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# TRENDING DATA ANALYSIS OF BOILER TECHNOLOGY IN THE UNITED STATES FOR THE YEARS 2012-2016

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## ABSTRACT

Given the many difficult standards and regulations surrounding energy production in the United States (as well as those to be implemented), variable fuel costs, climate concerns, and alternative technologies, industry members find themselves in challenging times. Remaining competitive and relevant requires efforts on multiple fronts, including innovations in technology, modeling and analysis tools, reductions in expenditures, and any other improvements available. For the fluidized bed combustion (FBC) industry and other combustion technologies, a benchmark study has been used to evaluate performance for the operating years of 2012-2016. The study, in the form of a voluntary survey and data analysis, has provided a unique view of the practices and concerns within the industry. Trends and consistencies are described when available and a broad picture of the modern combustion industry is described.

**Keywords:** *Power Generation, Industry Benchmarking, Coal-fired Power Plants, Combustion Technologies.*

## I. INTRODUCTION

The invention of boilers for industrial purposes dates back to the 1700s. Boilers have long been used for heating and power generation. In the late 2000's, the proliferating demand for power in multiple industries assisted with the advancement of boiler technologies having higher power generation efficiency. Two dominant contemporary combustion technologies, pulverized solid fuel firing technology and fluidized bed combustion (FBC) technology, were born in this period [1]. The increase in environmental concerns was an important contributor to the boiler technology advancement. Since a variety of materials were used as fuels in various types of boilers, the adverse effects of the combustion of these materials to the environment became of concern. The amount of hazardous air emissions due to the combustion of fuels during the whole power generation process was initially regulated under the Clean Air Act [2] and standardized specifically for each type of pollutant under the Boiler Maximum Achievable Control Technology (MACT) Rule [3]. To comply with these rules, boiler technologies deemed to be more harmful to the environment became obsolete. In their place, upgraded boiler technologies with effective emission control capabilities were developed. For instance, an FBC boiler could effectively and economically limit the emission amount of $SO_x$ and $NO_x$ within the standardized level [4]. However, the improvements in the power generation efficiency and environmental friendliness of the newer technologies was not enough to protect the uninterrupted availability of power. Rather, the lack of operational safety awareness and maintenance timeliness would cause boiler dysfunction and interruption of the power supply. As the second largest electricity consumer in the world with a total consumption of around 3.85 trillion kilowatt hours in year 2015, the United States should diligently work to protect its power supply stability [5].

The current research was done to diagnose the condition of the existing boilers in the United States, focusing on: (1) boiler efficiency and availability; (2) environmental concerns; (3) boiler operation concerns; and (4) possible future improvements. The data collection years to be analyzed for trends were the calendar years 2012-2016. For this project, it was determined that data be collected on the operating characteristics of combustion facilities that use a variety of fuels as their primary or secondary source of fuel. It was anticipated that the data to be analyzed could relate to plant operating information, efficiency and environmental performance of these facilities, and plant operations relating to lost operation hours over a multiple year period involving problems with, for example, burners, fuel supply, environmental emission limitations, emissions control equipment, and fuel quality. The results of this project could then be used to understand how combustion operations, environmental emissions, and other areas of concern have evolved over the time span in question. This could also provide information as to research and technology needs on the part of equipment manufacturers and government sponsored researchers.

## II. METHOD

Benchmarking is a popular method used to measure the quality and efficiency of an entity. It helps to determine the benchmark performance of an entity to help those peers who are in the same group compare and improve their own performance. In this way, the performance of the whole group would be able to improve by trying to reach and/or surmount the benchmark [6]. This research paper determines various benchmarks within the combustion boiler industry for consecutive five years from 2012 to 2016. In developing such benchmarks, this research should help the industry perform in a more efficient and effective way. That is, to supply power to the country in a more stable and sustainable manner by improving the power generation efficiency rate and lowering the amount of the hazardous air emissions during the power generation process.

To find the suitable benchmarks, a voluntary survey was sent out to power plant owners or operators by the Council of Industrial Boiler Owners (CIBO) in the United States every year for the years 2012 to 2016. All of the survey responses were based on their experience in the respective calendar year, except where otherwise indicated. The objectives of the surveys were slightly different in each year, as indicated by their titles (see Table 1), but the survey contents were almost the same. To consider the various factors influencing boiler operation performance and its environmental performance, the survey questions were designed under the following topics: (1) Plant Information, (2) Fuel Information, (3) Efficiency and Environmental Performance, (4) Plant Operations, (5) Forced Outage Causes, (6) Boiler Operation and Maintenance Concerns, and (7) others (see Table 2, indicating special topics in each year). The data collected from the surveys would be analyzed and compared to help plant owners and operators improve their boiler performance.

