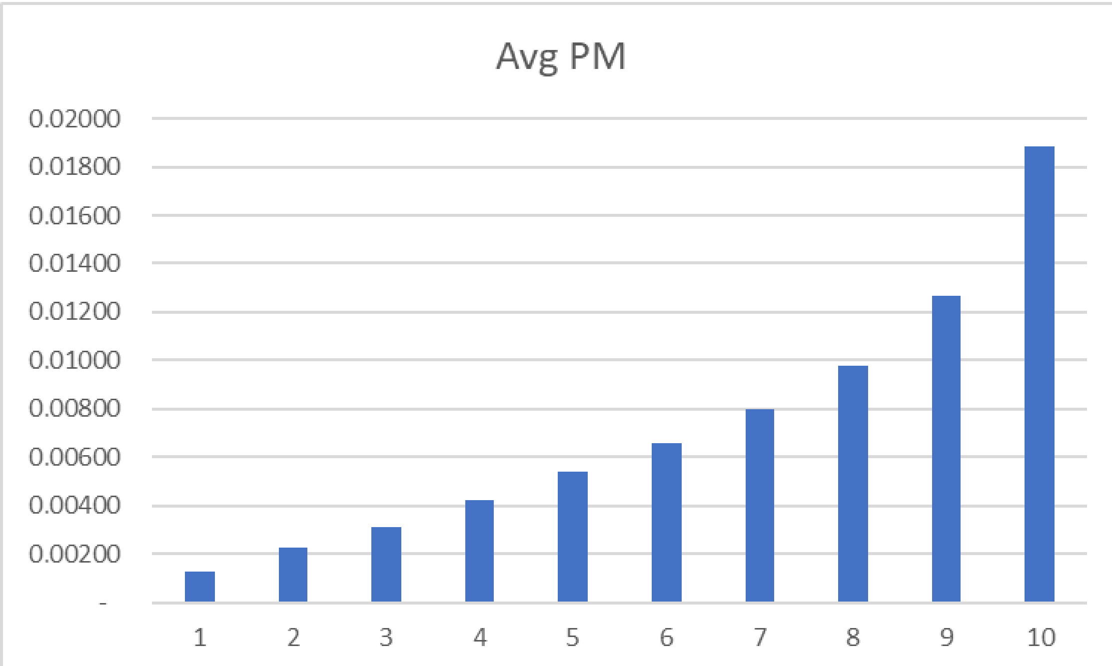
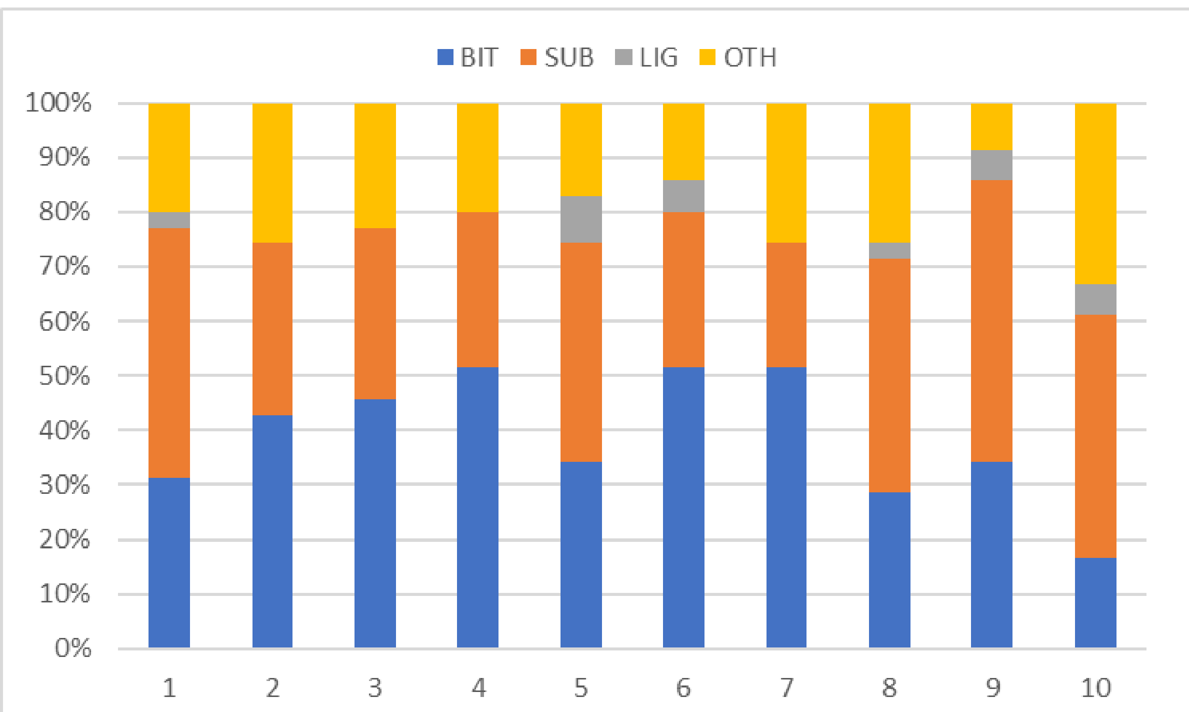
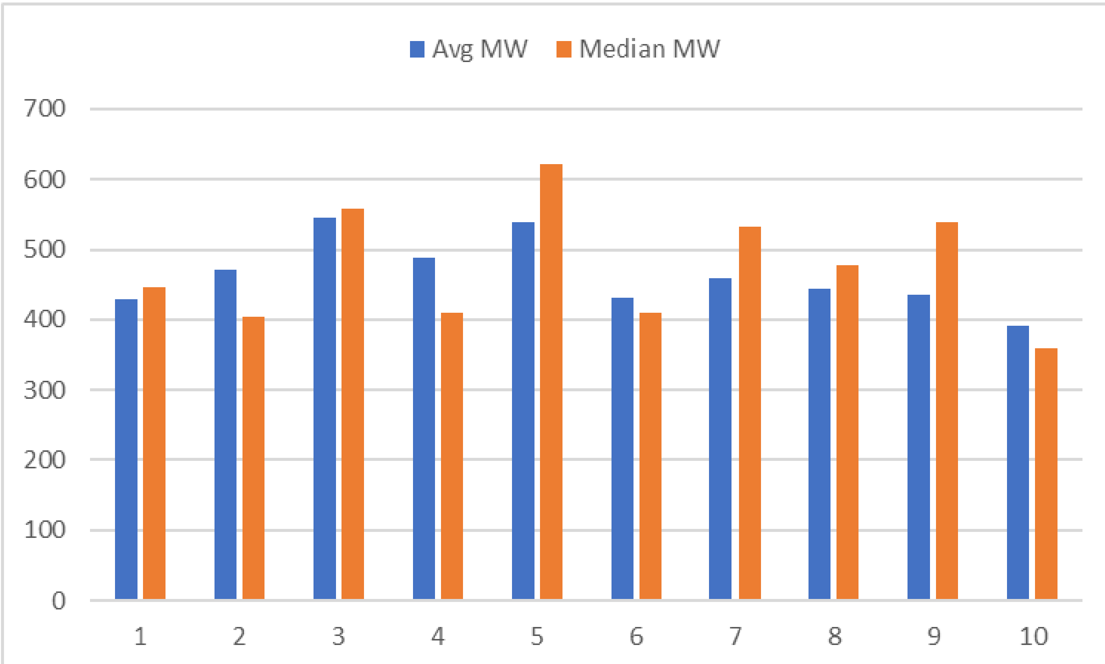


Figure 15. Coal type by decile



The unit size (in MW) was also examined. Figure 16 demonstrates that there is no apparent trend based upon unit size.

Figure 16. Average and Median MW size by decile



Trends were observed in the deciles when equipment was examined. As shown in Figure 17, perhaps as expected, the highest percentage of baghouses and dry FGD are in decile number 1.

Figure 18 shows the same data, but with both forms of scrubber combined. As shown, the top deciles are far more likely to be scrubbed than the bottom deciles. This likely has much less to do with the PM removal performed by the scrubbers than the fact that scrubbers, due to their high cost, are normally installed on the most important units which are therefore the best maintained and equipped. Scrubbers do improve PM capture, but they alone cannot account for the large difference in PM emissions between the top and bottom deciles. Wet scrubbers remove some PM, but not enough to explain the difference between top and bottom deciles. A large percentage of the top decile is equipped with dry scrubbers, which is reasonable because dry scrubbers are equipped with BHs. A well-functioning BH is the most effective filterable PM capture device. About two thirds of the top decile is equipped with BHs, well above the fraction of any other decile equipped with BHs.

It is also apparent by the ESP and BH percentages that a substantial number of the top decile units are TOXECON or COHPAC. Decile 6 is most likely to just have an ESP for PM control (but may also be scrubbed). It is also apparent from these figures that the top deciles are about as likely to have ACI as other deciles, confirming that ACI does not adversely impact PM emissions. Significantly, the top decile included three unscrubbed units with an ESP, ACI and no BH, demonstrating that this configuration is capable of having very low PM emissions.

Figure 19 shows the expected result that unscrubbed units with an ESP and no BH tend to be lowest in decile 1 and higher in lower deciles, as this is generally regarded as the most difficult situation to control PM. But, the presence of seven units with this configuration in the top two deciles shows that it is possible for PM to be very effectively controlled in this configuration.

Figure 17. Percent of decile with equipment

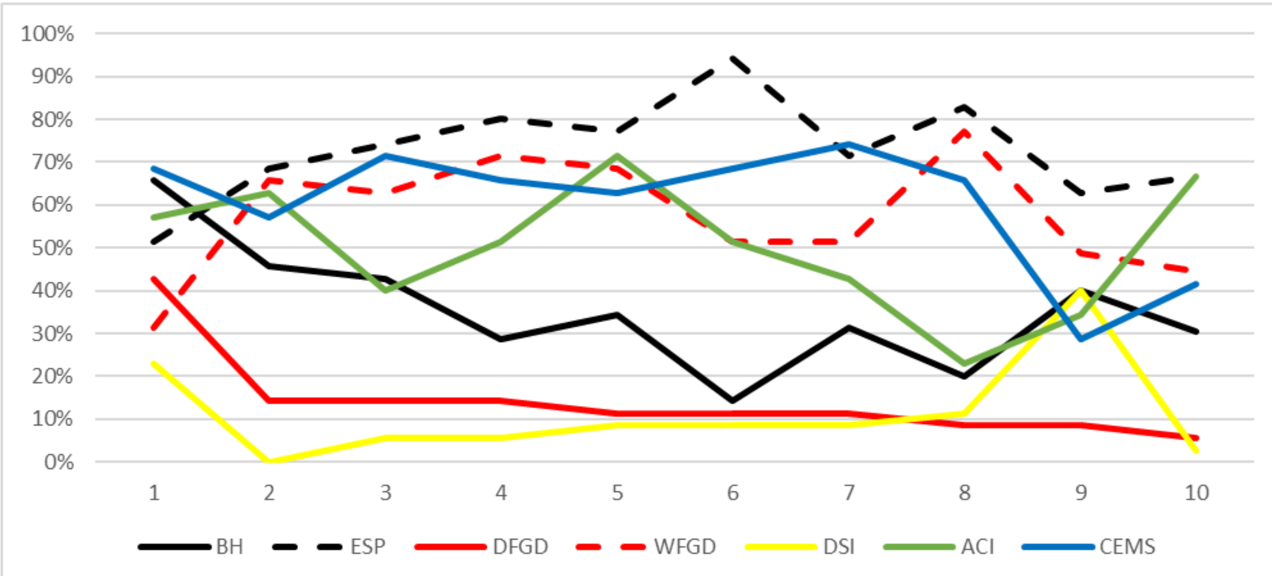


Figure 18. Percent of decile with equipment – scrubbers combined.