***Table 1. List of Survey Titles in Each Year***

| Year | Survey Title |
|---|---|
| 2012 | 2012 Annual Fluidized Bed Boiler Survey |
| 2013 | 2013 Annual CIBO Solid Fuel Fired Boiler Operations and Performance Survey |
| 2014 | 2014 Annual CIBO Solid Fuel Fired Boiler Operations and Performance Survey |
| 2015 | Annual CIBO Boiler Operations and Performance Survey |
| 2016 | Annual CIBO Boiler Operations and Performance Survey |

***Table 2. Special Topics in Each Year***

| Year | Special Topics | Questions |
|---|---|---|
| 2012 | Research and Development | #1. What is the most important area for advanced sensors development that could provide increased capability or cost advantage versus the state of the art? |
| | | #2. What advanced simulation development area would be most important for enhanced operation and performance today? |
| | | #3. What improvements in advanced material research could have the greatest benefit to current operations and performance? |
| 2013 & 2014 | Conversion to Natural Gas | #1. If converting to Natural Gas, are you: (1) Retrofitting the existing boiler, (2) Replacing one or more units with a new unit(s), (3) Becoming an area source, or (4) Other? |

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| | | |
|---|---|---|
| | | #2. If you are considering conversion to Natural Gas, what are your primary concerns: (1) Boiler de-rate, (2) Future NOx emissions regulations, (3) State permitting requirements, (4) Natural gas cost stability and availability; or (5) Other? |
| | | #3. If you are considering Natural Gas Conversion, are you also considering: (1)Combined Heat & Power (CHP), (2) Plant energy efficiency improvements, or (3) Other? |
| notes | #1. All questions in the special topics will not be discussed in the main research paper since they represented a yearly specialty. The data would then not be suitable for a year-by-year comparison. | |
| | #2. Years 2015 and 2016 did not have any special topics beyond the topics listed in the main research paper. | |

## III. RESEARCH FINDINGS AND DISCUSSIONS

### A. Plant Information

The first part of the survey investigated basic equipment information at the responding plants. According to the data collected, plants were separated into two categories by their net annual electricity generation unit (less than or equal to 70 MW and larger than 70 MW). The total heat generating rate (in BTU's/KWH) was estimated for each category. Plants with no more than a 70 MW net annual electricity generation unit had an average 12,958 BTU's/KWH annual heat rate. Plants with more than a 70 MW net annual electricity generation amount had an average 12,398 BTU's/KWH annual heat rate. All of these plants showed an annual average power generation efficiency rate of 83.2% in the past five years. This average rate was far below the rate in year 2012, which witnessed the highest annual average efficiency rate of 88% (see Table 3).

***Table 3. Plant Heat Rate and Efficiency Rate***

| Year | 2012 | | 2013 | | 2014 | | 2015 | | 2016 | |
|---|---|---|---|---|---|---|---|---|---|---|
| heat rate (in BTU's/KWH) | <= 70 MW | > 70 MW | <= 70 WM | > 70 MW | <= 70 WM | > 70 MW | <= 70 WM | > 70 MW | <= 70 WM | > 70 MW |
| | 12,958 | 12,579 | N/A | 12,337 | N/A | 12,337 | N/A | 12,337 | N/A | N/A |
| efficiency rate (in percentage | 88 | | 82.1 | | 82.1 | | 82.2 | | 82.2 | |

### B. Fuel Information

A variety of sources could be used as fuels for combustion boilers. The survey questions had a broad coverage of possible sources by listing 14 types of fuels from which to choose for respondents. They were: (1) coal, (2) culm, (3) gob, (4) wood, (5) sludge, (6) pet coke, (7) tires, (8) Refuse-derived fuel (RDF), (9) Oil #5-6, (10) Oil #2, (11) natural gas, and (4) others. As the survey results showed, coal, gob and pet coke were the most common fuels being used in year 2012 and 2013. After that, natural gas was rapidly added to the mix and became a major primary fuel source in 2016. Plants using renewable fuels, rather than fossil fuels, were rarely indicated in the survey results for the past five years.

### C. Efficiency and Environmental Performance

Boiler generation efficiency rate and environmental performance were evaluated by asking: (1) the average efficiency rate (in percentage) for different types of boilers, (2) the actual amount of SO2 and NOx gases as

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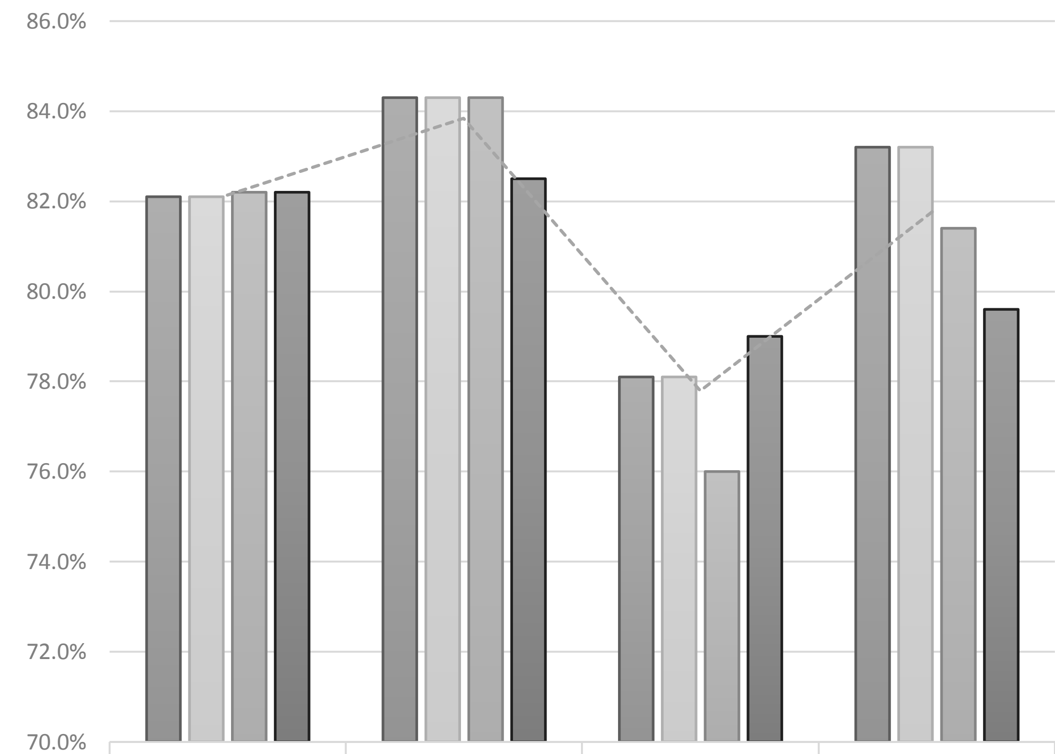
compared to the permit amount, (3) the actual calcium/sulfur ratio (Ca/S) compared to the permit ratio, and (4) the disposal process for the fly ash and bottom ash.

Boilers could be divided into three different groups by the combustion technologies being used. There are Fluidized Bed Combustion (FBC) boilers, Stoker or Cyclone boilers (combined into the same group for comparison purposes), and Gas-Fired boilers. Since the year 2012 survey did not have enough information for the last two types of boilers, the data in that year was not used. That is, only four years' data was compared and analyzed (see Figure 1). FBC boilers had the highest efficiency rate every year since 2013, averagely 83.9% during the investigated period. The efficiency rate of the gas-fired boilers showed a downward trend year by year from 83.2% in 2013 to 79.6% in 2016. Stoker/Cyclone boilers were the least efficient during this period, with an average efficiency rate (77.8%), which was far below the four-year average level for all boilers of 82.2%. The main reason for the different efficiency rates among each type of boiler was that various combustion technologies can lead to significant differences in boiler efficiency performance.




| | Overall | FBC Boilers | Stoker/Cyclone Boilers | Gas-fired Boilrs |
|---|---|---|---|---|
| 2013 | 82.1% | 84.3% | 78.1% | 83.2% |
| 2014 | 82.1% | 84.3% | 78.1% | 83.2% |
| 2015 | 82.2% | 84.3% | 76.0% | 81.4% |
| 2016 | 82.2% | 82.5% | 79.0% | 79.6% |
| Average | 82.2% | 83.9% | 77.8% | 81.9% |

2013 2014 2015 2016 Average

***Figure 1. Boiler Efficiency Performance***

With restricted regulations implemented to control the hazardous air emissions from boilers, such as the Major Source Boiler Maximum Achievable Control Technology (MACT) Rule, plants were required to limit certain types of air pollutantsto be within a standard level as set by the United States Environmental Protection Agency (EPA) [7]. As common combustion products, $SO_2$ and $NO_x$ were investigated by comparing the actual emission amount with the permit amount. The survey results indicated that all the responding plants had good control with respect to these two air pollutants, with the actual emission amount less than the permit amount in all three types of boilers.

The Calcium/Sulfur (Ca/S) ratio was another important factor in estimating the environmental performance of boilers since itrelates to both the emission amount of $SO_2$ and $NO_x$. This represents an indicator as tothe removal of $SO_2$ to a desired level during the combustion process. Previous research has shown that a Ca/S ratio range from 2.6 to 3.1 represents thatat least 95% of the sulfur is being removed instead of being emittedoutside. A higher Ca/S ratio tends to correspond with a higher levelof $NO_x$ emissions. That is, if less $NO_x$is being emitted, more $SO_2$ would be released. However, it was not possible to set up a desirable range for the Ca/S ratio for all types of boilers [8]. The five-year data for the environmental performance of the responding plants is listed in Table 4. Though the Ca/S ratio did not show exact correlations with the emission amount of $SO_2$ and NOx, as described by [8], it was found that the amount of $SO_2$ emission was inversely proportional to the amount of $NO_x$ emission. For example, year 2015 had the highest $SO_2$ emission (88%) and the lowest $NO_x$ emission (52%) and year 2016 had the lowest $SO_2$ emission (44%) and the highest $NO_x$ emission (76%).