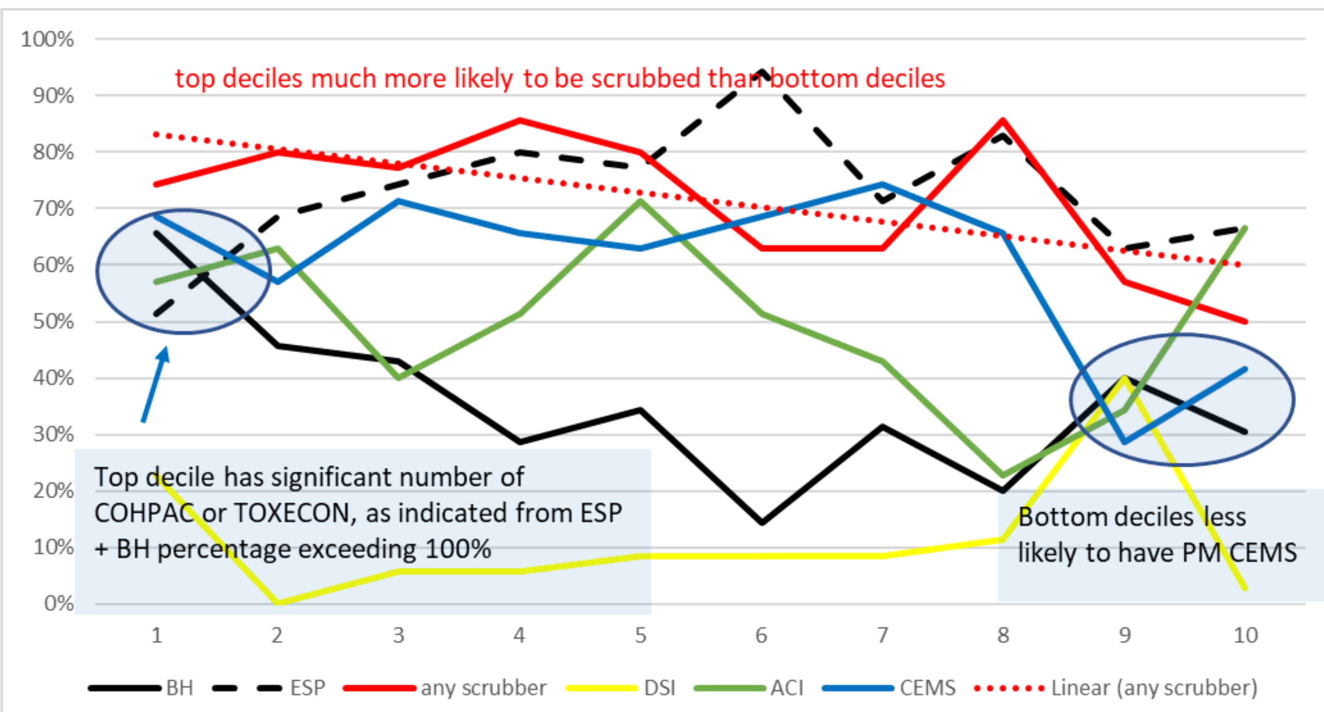
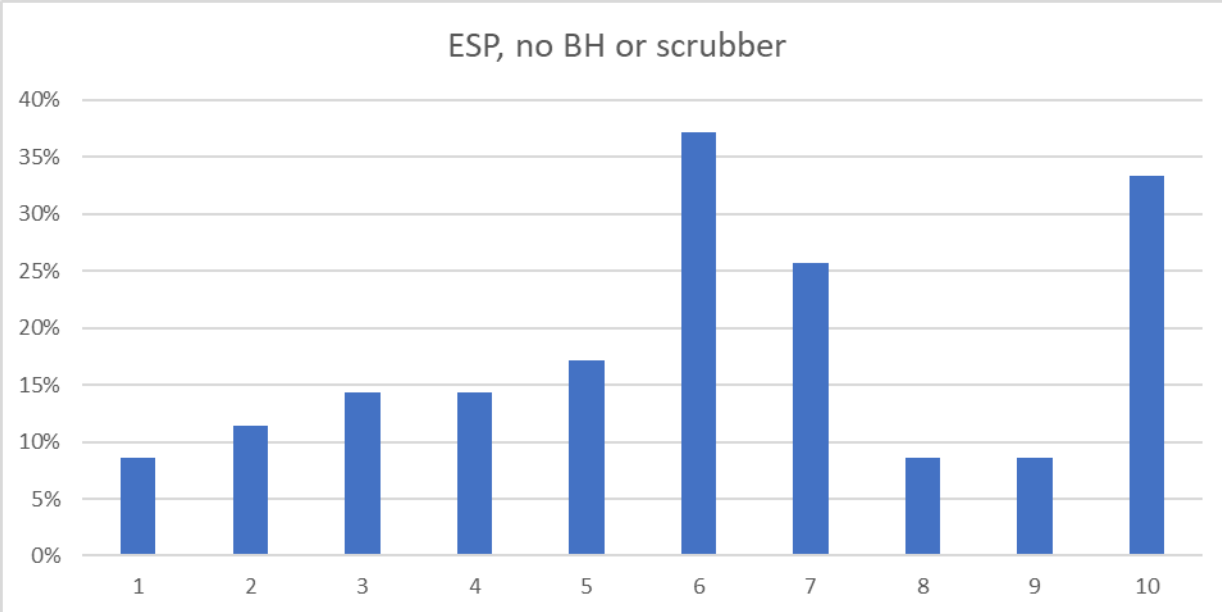


Figure 19. Percent of units in decile that are unscrubbed with ESP and no BH

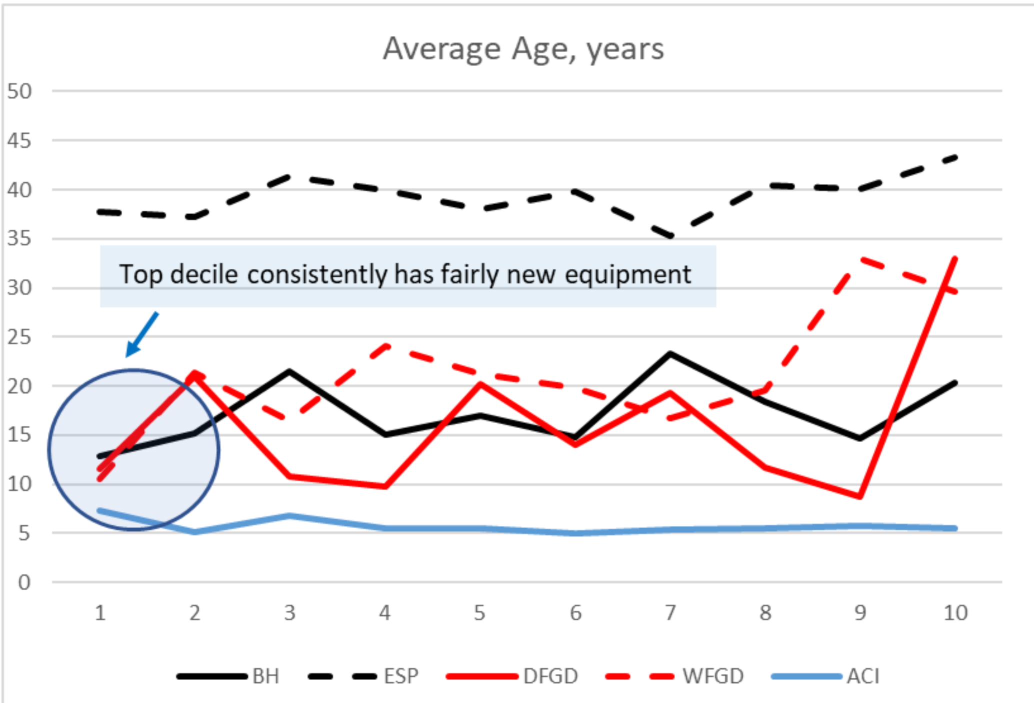


Except for decile 7, PM CEMS were generally more likely among the top deciles than in the bottom deciles. Decile 7 had the highest percentage of PM CEMS. Deciles 9 and 10 had the lowest percentage of PM CEMS. This suggests that the use of PM CEMS may be associated with better emissions performance. It is worth noting that, prior to MATS, PM CEMS were not in wide use. They were primarily used on units that installed the PM CEMS in response to a Consent Decree or a local requirement. As a result, at the time of MATS, PM CEMS were regarded by many in the industry as early stage and perhaps too risky to use. The utility industry had not yet broadly adopted the technology when MATS was being implemented. PM CEMS provide input that can be used to address problems right away, and the most knowledgeable utilities may have recognized this benefit. To this point about PM CEMS providing indication of a possible need for corrective action, Appendix A provides some examples showing that spikes in daily PM emissions, well above the 30-day average, occurred and there was a subsequent correction to a lower daily rate. In some cases it is unclear if there was a corrective action, or if there was another reason for the reduction in the spike. In some cases the data strongly suggests that a shutdown was taken to address high PM emission rates.

Utilities that were more familiar with this technology - that had not been widely deployed in 2011 - were able to take advantage of the real-time benefit of PM CEMS in reducing PM emissions. This would also be consistent with the fact that top decile units were more likely to be scrubbed (and had newer scrubbers) than bottom decile units. Companies that had recently installed scrubbers were likely to be more technically knowledgeable due to recent experience with sophisticated environmental controls or may have been more committed to investing in environmental controls for their units.

Figure 20, which shows the average age of equipment in each decile, shows another trend. It is apparent that the top decile consistently has relatively newer equipment. The trend is very apparent with the FGD systems. The bottom decile FGD systems are in the range of 25-30 years old while the top decile FGD systems are only about 10-15 years old. This is a clear indication that companies had made substantial, recent investments in the top decile units. The ESPs in most deciles were in the range of 35-45 years old. The ESP was consistently the oldest piece of air pollution control equipment on the power plant for every decile.

Figure 20. Average age of equipment in decile



F. Summary Analysis of PM data

Monthly PM data was collected and input to NRDC's database. The data published on NRDC's website, as shown in **Error! Reference source not found.**, indicates that:

- 59% of units and 61% of capacity had average annual emissions rates of 0.007 lb/MMBtu or less,
- 25% of units and 26% of capacity had average annual emissions rates of 0.003 lb/MMBtu or less,
- and 6% of units and 5% of capacity had average annual emissions rates of 0.0015 lb/MMBtu or less.

Table 5. Unit Level average, annual PM emissions rates

	Total	Unit average annual emission rate less than or equal to:		
		0.007 lb/mmBtu	0.003 lb/mmBtu	0.0015 lb/mmBtu
Number of Units	351	205	86	22
percent of total	100%	58%	25%	6%
Nameplate capacity (MW)	160,295	97,910	41,370	8,675
percent of total	100%	61%	26%	5%

As a result, reducing the PM emission limit from 0.03 to 0.007 lb/mmBtu would entail little or no additional expense for about 60% of the affected coal capacity (this does not include low-emitting EGUs that did not report quarterly emissions data in 2019). Plantwide averaging would provide additional compliance flexibility.

G. Conclusions regarding PM emissions and opportunities for reductions

The data indicates that a lower PM emission rate limit would not result in a large increase in cost for the majority of facilities. In fact, Table 6 shows that 50% of the units evaluated had emission rates at or below 0.006 lb/MMBtu, one fifth the current standard.[39] It also shows that 25% of the units had emissions levels one tenth or less of the PM standard. The top decile had a high percentage of BH, although a significant number only had ESPs. The second decile was far less likely to have a BH than the top decile, and less likely even than the bottom decile. So, while it would be expected that a BH will improve emissions, very low emissions are being achieved at units with only an ESP.

Table 6. Unit PM emissions from the population of units in the dataset [40]

Metric	Top 10%	Top 20%	Top 25%	Top 50%	All Data in Dataset
Number of units	35 (10% of 351)	70 (20% of 351)	87 (25% of 351)	175 (50% of 351)	351
Max avg, annual rate (lb/mmBtu)	0.0020	0.0026	0.0030	0.0060	0.0420
Max (lb/mmBtu) *	0.0050	0.0056	0.0090	0.0160	0.0626
Min (lb/mmBtu) *	-	-	-	-	-
Avg (lb/mmBtu)	**0.0013**	**0.0018**	**0.0020**	**0.0032**	**0.0073**
% avg is below standard	96%	94%	93%	89%	76%
* Max and Min are the maximum and minimum emissions reported for any period, not the maximum average, annual emissions for any units					

As previously noted, scrubbers (notably, dry scrubbers) were much more prevalent in the top deciles than the bottom deciles. Scrubbers alone are not the factor that determines if units are likely to have high or low PM emissions because there are a significant number of scrubbed units in the bottom deciles. And, the PM capture in a scrubber is not sufficient to explain the large differences. The higher percentage of units with BHs in the top deciles will certainly explain some of the difference. Scrubbers may also be an indicator of another important determinant of PM emissions. Scrubbers are costly investments. So, they are installed primarily on units that owners consider vital units and therefore the best maintained and equipped units. The scrubbers in the top decile were significantly lower in age than the scrubbers in the bottom decile. A more recent scrubber installation suggests that the owners recently believed the unit to be more vital and worthy of a large investment. In fact, the top decile units had consistently newer equipment, with the sole exception of ACI, which is generally newer equipment for all units.

This analysis also suggests that performance of units is driven by maintenance and operation of existing controls, regardless of configuration, as well as the equipment configuration. Units with ESPs were shown

[39] Units may comply either by maintaining a PM emission rate of 0.030 lb/MMBtu or less, or, alternatively, maintaining emissions of specific toxic metals below limits established in the MATS regulation. In this study we did not examine the metal emissions.

[40] Data from NRDC database

to be capable of low emissions, and it is expected that there are others that can further improve their emissions to a significant degree. On the other hand, factors that impact the ability of any individual ESP to achieve low emissions, most importantly treatment time and the available space to increase the size and treatment time of the ESP, might make it necessary to retrofit a baghouse on some units, while other ESPs can be upgraded to achieve very low emissions through the methods described in this report.

The emissions data summarized above raises the question: "How have so many facilities reported emission rates much further below the standard of 0.030 lb/MMBtu?" The answer is not that companies engaged in major retrofits. Relatively few BHs were installed in response to MATS. Few units with ESPs engaged in more expensive ESP upgrades, such as "gut and stuff", and fewer (if any) enlarged the ESP or added fields in response to MATS. Instead, what happened was that companies:

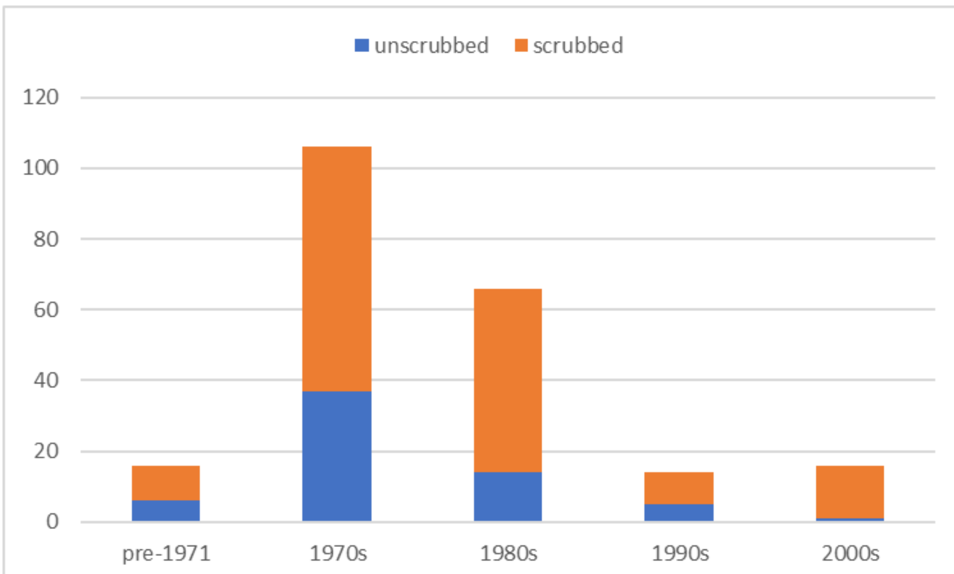
- Paid greater attention to their PM emissions because of the monitoring and reporting requirements of the MATS rule.
- Made efforts to restore their ESPs and other equipment to the performance level that they were designed for by correcting deficiencies (upstream leakage, failed electrodes and insulators, etc.). In some cases, old, corroded plates and electrodes were replaced. Most of the ESPs were originally installed 35 or more years ago and may have never undergone a complete rebuild. As a result, there was a great deal of improvement possible with the ESPs simply by correcting some of the deterioration that had occurred over the ESP lifetime.
- Made modest improvements to the ESPs when needed, such as addition of high frequency TR sets.
- Companies with BHs replaced and/or upgraded filter media as needed, made efforts to minimize wear and tear on filter bags, and paid more attention to BH operation.