***Table 4. Boiler Emission Control Performance***

| Boiler Types | FBC boilers | Stoker/Cyclone Boilers | Gas-fired Boilers |
|---|---|---|---|
| Year | Actual $SO_2$ as a Percent of Permit (per boiler) | | |
| 2012 | 52.0% | 39.0% | - |
| 2013 | 59.0% | 58.0% | - |
| 2014 | 76.0% | 60.0% | - |
| 2015 | 88.0% | 43.0% | 39.0% |
| 2016 | 44.0% | 26.1% | - |
| Year | Actual $NO_x$ as a Percent of Permit (per boiler) | | |
| 2012 | 70.0% | 68.0% | - |
| 2013 | 57.0% | 91.0% | - |
| 2014 | 74.0% | - | 89.0% |
| 2015 | 52.0% | - | 56.0% |
| 2016 | 76.0% | 85.0% | - |
| Year | Ca / S Ratio (per boiler) | | |
| 2012 | 2.7 | 1.6 | - |
| 2013 | 2.2 | - | - |
| 2014 | 1.72 | - | - |
| 2015 | 3.6 | - | - |
| 2016 | 2.75 | - | - |

Coal ash was the fourth item the survey analyzed. This is the collection of all leftovers from coal after combustion. Accounting for more than half of coal ash, fly ash refers to the light leavings going into the exhaust stacks of the facility. After being recycled, it may be reused again for different purposes. Bottom ash, composed of about 10%

coal ash, stays on the ground of boilers. It is less useful thanfly ash and contains toxic materials when recycled. However, it was still desired to use this 10% waste for beneficial purposes [9]. Statistics showed that all the coal plants in the United States produce 140 million tons of coal ash pollution, most of which is toxic [10].Therefore, the type of disposal of these two kinds of waste from coal burning is important for the environment. From Table 5, it is clear to see that more fly ash and bottom ash is being used for beneficial purposesin going from 2012 to 2016. It was noted that 100% of these two kinds of waste were being used for beneficial purposes in year 2015 in the surveyed plants. The survey results are a good indication that more attention has been paid by plant owners and operators to the settlement of coal waste as well as to environmental health.

***Table 5. Coal ash used for beneficial purposes (per boiler)***

| Year 2012 | Fly Ash | Bottom Ash |
|---|---|---|
| FBC Boiler | 50% | 53% |
| Stoker/Cyclone Boiler | 12% | 15% |
| Year 2013 | Fly Ash | Bottom Ash |
| FBC Boiler | 67% | 54% |
| Stoker/Cyclone Boiler | 100% | 100% |
| Year 2014 | Fly Ash | Bottom Ash |
| FBC Boiler | 69% | 75% |
| Stoker/Cyclone Boiler | 40% | 40% |
| Year 2015 | Fly Ash | Bottom Ash |
| FBC Boiler | 100% | 100% |
| Stoker/Cyclone Boiler | 100% | 100% |
| Year 2016 | Fly Ash | Bottom Ash |
| FBC Boiler | 100% | 100% |
| Stoker/Cyclone Boiler | 75% | 75% |

**D. Plant Operations**

Smooth plant operations are achieved by the continued availability of boilers for power and steam generation. Alternatively, the occurrence of boiler outages would cause the stoppage of such generation. This part of the survey focused on the annual availability of boilers in each plant and the frequency of outages in that year. Two types of outages were analyzed: planned/scheduled outages and forced outages. Planned/scheduled outages were planned, and notification was sent in advance for maintenance purposes. Whereas, forced outages were seen as interruptions and without advance warning. Reasons for the forced outages could be natural disasters, operation failure, etc. [11]. The current research will focus more on forced outages due to their unpredictability and severity.

The percent of time boilers are available was analyzed for various fuel types. As shown inTable 6, the five-year average boiler availability time as compared to the total operation time was 89%. The annual overall boiler availability time fluctuated somewhat during this period, with years 2012, 2013 and 2015 witnessing above average availability time and years 2014 and 2016 experiencingbelow average availability time. The forced outagetime as contrasted with the total outages time showed a downward trend, from 31% in year 2012 to 13% in year 2016 (see Figure 2). However, that percentage was relatively high in 2015 (23%).

*Table 6: Percent of time boilers available by primary fuel type*

| Year | Overall | Coal | Gob | Pet. Coke | Gas |
|---|---|---|---|---|---|
| 2012 | 92.6% | 91.1% | 93.6% | 93.1% | N/A |
| 2013 | 95.2% | 96.5% | 92.2% | N/A | N/A |
| 2014 | 88.4% | 90.1% | N/A | N/A | 88.40% |
| 2015 | 92.8% | 92.5% | 91.0% | N/A | 93.7% |
| 2016 | 76% | N/A | 88% | N/A | 76% |
| Average | 89.0% | 92.6% | 91.2% | 93.1% | 86.0% |

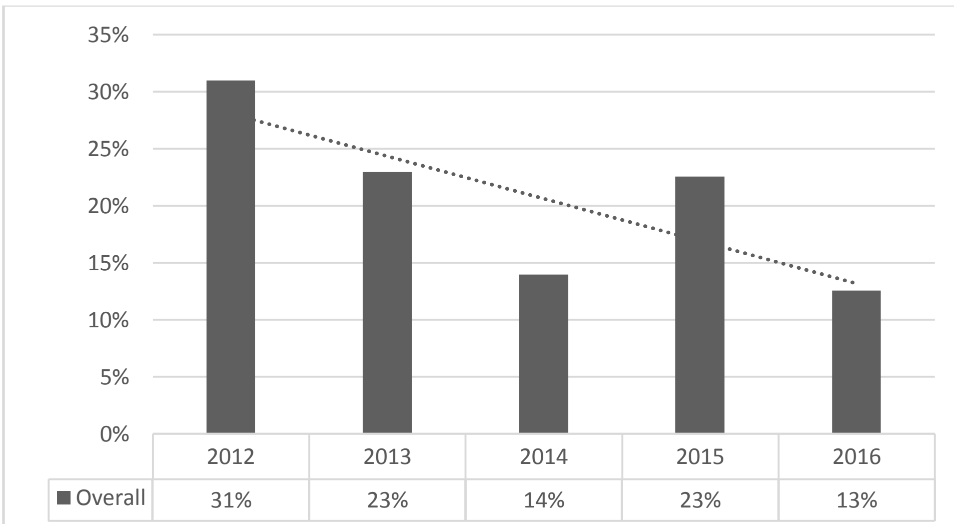



***Figure 2. Percent of forced outages time as of the total outages time***

**E. Forced Outage Causes**

The causality of forced outages was investigated. The forced outages were unpredictable events;therefore,the survey listed several possible reasons for them that were operations related. This was done to assist plant owners and operators in performing their work. These included: (1) Fuel handling/feeding/prep, (2) Combustor pressure parts (including tube failure), (3) Refractory, (4) Cyclone/U-beams separation, (5) Turbine & electrical, (6) Ash handling systems, (7) Backpass pressure parts(including tube failure), (8) Steam load/electrical generation load restriction, (9) Stoker, (10) Pulverizers, and (11) Cyclones. The survey results indicated that each year showed a somewhat different outcome (see Figure 3). Horizontally, operation failures related to “Combustor pressure parts”, which accounted for the majority of forced outages during the five-year period. Problems related to “Backpass pressure parts” and “Turbine & electrical” were the next two highest ranking causes. Vertically, the majority of percentagesrelated to operation outages were caused by different reasons. “Combustor pressure parts” led to the most occurrences of operations related outages in year 2012 (40.5%) and year 2014 (42%), respectively. The largest problem in year 2013 was “Ash handling”, accounting for 36.0% of the operations related outages. “Turbine & electrical” problems and “Backpass pressure parts” caused the largest number of operations related outages in year 2015 (40%) and year 2016 (49.4%). It is recommended that plant owners and operators consider these findings as part of the maintenance of their boiler parts/systems to try and reduce the number and severity of forced outages.

**F. Boiler Operation and Maintenance Concerns**

The operators working for the plants are the ones protecting the boilers from unnecessary outages, for instance, operation failure. Therefore, years 2015 and 2016 surveys asked about the benefit programs that operators could take to update their knowledge and improve their working skills. The maintenance frequency and tune-up requirements were also questioned (see Table 7) in the survey. The survey results (see Table 8) indicated that the majority of the responding plants had energy management programs in each year. However, around two thirds of the responding plants required their operators to have operator certifications. Eighty percent of the responding plants required operators to take training courses in year 2015. This percentage dropped in 2016, with only half of the responding plants having this requirement. For both years, most responding plants could provide in-house training for their operators. The external training was reimbursed by 100% by the responding plants in 2015 but only by 50% of the responding plants in 2016. Year 2016 showed the lowest average annual efficiency rate during the study period. The lack of sufficient training support from plants to their operators could be an important reason for this lower efficiency rate.