In effect, most of the improvements to comply with the MATS PM standard were achieved at relatively little expense – far less than anticipated by US EPA. As noted by Staudt in 2015, EPA anticipated that MATS would motivate many more baghouse installations than actually occurred.[41] There were a small number of ESP retrofits, such as the Marion unit 4 that restored original or somewhat better than original performance.[42] Major retrofit efforts that amounted to large improvements in ESP treatment time through casing enlargement, or addition of fields, or addition of a BH to comply with the MATS rule were rare. A relatively small number of BH installations occurred, but many of them were also associated with addition of dry FGD in response to the Regional Haze Rule. In effect, the industry, faced with a requirement to control PM emissions, found low-cost ways to achieve lower PM emissions that were not anticipated in 2011. It is reasonable to conclude that more operators could similarly deploy these lower cost improvements to reduce PM emissions if the PM standard were tightened. Or, operators that utilized lower cost improvements to comply with MATS could explore some moderate cost methods to further improve performance of their ESP.

[41] Declaration of James E Staudt to United States Court of Appeals for the District of Columbia Circuit, Case No. 12-1100, September 24, 2015. Many of these forecasted installations that did not occur may have been assumed by EPA to be necessary to provide adequate Hg or acid gas capture while remaining below the PM emissions limit.
[42] As noted earlier, the new plates were optimized to increase treatment time within the existing ESP casing.

Recalling Figure 3, older ESPs were designed for lower treatment times and therefore were not as large as more recently constructed ESPs. The population of ESPs that are not on units that also have a fabric filter was examined, and the results are in Figure 21. It showed that the largest number of ESPs were built in the 1970s (106 in total). Of them, 69 were on scrubbed units. Unscrubbed units are likely to be more challenged – in part because they do not benefit from the additional removal by the scrubber, but also because unscrubbed units are likely to have reduced the sulfur level of the coal as a means of reducing SO_2 emissions, which will increase fly ash resistivity. Nevertheless, in the top decile there are three units that only have ESPs and are unscrubbed. These are 38, 35 and 36 years old, built in the 1980s. In the second decile there were four units that had ESPs only and no scrubber with ages that ranged from a low of 21 years to a high of 41 years. Therefore, it is clear that some of the older ESPs can achieve low PM emission rates.

Figure 21. Units equipped with ESPs and no fabric filter/baghouse, by year of ESP construction.



An Upper Prediction Limit (UPL)[43] was calculated by EPA in 2011 to determine the PM emissions level in the MATS rule that could be used for the non-Hg metals limitation. An updated UPL was calculated using the 2019 data assembled by NRDC and this was compared to the UPL calculation by EPA in 2011. The result is shown in Figure 22. As shown, the UPL in 2011 resulted in a value of 0.028 lb/MMBtu, or 0.030 when rounded up. The calculation with the 2019 data resulted in a UPL of 0.005 lb/MMBtu, or about one sixth the previous estimate. This is due to two things:

1) generally lower average emission rates, especially for the 65 higher emitting units, and

[43] The UPL takes into account the average of the best units plus an allowance for variation that is determined by a confidence level that the UPL will not be exceeded. The allowance for variation is determined by the number of standard deviations from the mean for the confidence level and the standard deviation. A higher standard deviation and higher confidence level that the UPL will not be exceeded will result in a higher calculated UPL result, and lower standard deviation will result in a lower UPL for any given confidence level.

2) much less variability in emissions for each individual unit.

This is attributable to the aforementioned reasons for the improved emission rates, particularly the greater attention to PM emissions as a result of increased monitoring and reporting requirements.

Figure 22. Comparison of 2011 MACT floor UPL calculation to UPL calculation using 2019 data

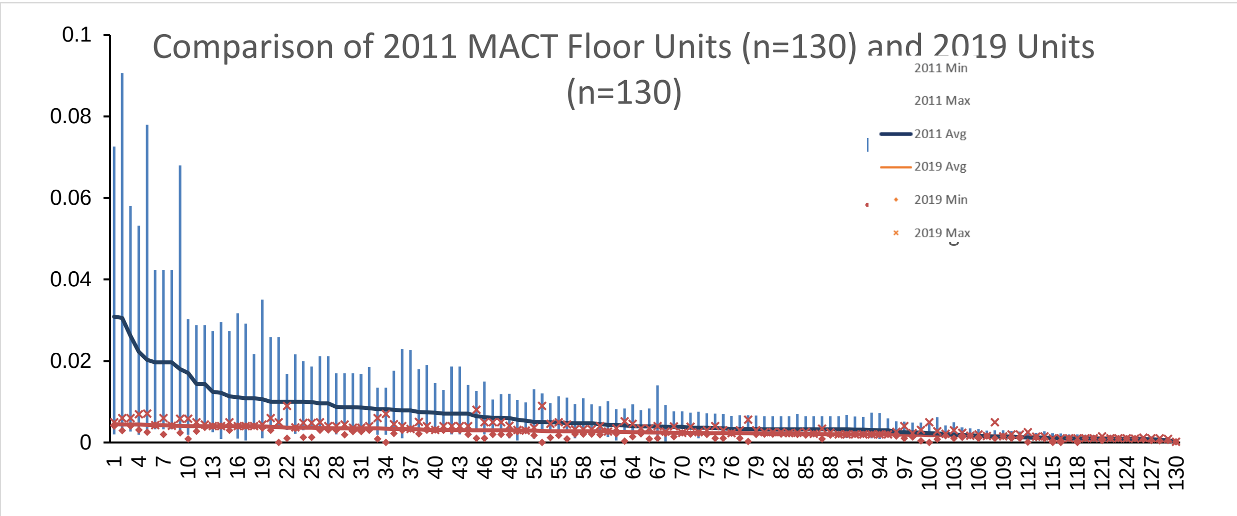


Table 7 shows the estimated impact of reductions in the PM emission standard. The current standard is 0.030 lb/MMBtu. As previously noted, half of the evaluated units had emissions at or below 0.0060 lb/MMBtu. This means that roughly half of the units can comply with an emission limit of 0.0070 lb/MMBtu with little or no modifications.[44] Units with ESPs might have to make some modifications to comply, some more involved than others, depending upon the age and current circumstances of the ESP. Units with baghouses could comply with little or no effort, perhaps upgrading filter bag material or improving operating practices to minimize bag failure rate. At 0.003 lbs/MMBtu, some units with ESPs would need to install baghouses but roughly half of units with ESPs are expected to be able to meet this standard with modest upgrades or no additional costs.

As emission standards tighten, the impact to the coal fleet will be increased. At a sufficiently low standard (0.0015-0.0020 lb/MMBtu or less), most units with ESPs would likely seriously consider installation of a fabric filter or another substantial upgrade. All units with fabric filters should be able to achieve such a standard, providing that they take measures to avoid significant leakage from filter bags or bypassing of filters, such as improved operating practices or installation of improved fabrics.

[44] The difference between annual averages and 30-day averages is acknowledged, as well as the need to maintain a degree of "compliance margin", controlling to a level below the standard to avoid exceeding the standard.

Table 7. Estimated impact of reduction in PM emission rate standard[45]

PM Limit (lbs/MMBTU) *(Current standard is 0.03 lbs/MMBTU)*	**Implications for facilities with ESPs**	**Implications for facilities with baghouses**	**Implications for fleet as a whole** *(Preliminary estimates)*
0.007	• Most units can meet with modest improvements • Units with ESP built in last 20 years should be able to achieve with modest maintenance costs (~$20/kW or less) • A few units with significantly older ESPs may need to undergo ESP upgrades/rebuilds (~$50/kW)	• Virtually all units can easily meet this limit with no additional costs • A few units may require some maintenance or bag replacement ($2-5/kW)	• More than half of all units can achieve with little to no additional costs, 42% of fleet is above 0.007 lb/MMBtu • $268M annualized cost with >7,200 tons PM reduction (preliminary estimate)
0.003	• Many units may need to make upgrades but should be technically feasible for all units • Roughly half of units with ESPs would need to install baghouses, especially those with ESPs older than 30 years ($150-200/kW) • Remaining units could achieve with modest upgrades ($20-50/kW • Units with ESPs and wet scrubbers may not be able to fit baghouse before scrubber, but could install wet ESP after scrubber ($100-150/kW)	• Many units can still meet this with little to no costs • Some units may need modest upgrades. For instance, units may need to replace bag ($2-5/kW) and replace every 3 years rather than 5 years.	• About 25% of fleet can achieve with little to no additional costs • $1.29B annualized cost with >16,800 tons PM reduction (preliminary estimate)
0.0015-0.002	• Most units with ESPs would need to install baghouses, especially those with ESPs older than 30 years ($150-200/kW) • Remaining units could achieve with modest upgrades ($20-50/kW) • Some ESPs would still not require additional investments	• Many units can still meet this with little to no costs • Some units would need modest upgrades ($5/kW)	• 12-20% of the fleet can achieve with little to no additional costs • $2.4B annualized cost with >22,900 tons PM reduction (preliminary estimate)
Less than 0.0015	• Nearly all units with ESPs would need to make substantial upgrades, including installing baghouses	• Most units would need to make modest upgrades	• Most units would require modest to substantial improvements • $2.5B+ annualized cost (preliminary estimate)

[45] Estimated costs and PM reductions are approximate, and based upon an assumed BH upgrade cost of $5/kW for upgraded bags, $20/kW for a minor ESP upgrade, $50/kW for major upgrade, and $150/kW for installation of BH.

III. Methods of mercury (Hg) control

Setting aside the vacated Clean Air Mercury Rule (CAMR), MATS was the first nationwide Hg emission standard requirement for coal-fired power plants. Prior to MATS, Hg emissions were only controlled and reported in those states that had Hg control and reporting standards. Moreover, the requirements varied from state to state. As a result of the changing regulatory requirements and the relative novelty of Hg regulation, technology has evolved rather quickly for control and monitoring of Hg. In the following section the methods of controlling Hg will be discussed.

A. Control from PM and SO_2 control devices

How they work

PM and some SO_2 control devices will capture Hg. Some NOx control devices will also enhance Hg capture in the PM or SO_2 control device. The Clean Air Mercury Rule (CAMR) was intended to primarily take advantage of increased Hg capture from the addition of new SO_2, PM and NOx control devices associated with other rules. For example, a PM collection device will capture that Hg that is contained in the filterable PM. Scrubbers will capture Hg as well. Wet FGD systems will capture that Hg that is in a water-soluble form. Dry scrubbers capture Hg in a baghouse. SCR NOx control systems enhance Hg capture by converting more Hg to the oxidized form, which is easier to capture in downstream PM or SO_2 control systems.

Hg may be in one of three forms:

1) Elemental Hg – this is in a gaseous form and tends to be difficult to capture unless it is first converted to one of the other forms of Hg.
2) Oxidized Hg – this is water soluble and is also readily attracted to PM surfaces. As a result, it is captured in wet scrubbers and, to some degree, in PM control devices.
3) Particulate Hg – this is effectively captured in PM control devices.

Therefore, one of the ways to optimize inherent capture of a PM or SO_2 control device is to convert elemental Hg to one of the other forms that is easier to capture and also to prevent Hg that is in the oxidized form or particulate form from transforming to the elemental form. Once Hg is in the particulate form, it is generally quite stable and will not convert back to the elemental form.

For PM control systems, Hg that is contained on the PM is captured in the ESP or BH and removed from the exhaust gas. Hg is more effectively captured in a BH because the intimate contact between the PM and the exhaust gas as the gas passes through the filter enhances oxidation of elemental Hg to oxidized mercury and enhances conversion of Hg to the particulate form. Halogens are necessary for mercury to be in the oxidized form. One way to enhance Hg oxidation is to add halogens, especially bromine, to the gas through the coal or other means.

ACI is a means for enhancing Hg capture in the PM control device, but it will be discussed separately.

Developments in enhancing the inherent Hg capture of PM and SO_2 control devices

The MATS rule created motivation for industry to optimize the inherent Hg capture of their FGD and PM control systems. Pre-2011 there were limited "best practices" because Hg controls had only been only deployed in a few states. In the case of mercury regulation, necessity has been the mother of invention; with a widespread requirement to control Hg emissions, power plant owners and technology providers became creative in finding better ways to reduce Hg emissions.

Developments for wet FGD

Prior to MATS, wet FGD systems were considered highly effective at capturing oxidized mercury in most situations. Therefore, efforts were made to fully understand mechanisms for oxidizing elemental mercury prior to the scrubber so that it could be captured. In 2011, chemicals for oxidizing mercury prior to a scrubber were under development but not yet deployed widely. And, the interrelationships between SCR catalyst activity, ammonia injection and mercury oxidation across the SCR catalyst were not well understood.