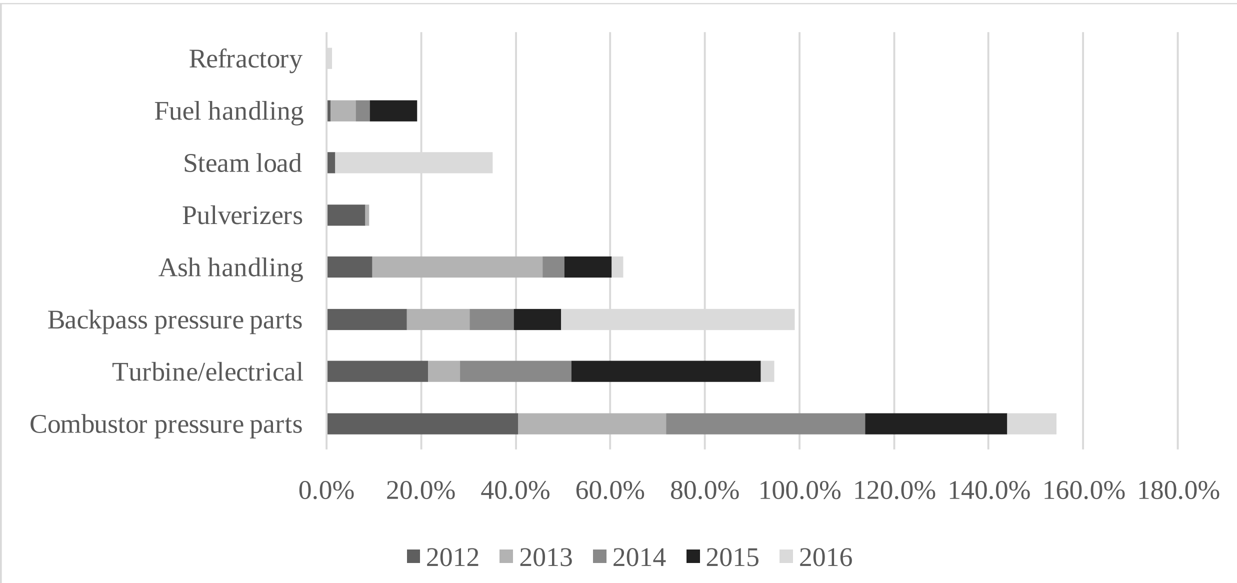



***Figure 3. Operation related causes of forced outages in each year***

A thorough and timely maintenance plan should also help plants improve efficiency and availability. As the data shows, all of the responding plants had formal maintenance plans in both years. However, the frequency of such maintenanceplans varied significantly. In year 2015, 60% of the responding plants had formal "daily" maintenance plans and 20% of the responding plants had formal "monthly" maintenance plans. The remaining 20% did not indicate the length of their formal maintenance plan. The situation was similar in year 2016. Half of the responding plants had a formal "daily" maintenance plan. One third of the responding plants would do formal "monthly" maintenance. The remaining 17% chose "other", which could reference a variety of responses.For maintenance purposes, it is necessary to "tune-up" the boilers at various times. However, the tune-ups could be scheduled according to a variety of time frames orrequired by regulations with certain frequencies. The survey results showed that 40% of the tune-ups in 2015 and 33% of the tune-ups in 2016 were done "as required". Yearly tune-ups accounted for 40% of the total tune-ups in 2015 and 67% of the total tune-ups in 2016, respectively. Biyearly tune-ups represented 20% of the annual tune-ups in both years.

***Table 7. Questions for operation and maintenance schedule***

| | |
|---|---|
| #1 | Have energy management program? |
| #2 | Is operator certification required? |
| #3 | Is operator training available or required? |
| #4 | Is operator training available in-house? |
| #5 | Is external operator training company funded? |

| | |
|---|---|
| #6 | Is external operator training individual funded? |
| #7 | Does your plant have a formal maintenance plan? |
| #8 | What is the length of your formal maintenance plan? |
| #9 | How often are tune-ups required? |

***Table 8. Survey results for questions #1 to #6***

| Year | 2015 | 2016 |
|---|---|---|
| Management Program (Yes, have) | 80% | 83% |
| Certification Required (Yes, required) | 60% | 67% |
| Training Required (Yes, required) | 80% | 50% |
| In-house Training Available (Yes, available) | 80% | 83% |
| Company Funded External Training | 100% | 50% |
| Individual Funded External Training | 0% | 17% |

Plant owners and operators not only need to pay more attention to the causes of past outages, but also need to be aware of potential future problems during the operation process. Therefore, the survey asked the respondents to list the future possible operation and maintenance concerns with priority rating from“1” to “10”(the larger the number, the larger the concerns). Thirty possible concerns were listed in the survey (see Table 9) and the survey results in each year were combined together in Figures 4& 5 (only ratings above “5” are shown) for FBC boilers and Stoker/Cyclone boilers, respectively. Figure 4 illustrates that 14 possible issues were selected with an above average degree of concern. “Boiler: Back Pass” and “Tube Erosion” were the two biggest operation and maintenance concerns for FBC boilers over the past five years.Of next most concern were“Turbine/Electrical” and “Refractory”. When looking at particularlyimportant concerns in each year, the respondents ranked “Air Heater” with “9” as degree of concernand “Boiler: Back Pass” with “8.5” degree of concernin year 2015. “Loop Seals”, “Turbine/Electrical”, “Refractory”, and “Tube Erosion” were ranked between “8” and “7” in various years. Compared with FBC boilers, stoker/cyclone boilers might experience more problems in the future, with 20 possible issues ranked above “5”. “Boiler: Combustion” and “Pressure Parts” were the main issues that could possibly cause operation failures during the research period. “Fuel Quality”, “Ash Regulations”, and “Ash handling” were in the second group, reflecting more concerns in restricted emission controls. Though “Expansion Joint” and “Igniters” only appeared once in year 2015, they ranked “10” and “9”, separately. The same situation occurred for “Ash Disposal” in year 2012 and “Turbine/Electrical” in year 2015. Both of them were given an “8” degree of concern by the respondents.