In the time since MATS implementation, chemicals for oxidizing Hg have been developed and deployed. Also, the interrelationships between mercury oxidation across the SCR catalyst and SCR system operation and catalyst design and activity are better understood. Catalyst suppliers now supply catalyst that is optimized both for NOx reduction and mercury oxidation.[46] These innovations were not available prior to MATS implementation.

However, the improved understanding of mercury oxidation was not enough. Pre-MATS a phenomenon called "re-emission" made mercury capture in wet scrubbers lower in some cases, with higher elemental mercury measured at the outlet than at the inlet of the scrubber. This phenomenon was later determined to be a result of unstable scrubber chemistry that, under some conditions, caused Hg captured in the scrubber liquor to reduce to elemental Hg and be "re-emitted." In the period since 2011, chemicals and operating practices have been developed to prevent captured mercury from reducing back to elemental mercury and rather be retained in the scrubber solids. By 2014, Nalco-Mobotec had introduced the MerControl family of chemicals that included chemicals for mercury speciation and chemicals for wet and dry scrubbers.[47] Operating practices included measuring the redox potential of the scrubber liquor to prevent reducing reactions and manage the redox potential through the sparging of the liquor. In addition, activated carbons and other chemicals were developed to keep the captured Hg in the scrubber solids, where it would later be removed. Many of these methods are described in a 2014 ICAC document.[48]

Other technologies that were under development, but not available in 2011, included absorber systems that could be installed in the mist eliminator section of the wet scrubber. One version of this technology made by W.L. Gore Mercury Control System is a fixed bed absorber that captures both Hg and SO_2. This

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[46] https://cormetech.co/advancedscrcatalysts/; https://www.jmsec.com/air-pollutants/mercury-hg/?L=0

[47] Meier, J., "Alternatives to Activated Carbon Injection", 2014 APC Round Table and Expo Presentation, July 14-15, 2014, Louisville, KY

[48] Institute of Clean Air Companies, "Improving Capture of Mercury Efficiency of WFDGs by Reducing Mercury Emissions", June 2014

technology can also be installed downstream of a PM control system, but the most widely used application has been in combination with a wet FGD system. These systems have been found to be effective means of Hg capture for scrubbers that have the space available for the fixed bed absorber in what normally would be the mist eliminator of the scrubber.[49]

Activated carbon is also an option for increasing the Hg capture through injection upstream of the ESP or BH. However, carbons available in 2011 were not effective in environments typical of that location due to high SO_3 concentrations that interfered with Hg capture. Activated carbon has also been used in situations where it is injected upstream of a wet scrubber so that the captured mercury remains with the scrubber solids. Advances in activated carbon are discussed further in a later section.

Developments for dry FGD systems

For bituminous coal units equipped with dry FGD systems, Hg capture was generally found to be very effective – frequently achieving well over 90% Hg capture without addition of ACI. However, for coals that are low in halogen content, such as western coals, Hg capture was determined to be poor in many cases.

Although the solution of introducing halogens was generally known in 2011, it was not being deployed widely. In the time since MATS, it has not only been deployed on systems with dry FGD systems that have insufficient inherent halogen content, but suppliers have also refined chemicals and methods for delivery, to include introduction in the fuel, introduction on activated carbon, and other means. These efforts have improved performance and reduced cost.

Developments for unscrubbed units only equipped with PM control devices

The capture in PM control devices can be enhanced by converting more of the gaseous mercury to particulate mercury. One way is with the use of ACI. ACI will be discussed separately.

Another way is to add halogens to the flue gas – either by addition to the coal or injection into the flue gas. This will increase oxidation of elemental mercury to oxidized mercury, which more readily attaches itself to fly ash that is captured in the downstream PM control device. Depending upon the circumstances, this may be sufficiently effective in reducing Hg emissions that the emissions limit may be achieved without ACI. At the very least, it will enhance ACI effectiveness. This is an approach where experience was limited prior to 2011, but experience expanded rapidly once MATS was implemented. In fact, as late as 2013, activated carbon was considered the principal method of controlling mercury for unscrubbed units, but by 2015 bromine injection started to be recognized as another very viable approach to be used alone or in combination with ACI. [50]

B. Activated Carbon Injection (ACI)

Most unscrubbed units will rely largely on ACI for Hg capture. In some cases units with a BH will have sufficient inherent Hg capture without addition of ACI. ACI is discussed further in the following section.

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[49] https://www.gore.com/products/gore-mercury-control-systems

[50] https://cen.acs.org/articles/93/i11/Bromine-Comes-Rescue-Mercury-Power.html

Developments in ACI

Units that were unable to achieve Hg capture in the scrubber needed to capture Hg in the PM control device. To do that, the gas-phase Hg had to first be converted to particulate Hg. ACI was found to be the most effective means of doing that. ACI essentially is a "dial up" technology that increases the mercury capture beyond that provided purely by the inherent Hg capture in the PM control device or scrubber. Hg capture could be increased through increased carbon injection. How responsive mercury capture is to carbon injection was found to be related to many factors, including:

- How effectively the carbon was introduced into the flue gas
- The type of PM control device installed, with BH being much more effective than an ESP
- The presence of SO_3 in the exhaust gas – SO_3 interferes with Hg capture
- The presence of NO_2 in the exhaust gas, which is often increased when sodium-based DSI is in use, with NO_2 interfering with Hg capture
- The presence of ammonia in the exhaust gas, which could also interfere with Hg capture

In addition to these considerations, the impact of carbon on the marketability of fly ash was a concern. The best market for fly ash is as a Portland cement substitute; however, the presence of activated carbon can adversely impact that use. Activated carbon suppliers were challenged to develop carbons that have less adverse impact.

In 2011, ACI was generally viewed as ineffective in situations where PM control was with an ESP and SO_3 was present in significant levels, especially where units were burning high sulfur coals or where SO_3 was injected for flue gas conditioning. Similar issues were being found in applications where trona or sodium bicarbonate were being used for SO_2 or HCl capture – a particular problem for units when considering the importance of controlling HCl for MATS compliance. And, although "concrete friendly" activated carbon formulations did exist, they were often not as effective in capturing mercury – increasing injection levels and cost of control.

In the time since 2011, activated carbon suppliers have made great advances in activated carbon technology for Hg capture. In fact, in 2011 it was anticipated that a BH was necessary for high Hg capture in many situations. Circumstances where DSI was in use or SO_3 was elevated were among those situations. Along with other factors, this contributed to a large overestimation by EPA of the number of BHs by 100 GW and dry FGD by 18 GW to be installed in response to MATS as described in a declaration to the DC Circuit.[51] However, in practice, during and since MATS implementation, technology suppliers responded with far more effective carbons and other technology choices.

Pre-MATS activated carbons that were available were mostly first- or second-generation carbons. First-generation carbons were carbons originally used for other purposes, but then repurposed for Hg capture. Second-generation carbons had some degree of modification, such as addition of halogens or treatment to reduce concrete impact.

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[51] Declaration of James E Staudt to United States Court of Appeals for the District of Columbia Circuit, Case No. 12-1100, September 24, 2015

The third-generation carbons were developed in the years since MATS implementation. The third-generation carbons were specifically engineered for Hg capture in flue gas. The porosity and the surface chemistry of these products were specifically designed to address the more difficult situations such as high SO_3, NO_2, etc. They were also designed for much lower treatment rates and lower impact on the fly ash marketability. Because the market for activated carbon used for Hg control is highly competitive, activated carbon research and development continues at the major carbon suppliers, and this activity is focused on continuing to improve treatment rates and Hg capture on the various flue gas conditions that exist.

Fessenden[52] contrasted the performance of 1st and 2nd generation carbons with 3rd generation carbons available in 2017. As shown in Table 8, the costs of control for several applications using early-generation carbons, particularly for ESP applications, are all at or over about 1 mill/kWh and are as high as 3 mills/kWh for a moderate sulfur bituminous coal controlled to 90% Hg capture. It also illustrates some of the more challenging applications. For example, sites C and E are both low sulfur subbituminous units with ESPs. However, site C is capable of 90% removal at a cost of 0.92 mill/kWh with a halogenated carbon (designated as LH), while site E was capable of only 67% capture at a cost of 1.49 mill/kWh using unhalogenated carbon. It also shows the challenges with SO_3 are present in sites F and G.

Table 8. Estimated cost of Hg control for first and second generation carbons.[53]

Coal-Fired Site	Product	AQCS	Fuel	FGC	% Removal Hg	mill/KWh
A	DARCO® Hg	ESP/FF (TOXECON)	Low Sulfur Bit.	None	90	0.53
B	DARCO® Hg-LH	SDA/FF	Low Chlorine Subbit.	None	90	0.55
C	DARCO® Hg-LH	ESP	Low Chlorine Subbit.	None	90	0.92
D	DARCO® Hg	ESP	Blended Subbit./Bit	None	80	1.06
E	DARCO® Hg	ESP	Low Chlorine Subbit.	None	67	1.49
F	DARCO® Hg-LH	ESP	Low Chlorine Subbit.	SO3 (5.2 ppm)	75	1.50
G	DARCO® Hg	ESP	Moderate Sulfur Bit.	None	90	2.98

Table 9 shows the results for third generation carbons. Some applications with ESPs are only about 0.25 mill/kWh and the most difficult application shown, a high sulfur bituminous coal, is just under 1 mill/kWh at 96% Hg removal. These demonstrate that applications that were regarded as very difficult can now be addressed more easily. Also, sites 2, 3, and 4 are very similar sites, using the same activated carbon. Sites 2 and 3 have the same Hg removal, and have very similar costs of 0.222-0.244 mill/kWh. On the other hand, site 4 has a higher Hg capture rate of 87%, but this also shows a higher cost of 0.328 mill/kWh. This illustrates that increased Hg capture is possible at a higher cost, and demonstrates that ACI will be injected up to the point where the necessary Hg capture is achieved. Because there is no advantage to controlling beyond a target emission control level and there is an increased cost, ACI is generally only operated up to the level that is necessary to meet the Hg limit with some margin (perhaps 20% or so). This "dial up" aspect of ACI is discussed later.

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[52] Fessenden, J., Satterfield, J. "Cost Effective Reduction of Mercury Using Powder Activated Carbon Injection", March 2, 2017

[53] Ibid., % removal is removal attributed to the activated carbon

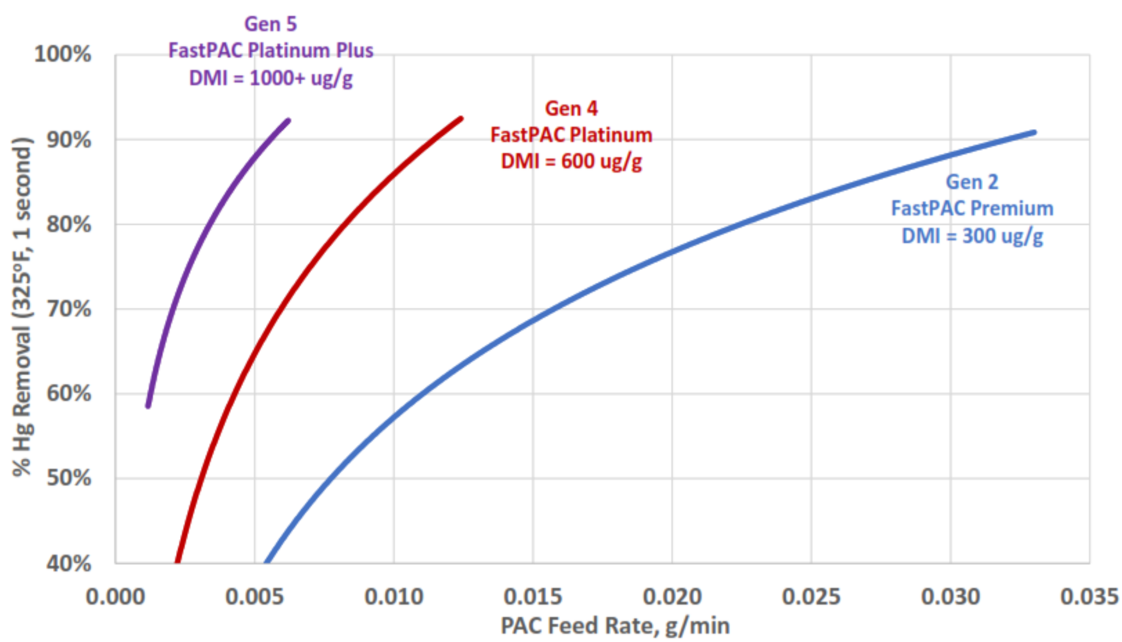
Table 9. Estimated cost of Hg control for third generation carbons[54]

Coal-Fired Site	Product	AQCS	Fuel	DSI	FGC	% Removal Hg	mill/Kwh
1	DARCO® Hg-LH EXTRA SP	SCR/FF	Low Chlorine Subbit.	None	None	94	0.086
2	DARCO® Hg-LH EXTRA SP	CS-ESP	Local W.Subbit	None	None	80	0.222
3	DARCO® Hg-LH EXTRA SP	CS-ESP	Local W.Subbit	None	None	80	0.244
4	DARCO® Hg-LH EXTRA SP	CS-ESP	Low Chlorine Subbit.	None	None	87	0.328
5	DARCO® Hg-LH EXTRA TR	CS-ESP/wFGD	High Sulfur Bit.	Calcium-based	None	82	0.375
6	DARCO® Hg-LH EXTRA TR	CS-ESP	PRB/Bit. Blend	Sodium-based	None	88	0.663
7	DARCO® Hg EXTRA	CS-ESP	Low Chlorine Subbit.	None	SO_3 (6ppm)	90	0.789
8	DARCO® Hg-LH EXTRA SR	CS-ESP	PRB	None	SO_3 (7ppm)	90	0.872
9	DARCO® Hg EXTRA SR	SNCR/ESP/wFGD	High Sulfur Bit.	None	None	96	0.980

Pre-MATS, 90% mercury capture was viewed by many as the practical upper limit of Hg control in nearly any circumstance. Some situations were recognized as being easier than others (for example, situations with bituminous coals and dry FGD). Some were much more difficult and it was believed that a BH retrofit would be necessary (situations with bituminous coals and an ESP, for example). However, technology developments proved otherwise.

The impact of carbon advancement is also illustrated by laboratory data for different generations of carbon developed by ADA Carbon Solutions.[55] As shown, in Figure 23, treatment rates to achieve 90% removal were reduced by roughly a factor of 6 from the Gen 2 to the Gen 5 FastPAC products.

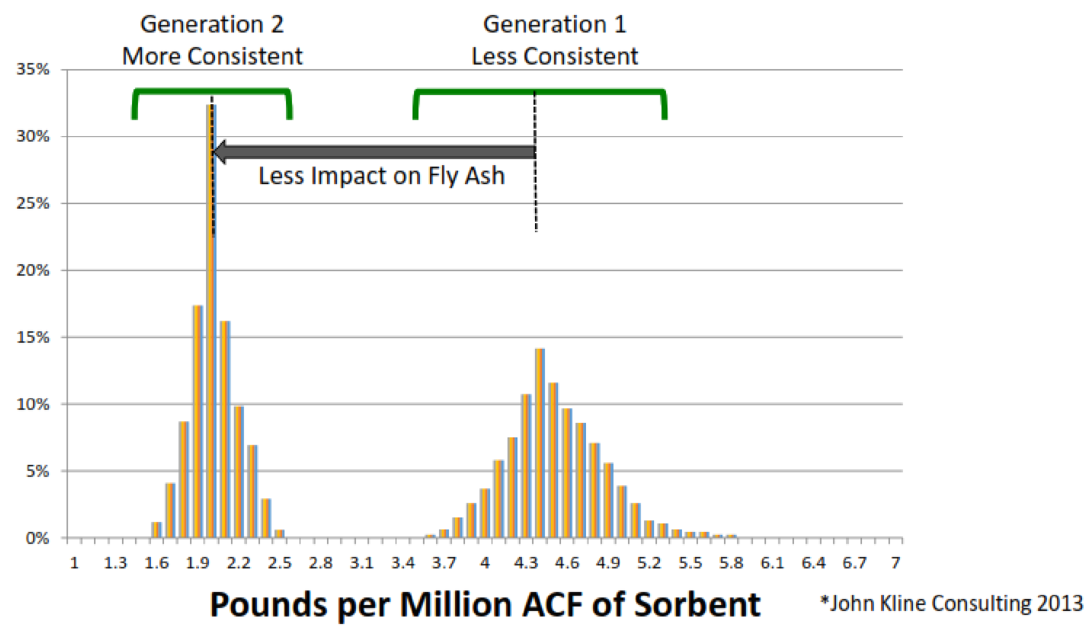
Figure 23. Comparison of laboratory data for different carbons[56]



[54] Ibid., % removal is removal attributed to activated carbon
[55] Huston, R., "State-of-the-Art PAC", ADA Carbon Solutions Activated Carbon User's Group, September 11, 2018
[56] Ibid., DMI stands for Dynamic Mercury Index, and is a measure of the sorbent's ability to capture mercury

Improvements leading to lower treatment rates also led to less adverse impact on fly ash marketability. This is illustrated in Figure 24, which shows lower treatment rates for actual ACI projects in terms of pounds of sorbent per million actual cubic feet (lb/million ACF)[57] of exhaust gas.

Figure 24. Impact of advanced PACs on fly ash – Generation 1 versus Generation 2 PACs[58]



C. ACI, a "dial up" technology

PM and SO_2 controls provide varying degrees of Hg control. Greater capture of Hg beyond that possible from the inherent capture of the PM or SO_2 control device may be desirable. This is especially the case for units that are only equipped with ESPs for pollution control. The units with only ESPs tend to have lower inherent Hg capture than units with scrubbers or fabric filters and are therefore more likely to require additional Hg capture. ACI was originally developed to increase Hg capture beyond the inherent capture of the other devices. By adding ACI it is possible to increase Hg capture, and the capture will increase with treatment rate. But, is there a practical limit to the removal rates of activated carbon? This will be examined with unit data later in this document and will be examined here from a more theoretical perspective.

Hg capture with ACI relies upon three critical mechanisms, as described by Huston[59]:

- *Contact* – getting the carbon in contact with the mercury.
- *Conversion* – converting elemental mercury to oxidized form.
- *Capture* – capturing and retaining the mercury in the carbon.

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[57] This relates to the amount of carbon injected per actual volume of flue gas being treated, and relates to the concentration of activated carbon in the exhaust gas.
[58] Huston, R., "State-of-the-Art PAC", ADA Carbon Solutions Activated Carbon User's Group, September 11, 2018
[59] Huston, R., "State-of-the-Art PAC", ADA Carbon Solutions Activated Carbon User's Group, September 11, 2018

Contact is achieved with injection systems designed to get the carbon distributed so that the entire gas field is treated. In some cases, mixing devices have been installed. Recognizing this limitation on performance, the technology associated with carbon injection technology has advanced rapidly. It has become standard practice to model injection systems on the computer to optimize the design. In some cases, physical models are also performed. This enables the designer to develop a highly effective injection system. So, while this may have been a very limiting issue in the early days of activated carbon systems,[60] it is not such a large limitation now.

Conversion is generally effective when sufficient halogen is present either in the exhaust gas or on the surface of the carbon. Halogen addition to the coal, to the exhaust gas, or to the carbon is a common approach to this challenge.

Capture: Once the mercury is captured, it is usually well retained by the carbon. However, some situations are more challenging for capture because SO_3, NO_2 or other species that may be present in exhaust gases can compete with mercury for capture and reduce the capture efficiency of the activated carbon. This has been a major focus for carbon developers – to optimize the surface chemistry and physical characteristics of the carbon to capture Hg when these other species are present.

Furthermore, at the time MATS was being developed, there were numerous misunderstandings about ACI technology. Staudt addressed some of these in 2008,[61] but most of these misunderstandings persisted for several more years. Today, these misunderstandings about the technology are largely cleared up. So, in combination with improved understanding of the capabilities of activated carbon and the very substantial improvements in ACI technology, ACI today is capable of much more than it was in 2011.

In the face of the dramatic improvements, it is reasonable to ask whether there is a limit to Hg capture from ACI. The answer is:

- Theoretically, perhaps, but experience shows that we are not close to having reached any such limit
- Practically, however, there is a level of diminishing returns.

As will be shown later in this report, Hg emissions from coal power plants have been controlled to levels about 0.060 lb/TBtu – one twentieth of the MATS limit. This demonstrates that if there is a theoretical limitation to the ability to reduce Hg, such as a thermodynamic equilibrium limitation, the level must be below that concentration.

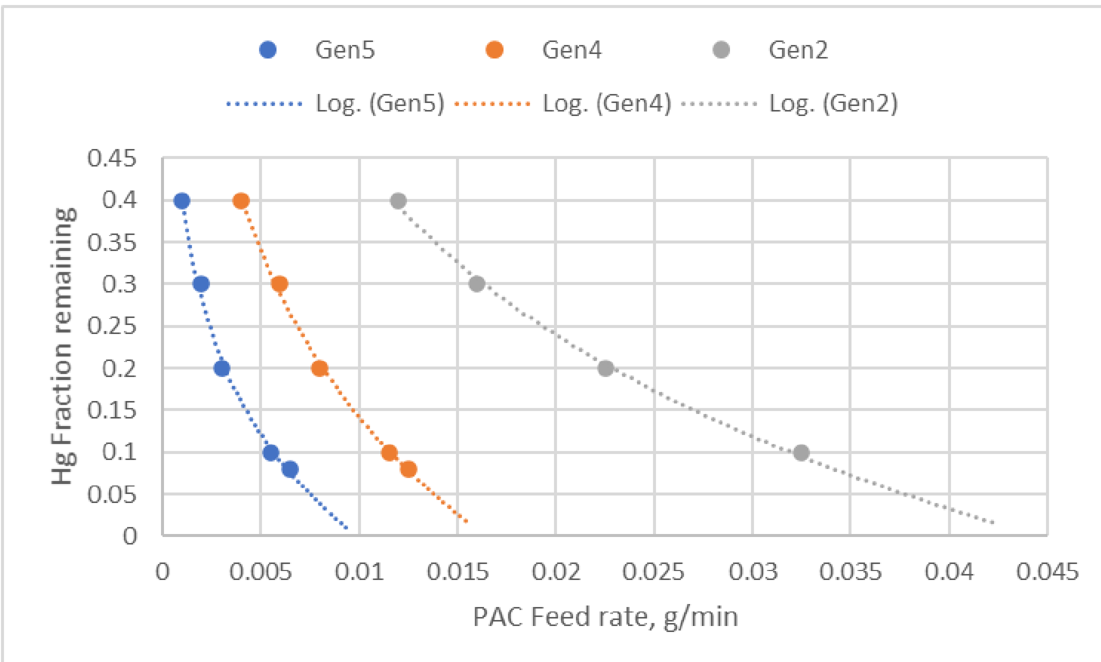
Reducing Hg with activated carbon further on any given unit to lower levels than currently achieved will require additional carbon injection, or some other means of incremental control. Figure 25 shows the data of

[60] Staudt, J., "Does ESP Size Really Matter", at https://www.andovertechnology.com/wp-content/uploads/2021/06/Does-ESP-size-really-matter.pdf; See discussion on Yates unit 1

[61] Ibid., this paper was intended to address numerous misunderstandings regarding ACI technology that, unfortunately, persisted for several years.

Figure 23, but plotted differently. The data, plotted as Hg fraction remaining versus feed rate, plots exactly as a log function, consistent with a single-step reaction mechanism. This doesn't mean that it is truly single step, but that one step is the most important one because it is the most limiting. That is consistent with most real reaction mechanisms. It is reasonable to assume that this trend could be extended beyond the data, and this forecast is shown. But, does the trend in Figure 25 match the data? Recalling Table 9, coal power plant sites 1 and 9 show Hg capture rates well above 90%. Site one is a fabric filter application, but site 9 is an ESP application. Clearly, Hg capture with ACI and an ESP can go beyond 90%. However, there is more data to examine as will be addressed in the following discussion.

Figure 25. Data of Figure 23, plotted as Hg fraction versus feed rate



ACI is not the only means to achieve additional Hg capture. For scrubbed units it can be done with scrubber chemicals. Some of these chemicals are halogens to promote oxidation. Other chemicals are used to promote precipitation of mercury into scrubber solids. Some of these are flocculants. These tend to be widely used in wet scrubber applications, sometimes in combination with ACI. But, although other means to enhance mercury capture exist for both PM and SO_2 control equipment, ACI provides a means for estimating the additional cost of mercury capture while recognizing that less expansive approaches may be available in some cases, and this will be examined further.

D. Evaluation of Hg data

Except for a small number of low mass emitters, coal power plants must monitor Hg emissions continuously. The NRDC's database shows reported monthly Hg capture from for 2020 for both not low-rank coals and low-rank coals. Of these 416 units where data were collected and emissions information was available on a unit basis, 393 were not low-rank coal and 23 were low-rank coal.

Not low-rank coals

Table 10 compares the Hg emission rates of the top 10% of reported not low-rank coal units to those of the bottom 10% of reporting not low-rank coal units. “Min” and “Max” are the minimum or maximum for any given period. As shown, there is close to a fifteen-fold difference in the average emissions level between the top and bottom performing units. However, among the top and bottom units are significant numbers of each listed coal type (bituminous, subbituminous, and refined coal).

Table 10 Emission rates of top and bottom 10% not low-rank coal units

	No. of Units	Emission Rates (lb/TBtu)		
		Min	Max	Avg
Top 10%	39	-	0.1660	0.0905
Bottom 10%	39	0.8386	1.3861	0.9427

ATP further examined the NRDC database and broke the data into deciles by mercury emissions rate. The lowest emitting units were in decile 1 and the highest emitting units were in decile 10. ATP also took the step of estimating the Hg capture rate – comparing the outlet emissions rate to the Hg content of the coal. Coal Hg content was estimated from IPM documentation. IPM documentation chapter 9 has representative coal mercury content for coals from different regions.[62] Subbituminous coals were assumed to be Wyoming PRB. Bituminous coals were assumed to be IL basin, PA, central Appalachian or western bituminous coals, depending upon location. Lignite coals were assumed to be local lignite. This provides an approximate estimate of percent mercury capture since actual coal mercury content data wasn’t available, but rather, an estimate from IPM documentation.

Figure 26 shows the Hg concentration and estimated capture efficiency. For decile 1, the average emissions rate is 0.0905 lb/TBtu with an average estimated capture efficiency of 98.7%. This decile includes units with only ESPs and ACI, demonstrating that high levels of Hg capture are possible using this control configuration. The bottom decile has an average emission rate of 0.9427 lb/TBtu and an average estimated capture rate of 85.4%.

Figure 27 shows the trends in coal type. The top decile is majority bituminous coal. In this analysis, refined coal was examined to determine the type of origin coal and categorized by the origin coal type. The bottom deciles are majority subbituminous.

[62] See Figure 9-1 and Table 9-5 in the Integrated Planning Model documentation, Chapter 9.