***Table 9. Possible future operation and maintenance concerns***

| | | | | | |
|---|---|---|---|---|---|
| Fuel quality | Cyclones (fly ash) | Ash handling | Fuel handling/crushing | Air heater | Bed ash |
| Fuel feeding | Loop seals | Pressure parts | Expansion joints | Ash regulations | Fly ash |
| Boiler: combustion | Electrical & controls | NSR definition changes | Boiler: back pass | Turbine/electrical | Seasonal emissions |
| Refractory | Tube erosion | CFBC cyclone | Ash cooling | Combustor | Cyclones (combustion) |
| Stokers | Emission Control | Pulverizers | Igniters | Ash disposal | Ash regulations |

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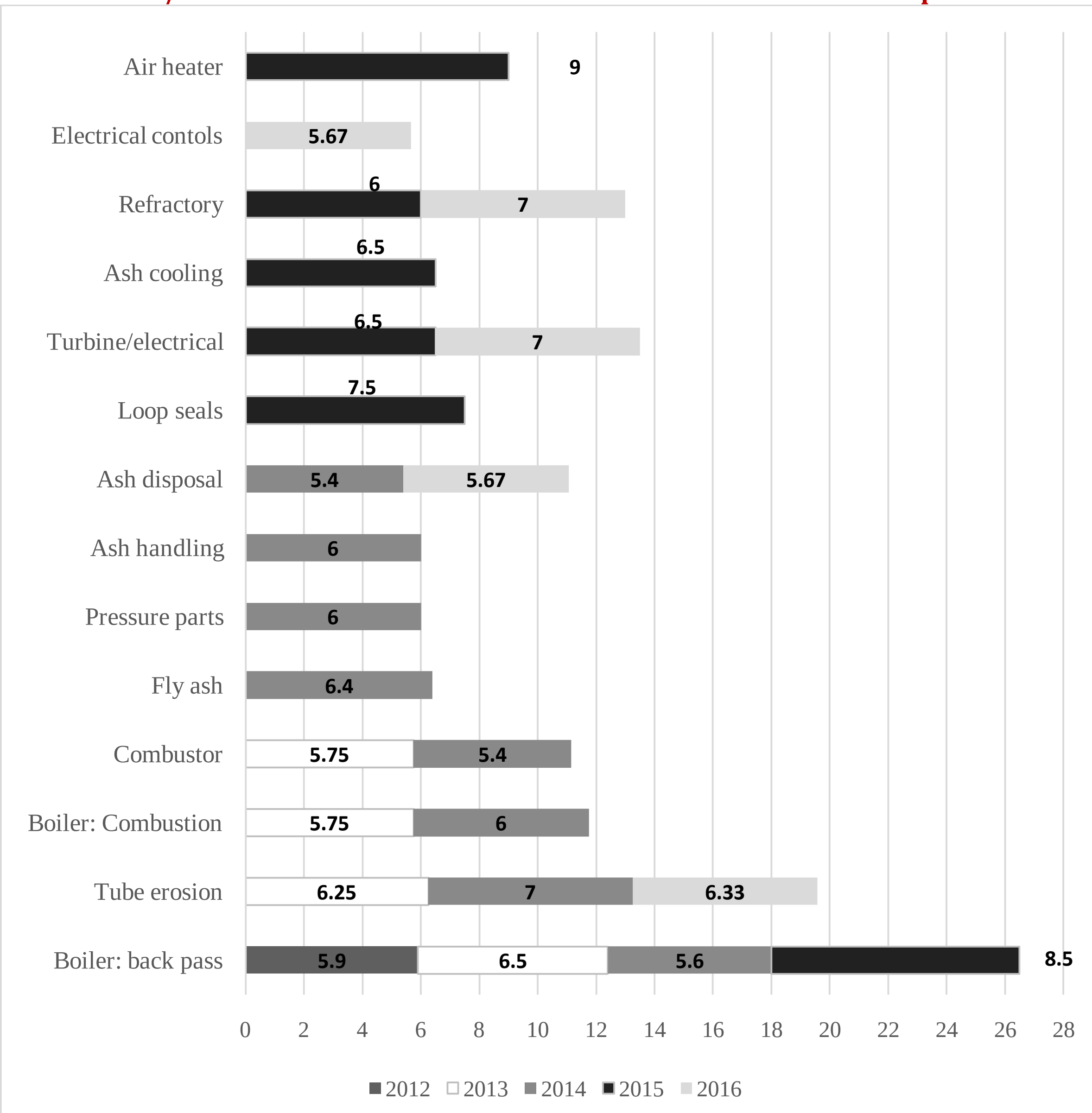