Figure 26. Average Hg concentration and estimated percent capture by decile for not low-rank virgin coal

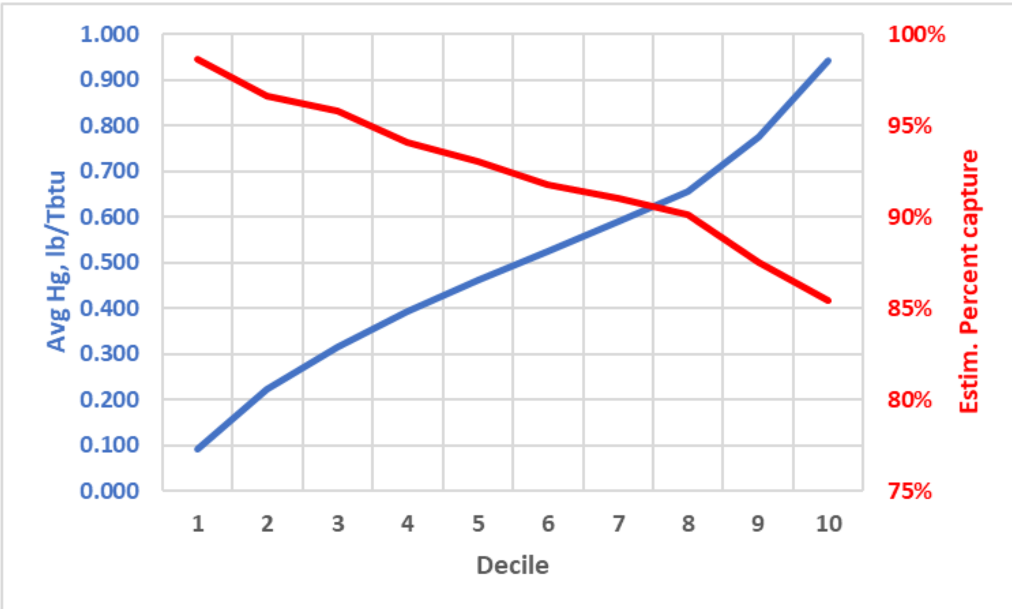
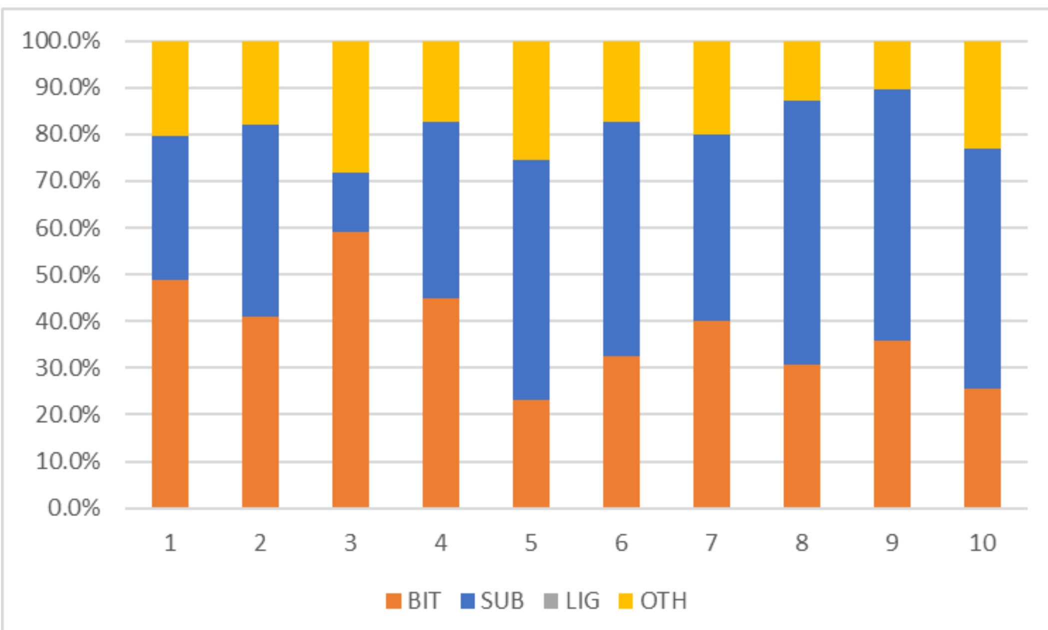
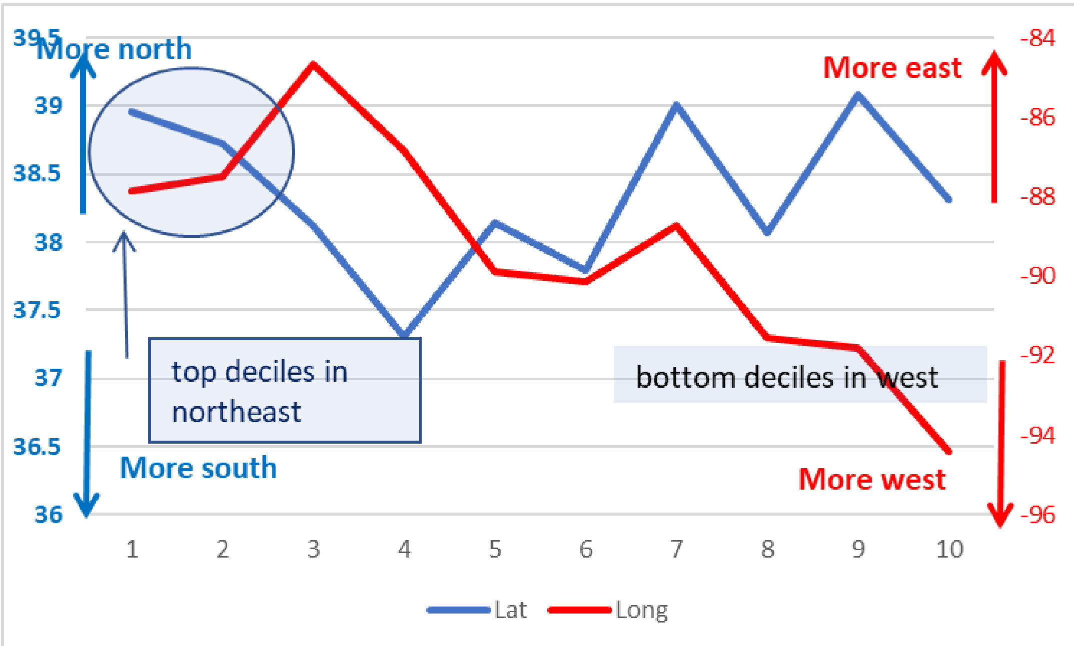


Figure 27. Coal type by decile, not low-rank virgin coal



Top deciles of not low-rank coal are more likely to be northeast (consistent with higher likelihood of bituminous coal). Figure 28 shows the average latitude and longitude by decile. Consistent with the finding that the top deciles were likely to be bituminous coal units and the bottom deciles were more likely to be subbituminous coal units, the top deciles are located in the east and the bottom deciles in the west. The top two deciles are solidly in the Northeast US.

Figure 28. Average latitude and longitude by decile

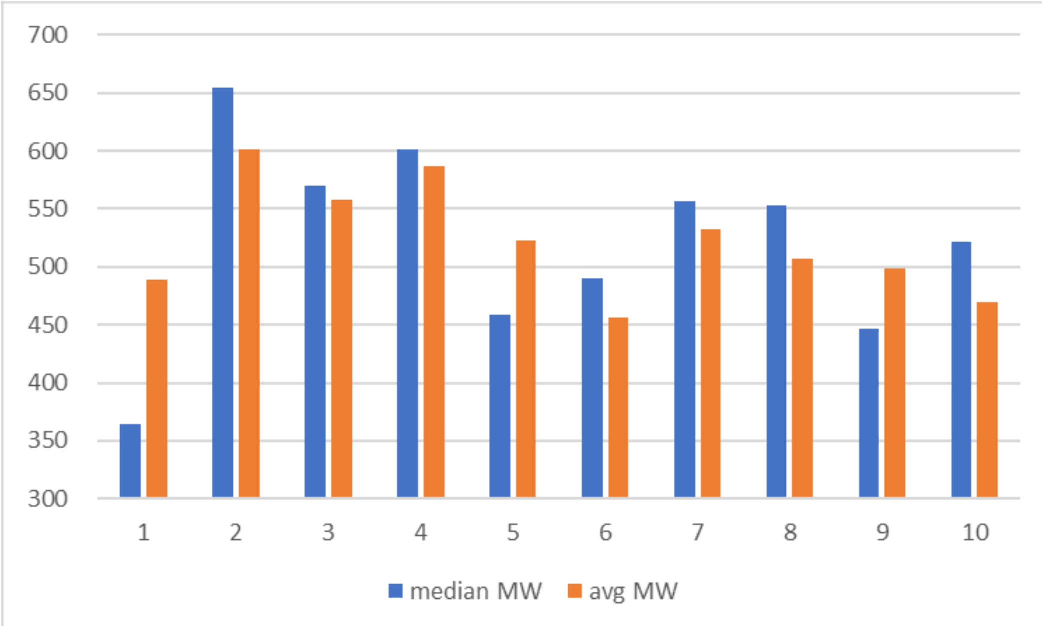


Bituminous coal has higher sulfur, which usually has a negative impact on Hg capture. Therefore, it is surprising to see a higher capture rate, and lower emissions from bituminous units. Subbituminous has lower halogens, but this is easily addressed.

There is no reason to believe that subbituminous coal is more difficult to capture mercury from than bituminous. Lower sulfur is a good impact while shortage of halogens is easily addressed. It is likely that this is more of an impact of equipment. Therefore, equipment configurations were examined.

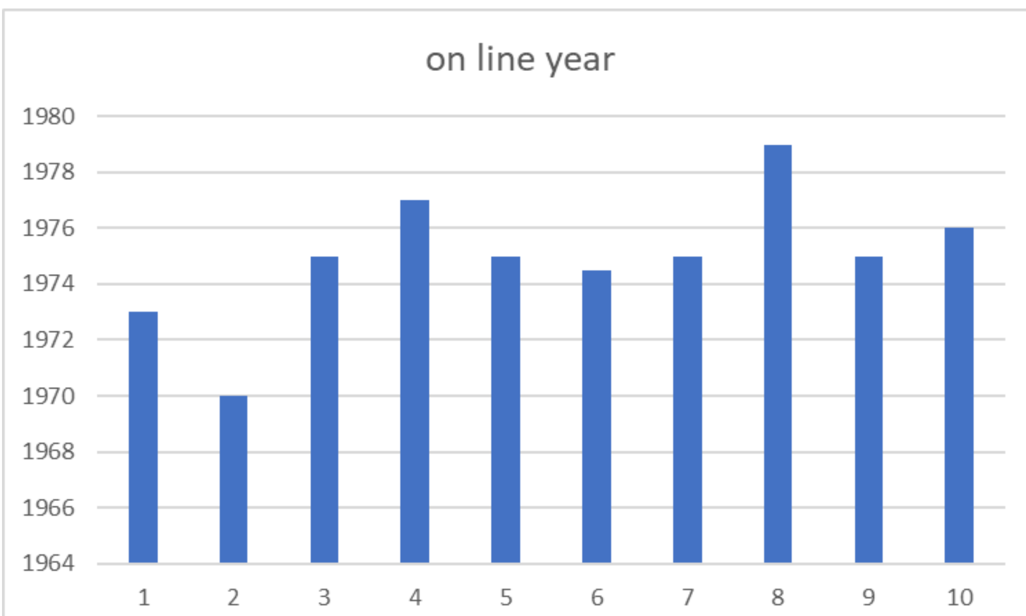
Figure 29 shows the median capacity of each decile. Decile 1 has the smallest units and decile 2 the largest, and there is no real pattern to the rest. Decile 2 has significantly larger units than any other decile. The size of the units can be significant in that it can be an indication of the importance of the unit in the utility fleet.

Figure 29. Median MW capacity by decile



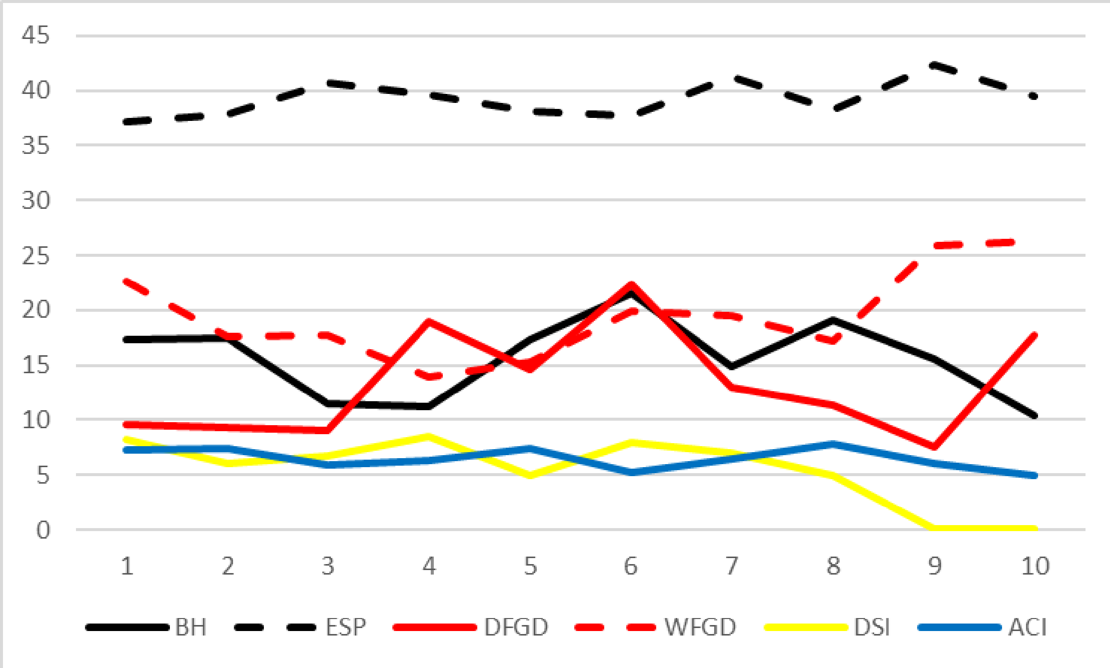
As Figure 30 indicates, the lower deciles may have a slightly more recent on-line year than the top deciles. However, it is not a large difference.

Figure 30. Median on-line year of each decile



The average age of equipment is shown in Figure 31. There are no apparent trends in air pollution equipment age, except that ESPs in top deciles are slightly newer than those in bottom deciles.

Figure 31. Average age of equipment (years) by decile



Baghouses are more likely in the top decile, as shown in Figure 32. ACI is more likely in the lower deciles, wet FGD is most common in mid-deciles. DSI is more common in top deciles. Because BHs are highly effective for mercury control, it is not surprising to see them in the top decile. The significance of ACI in the bottom deciles is consistent with ACI being one of the few technologies that owners and operators can "dial up" to get the level of capture needed because those units are only barely complying with the standard. For these ACI-equipped units that can effectively adjust their treatment rate to achieve just below the standard, there is little incentive for achieving a Hg emissions rate well below the limit because it would require additional cost associated with activated carbon.

As shown in Figure 33, baghouses in combination with ESPs are more frequent in the top decile – 30% of the top decile. ACI is most common in lower deciles. Scrubbers are most common in mid deciles.

Figure 32. Percent of decile having equipment

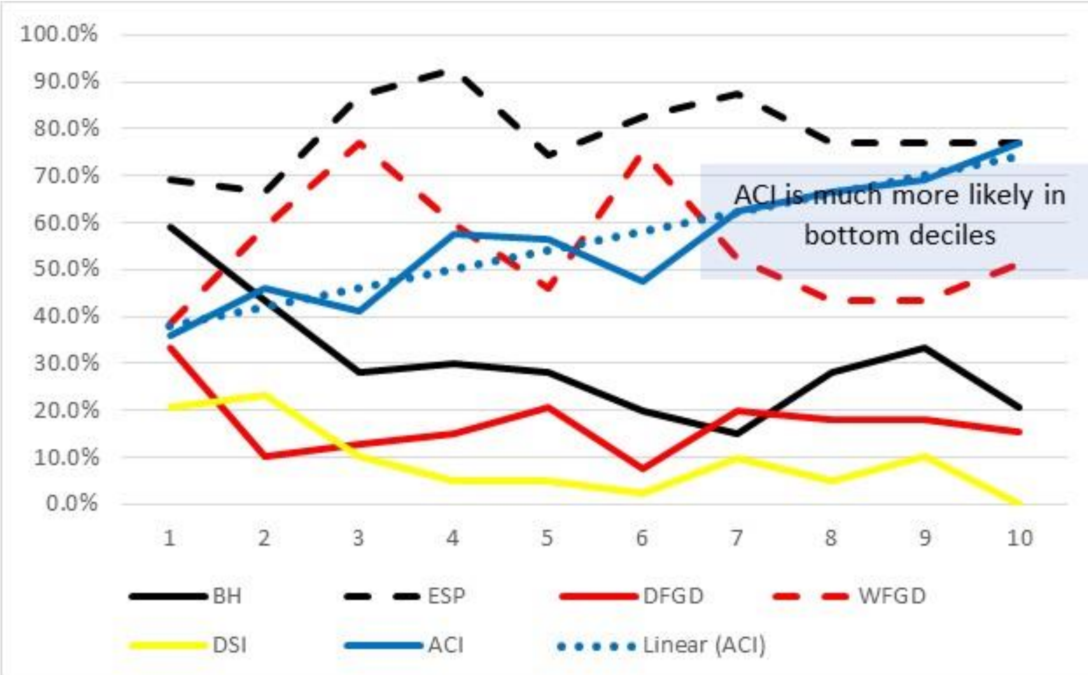
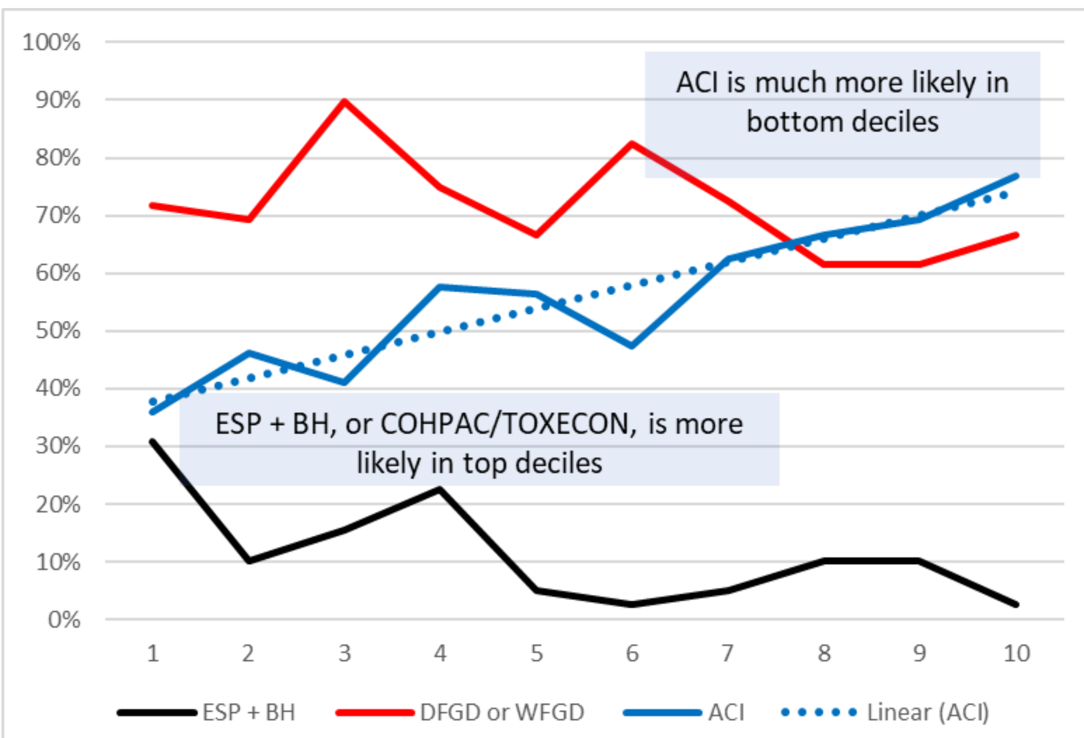


Figure 33. Percent of decile with equipment. Any type of FGD, ESP plus BH, ACI



The ability to control Hg while equipped with only an ESP and ACI was examined. As demonstrated in Figure 34, when there was only an ESP (no baghouse or scrubber), most units were estimated to have greater than 90% capture efficiency, and some well over 95%. ACI is the method of control. As a result, high capture efficiencies of 95% or better are possible when simply using ACI with an ESP.

Note that only units reporting unit level Hg emissions rate data are included. Excluded from this evaluation are those units where only plant level Hg emissions data was available.

Figure 34. Emission rate and estimated capture efficiency for not low-rank coal, unscrubbed units, with only an ESP and ACI.

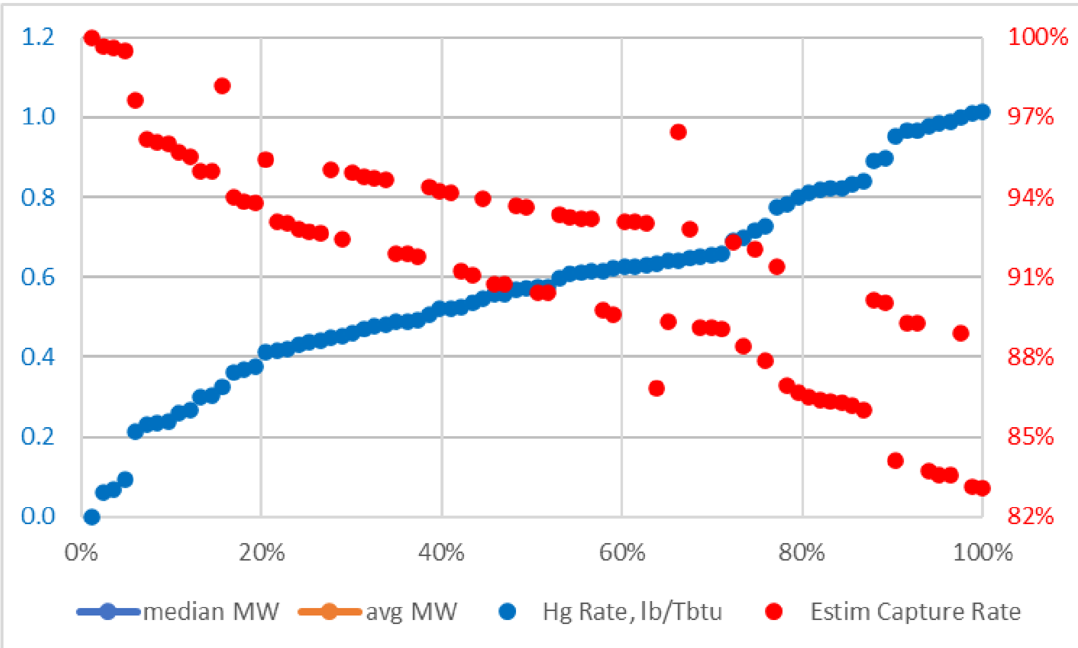


Table 11 shows a summary of the equipment for the top and bottom deciles. Top units are much more likely to:

- Have a baghouse
- Use bituminous coal
- Not rely upon ACI

Top decile units are also:

- Somewhat more likely to have a dry scrubber
- Somewhat less likely to have a wet scrubber

Table 11. Summary of equipment for top and bottom decile

Top Decile						
Row Labels	**Count of Coal Units**	**Sum of BH**	**Sum of ESP**	**Sum of DFGD**	**Sum of WFGD**	**Sum of ACI**
BIT	19	11	17	6	8	4
OTH	8	4	7	2	6	5
SUB	12	8	3	5	1	5
Grand Total	**39**	**23**	**27**	**13**	**15**	**14**

Bottom Decile						
Row Labels	**Count of Coal Units**	**Sum of BH**	**Sum of ESP**	**Sum of DFGD**	**Sum of WFGD**	**Sum of ACI**
BIT	11	1	10	0	11	3
OTH	9	0	9	1	3	9
SUB	20	8	11	5	7	19
Grand Total	**40**	**9**	**30**	**6**	**21**	**31**

The following are some caveats and summary of data on not low-rank coal.

- The data doesn't include use of oxidizing agents or scrubber re-emission additives
- The analysis only examined unit-level emissions data – not common stack data
- Top deciles have highest use of baghouses and combination of baghouses and ESPs
- Wet FGD units are most likely to be in mid-deciles
- Bottom deciles have the highest use of ACI and lowest use of baghouses
    - Consistent with "dial up" nature of ACI
- Even units equipped only with ESPs and ACI can achieve very high mercury capture

2. Low-rank coals

Table 12 shows the overall emission rates for the 23 low-rank units from the NRDC database. The emission rates, in some cases, were well under the limit of 4 lbs/TBtu. As shown in Table 13, the lowest emitter was an unscrubbed unit with a BH and ACI, and the highest emitter was scrubbed. Of the 23 units, all but four were listed as using ACI. The four without ACI were scrubbed units that were able to achieve Hg capture in the scrubber. One unit had a venturi scrubber and ACI. The scrubber's capture may have been aided by the addition of chemicals; however, this information is not available because it is not reported. Table 14 shows the coal types were primarily lignite and refined coal (mostly, lignite that has been modified to be refined coal).

Table 12. Overall Hg emission rates of low-rank coal units

No. of Units	Emission Rates (lb/TBtu)		
	Min	Max	Avg
23	1.04	3.81	2.34

Table 13. Control technologies and associated Hg emission rates for low-rank coal units

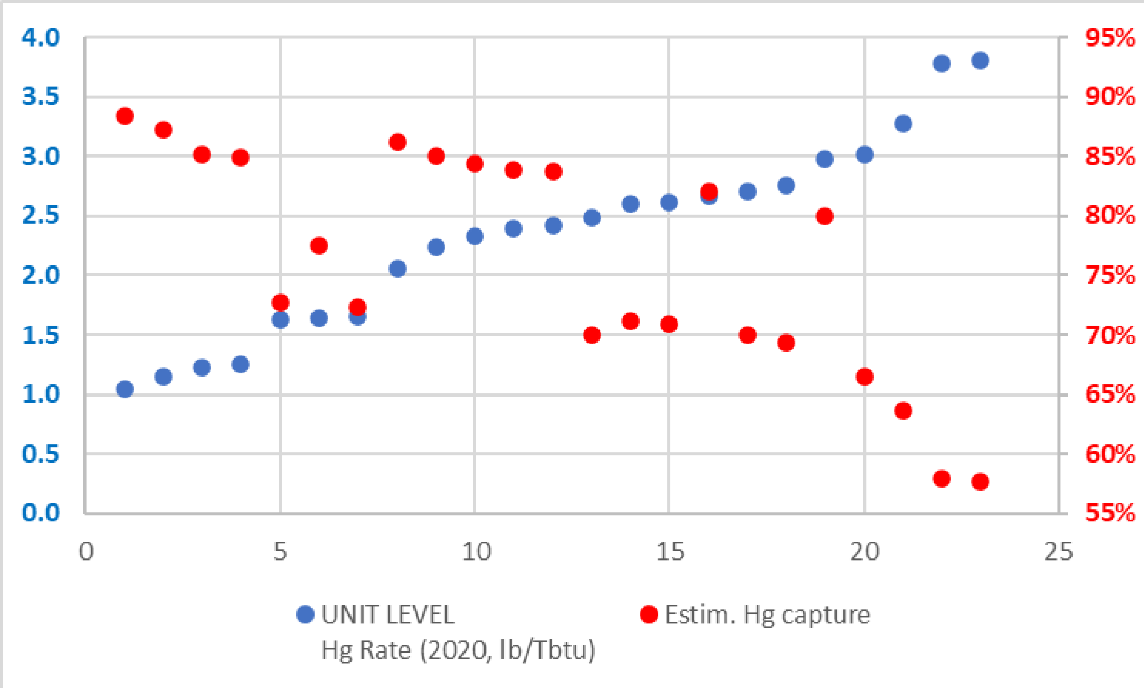
Row Labels	number	Average of Hg Rate, lb/TBtu	Max of Hg Rate, lb/TBtu	Min of Hg Rate, lb/TBtu
BH + FGD	2	2.69	2.76	2.62
BH + FGD+ACI	4	2.03	2.49	1.23
BH + ESP + FGD+ACI	1	1.65	1.65	1.65
BH no FGD+ACI	2	1.09	1.15	1.04
ESP + FGD	2	3.80	3.81	3.79
ESP + FGD+ACI	11	2.51	3.28	1.64
Only FGD+ACI	1	1.25	1.25	1.25

Table 14. Coal type and associated emission rates for low-rank coal units

	SUB	LIG	OTH
Avg Emission Rate, lb/TBtu	1.65	2.15	2.68
No. of units	2	11	10

The 23 units were ranked from lowest emission rate to the highest emission rate and the estimated capture efficiency was calculated for each unit. The results are shown in Figure 35. As this shows, capture efficiencies were estimated to be below 90% in all cases, with some only about 60% capture.