***Figure 4. FBC Boiler Operation and Maintenance Concerns***

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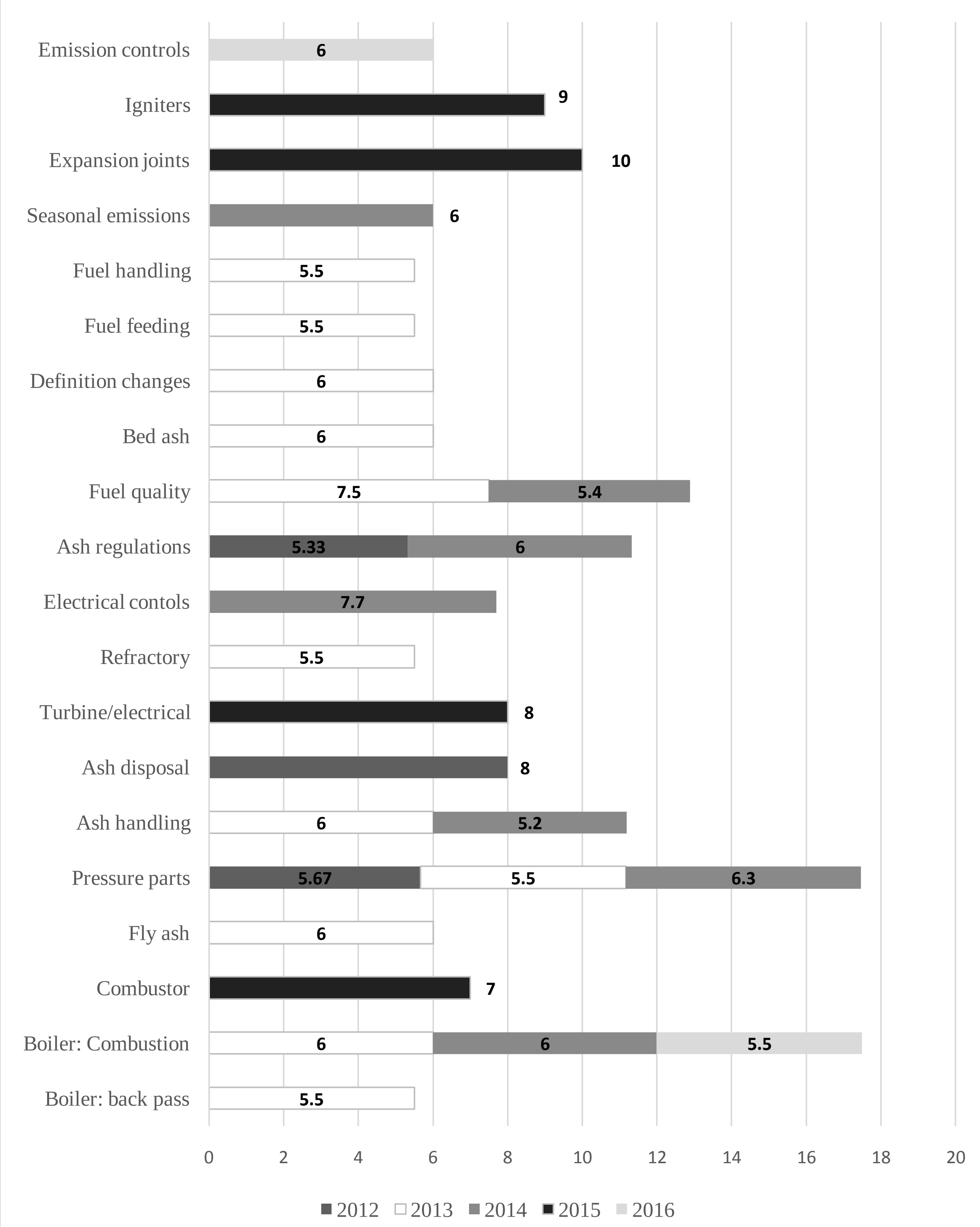


*Figure 5. Stoker/Cyclone Boiler Operation and Maintenance Concerns*

## IV. CONCLUSIONS

The key element of this research paper was in trying to provide operating benchmarks for plant owners and operators. It was important to provide comparisons between the benchmark results and their own conditions so as to make suitable adjustments to improve the overall operation performance.The future operation and maintenance concerns in the past five years also deserve plant owners and operators' awareness. After meeting all the requirements by regulations and laws and avoiding as many operation-related outages as possible, the next goal for plants should be to improve their operation efficiency. The relatively low boiler efficiency rate (76% on average) in year 2016 could have been influenced by explainable factors, such as fuel changes/adaptions (coal to natural gas), boiler age, boiler combustion technology, maintenance frequency, etc. Hopefully, this situation will not last for long. In the near future, the replacementof old boilers with new boilers, the elimination of less advanced boiler technologies, the requirement of having more certified operators, the implementation of more restricted emission control regulations, and the introduction of renewable fuels should all compel plants to be more efficient and environmentally-friendly.

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