Figure 35. Hg emission rate and estimated capture efficiency for low-rank coal.



E. Summary and conclusions for Hg control

Because there were only a few state rules for Hg control prior to MATS, there was far less experience with Hg control in 2011 than there is today. MATS motivated a nationwide effort to control Hg emitted by power plants. As a result, MATS also motivated extensive research and development by industry to find ways to economically control Hg to the required levels.

Advances in technology included advances in means to enhance Hg capture by scrubbers and means to enhance Hg capture by PM control equipment. ACI, the technology that was most commonly used to increase Hg capture in the PM control devices, saw extensive advances. Applications that had been very challenging in the past, such as when SO_3 was present or when sodium-based DSI was being used, were later more easily addressed thanks to advances in technology – specifically, through the development of specialized activated carbons to address these difficult situations. Such carbons were not available in 2011, but they are available now. Much higher removal rates with lower carbon injection rates are possible because of these advances. In addition, new chemicals and operating methods were developed to address some of the challenges with capture in wet scrubbers, especially, re-emission of Hg. These chemicals and operating methods kept Hg from being reduced to elemental Hg, assuring high Hg removal rates in the scrubbers.

Like the PM emission data, it is apparent from the data that some units are controlling Hg to much lower levels than others. Setting aside low-rank virgin coal for the moment, this was not found to be the result of the coal type, although bituminous units were the majority of the top decile, while subbituminous units were the majority of the bottom decile. This is an unexpected result because the challenges with controlling Hg in bituminous units have generally been greater than for subbituminous units due to the relative sulfur content of the two types of coals. The difference was found to be the result of the equipment installed at the facility.

The bottom deciles tended to be smaller, although not universally. They were also much more likely to be controlled with ACI, and less likely to have a baghouse. There is little incentive for controlling far below the emissions limit with ACI because additional Hg reductions come at an increased cost. Therefore, it is not surprising that, although ACI has been shown to achieve very high Hg reductions, in practice many units only use it to achieve just below the emission rate limit.

The cost of added Hg control and the impact of lower Hg emission rates

The data indicates that higher removal rates are definitely achievable for many units, and at a modest incremental cost. Using the data from Figure 25, an increase in capture efficiency from 80% to 90% requires about 50% increase in treatment rate. An increase from 90% to 95% requires roughly a 15% increase in treatment rate. Conservatively increasing that to 25% and assuming that 90% capture costs roughly 1 mill/kWh or less, this means that an increase in cost of 0.25 mill/kWh or less would result from increasing capture efficiency from 90% to 95% capture. Using the same graph, an increase of capture from 90% to 97.5% requires roughly 30% more carbon injected. Conservatively increasing that to 50% means that an increase of capture from 90% to 97.5% will cost 0.50 mill/kWh or less.

If the majority of the not low-rank coals have a Hg content of about 6 lbs/TBtu, 90% capture results in 0.60 lb/TBtu. Controlling to exactly the limit represents roughly 80% control. More than half of the units are already controlling to this level. For not low-rank coals, a lower Hg standard of 0.7 lb/TBtu could be achieved at a modest cost to some units, and no cost for most units. Reducing emissions to 0.3 lb/TBtu would be, on average, 95% capture, and about 25% of all units are already at or below this level. Therefore, in this case 75% of the units would incur additional control costs. An increase in Hg capture from 80% to 95% would likely result in a doubling of carbon injection rate. From the data in Table **9**, 80% capture is likely achieved at well below 1.0 mill/kWh – probably in the range of 0.25 mill/kWh to around 0.60 mill/kWh, depending upon the specific circumstances. An assumption of an increase of 1.0 mill/kWh would constitute an absolute worst-case situation. 95% capture from the average coal Hg content would result in an emission rate of about 0.3 lb/TBtu. For not low-rank coals a Hg standard of 0.3 lb/TBtu could be complied with at a modest cost to most units, and no cost for some units. The cost would not exceed 1 mill/kWh, and would likely be much less. Units with fabric filters would have very little, if any, cost increase.

For low-rank coals, estimated Hg capture is low and could be increased. Nearly all of the low-rank virgin coal units use ACI and could increase their treatment rate to achieve higher capture rates. The low estimated capture efficiency of these units suggests that the ACI treatment could be improved. Assuming typical coal Hg content of about 10 lb/TBtu for virgin low-rank coal, an emission rate of 0.3 lb/TBtu is about 97% capture. Figure 26 demonstrates that this capture efficiency is being achieved for not low-rank units. The cost would also likely be at or below 1.0 mill/kWh. The highest estimated coal Hg content is 14.9 lb/TBtu. These seven units are all units burning Texas Lignite, and they are equipped with scrubbers. Two have baghouses, and five have ESPs. Therefore, as scrubbed units, they are all capable of achieving higher capture rates (current capture rates for low-rank coal units are estimated at 80%-85% based upon 2019 data). About a third of all low-rank coal units are already controlling to below 2 lb/TBtu, and five of the seven Texas Lignite units are controlling to below 2.4 lb/TBtu. A standard of 2 lb/TBtu would necessitate modest increased cost that would likely be well below 1 mill/kWh as this is consistent with under 90% removal in all cases. A control level of 1 lb/TBtu might also be justified, as this would require less than 95% capture in every case, and in most cases much less. Units with fabric filters would experience very little cost increase because of the high efficiency of ACI in this configuration. Wet scrubbed units could enhance capture using scrubber chemicals at a modest cost, likely well below 1 mill/kWh.

Table 15 shows the estimated impact of reducing Hg emission rate standards.

Table 15. Estimated impact of reduction in Hg emission rate standards

Hg limit for not-low rank coal units (current standard 1.2 lb/TBtu)	Units with Electrostatic Precipitators	Units with Baghouses	Overall
0.7 lb/TBtu (equivalent to 90% Hg removal)	▪ Majority of units would have little to no additional cost ▪ Roughly 25% of units would need to increase ACI treatment at additional cost of 1 mill/kWh or less	▪ Virtually all units can control to this level with little to no incremental cost	▪ Less than 50% of units are above 0.7 lbs/TBtu
0.3 lb/TBtu (equivalent to 95% Hg removal)	▪ 75% of units with ESPs would need to increase ACI treatment at cost of 1 mill/kWh *or less* ▪ If a unit installs a baghouse to meet the PM standard, it would not need any additional ACI	▪ Most units can control to this level with little or no incremental cost ▪ A few units would incur 0.25 mill/kWh cost or less	▪ Roughly 50% of units are above 0.3 lbs/Tbtu

Hg limit for low-rank units (current standard is 4 lb/TBtu)	Scrubbed units	Unscrubbed units
2 lbs/TBtu (< 90% Hg removal)	Low-Modest cost for most units, no cost for about a third of units	No cost for one unit; modest cost well under 1 mill/kWh for other two
1 lb/Tbtu (< 95% Hg removal)	Low-Modest cost of up to 1 mill/kWh for most units	No cost for one unit; cost of up to 1 mill/kWh for other two

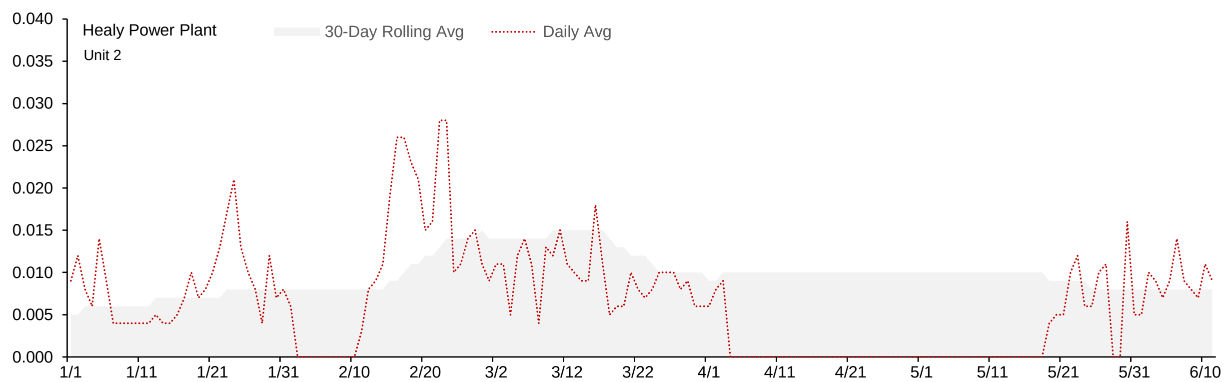
IV. Appendix

A. One-Day PM emissions v. 30-day average

A comparison of one-day PM emissions rates to 30-day average rates was made for some units. Not all companies report daily PM rates in Webfire reports, so that analysis of daily emissions is not possible for all units. For these units PM emissions dropped (or there may have even been a shutdown) after a spike, suggesting some corrective action. Notably, what is shown here are daily averages, not hourly averages, along with 30-day averages. Hourly averages would show greater variability. One would not expect significant peaks in daily averages lasting for days before or after a shutdown. So, there would have to be other factors that would cause such peaks. It was not possible in this effort to examine what other factors might have contributed to the PM variability. Data is taken from US EPA Webfire reports.

1. Healy Unit 2

Healy unit 2 is a 60 MW circulating fluid bed plant with limestone injection and a dry scrubber with fabric filter. One-day averages of PM appeared to be high under some conditions, even approaching the MATS emission limit in the days near February 20. Subsequently, PM emissions fell, which may have been a result of some corrective measures.



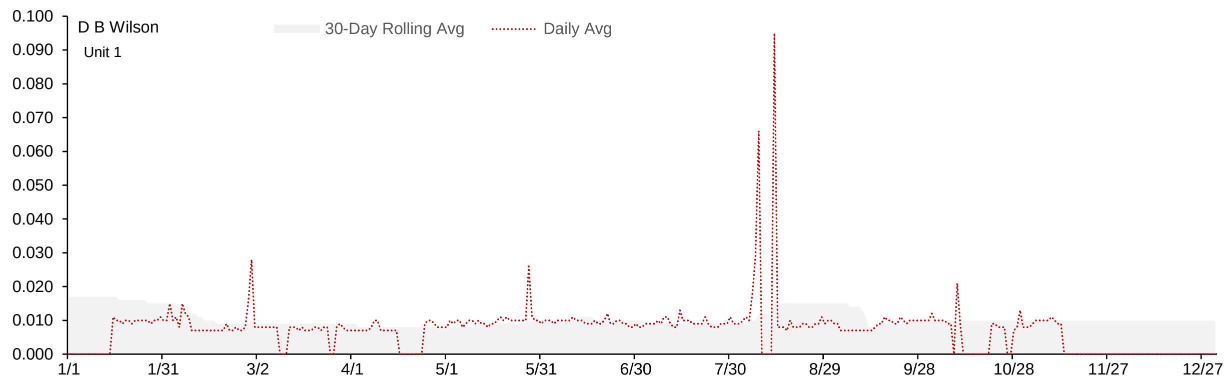
2. D.B Wilson, Unit 1

DB Wilson unit 1 is a 500 MW unit with an ESP, SCR and FGD. Looking at the 2019 data, from 2/25 to 2/28, emissions increased from 0.007 lb/MMBtu to 0.016 lb/MMBtu on 2/27, and to 0.028 lb/MMBtu on 2/28. Emissions then dropped to 0.008 lb/MMBtu. This was followed by a shutdown from 3/9 through 3/11. There was an emissions spike on 8/8 to 0.066 lb/ MMBtu (daily avg; 14 valid hours). The unit went offline from 8/9 to 8/12. Two "valid hours" were on 8/13. There was an emission spike again on 8/13 to 0.095 lb/ MMBtu (daily avg). By 8/14, emissions were back down to 0.008 lb/ MMBtu and the unit was reporting 24 valid hours each day. Monitoring issues were reported. The spike in reported PM may have been related to that. But, 2018 data appears more compelling that there was work being done on this unit relating to PM emissions control.

Looking back to the second half of 2018, after months of fairly consistent daily average emissions rates between about 0.015 and 0.020 lb/MMBtu, in mid-September daily average emissions climbed up to as high as 0.028 lb/MMBtu on 9/28, after which the unit shut down until the end of December for two days

(12/29 and 12/30, where emissions were still high). The unit shut down again until 1/15/19 where the emissions were well controlled to about 0.010 lb/MMBtu for a daily average rate. In this case it appears very likely that shut downs may have been taken to address PM emission issues.

DB Wilson 2019 PM Emissions control data – full year



DB Wilson 2018 PM Emissions control data – July through December