Range and Applicability of Heat Rate Improvements

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NOTE

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ABSTRACT

Reducing a power plant's heat rate can lower emissions, fuel consumption, and costs, thus contributing to the plant's bottom line. A significant improvement in heat rate can often be achieved with a re-commitment to best operating practices, which can minimize the need for capital expenditures on new technology. However, because the current fleet of coal-fired plants has endured age-related degradation; changed operational requirements such as fuel quality, low emissions, and flexible operations; and made physical modifications, achievable heat rates may be significantly different from initial design values. As a result, power plant owners and operators are unable to assess the range of possible heat rate improvements in many cases.

This report summarizes methodologies and tools for assessing and implementing measures for improving heat rate in coal-fired power plants. In addition, the report attempts to better bracket the range of achievable improvements possible for an existing coal-fired power plant.

Keywords
CO_2 reduction
Cycle alignment
Efficiency improvement
Heat rate
Plant performance
Remote monitoring centers
Sliding pressure

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INTRODUCTION

Heat Rate

The heat rate of a coal-fired power plant measures the amount of heat, typically in Btus, needed to generate 1 kilowatt-hour (kWh) of electricity. Accordingly, typical units for heat rate are Btu/kWh.

Heat rate is the heat energy input per unit of electrical energy output, or fuel consumption rate for specific levels of power plant output. Heat rate is also the inverse of plant efficiency. In this sense, it is comparable to a golf score: lower is better.

Calculating Heat Rate

For each power plant, heat rate depends on the plant's design, its operating conditions, and its level of electric power output. In theory, 3,412 Btu of thermal energy is equivalent to 1 kWh of electric energy. For existing coal-fired power plants, heat rates are typically in the range of 9,000–11,000 Btu/kWh. Note that a plant with the industry average heat rate of 10,300 btu/kwh is operating with an overall plant efficiency of about 33%. (3,412 / 0.33 = 10,339)

All heat rates discussed in this and referenced EPRI reports have been determined based on net generation. Plant net generation accounts for the auxiliary power consumption required to operate the machinery in the plant. Using net station or unit output as the denominator helps one maintain a holistic view of plant performance, permits us to include the effect of all modifications, including emissions controls, that change aux power consumption. Net heat rate permits one to better compare units using steam driven components to those using electrical motors. The steam used to drive large components is typically less expensive than electricity, but robs the steam turbine of some capacity.

Benefits of Lowering Heat Rate

The heat content of coal is in the range of 8,000 to 12,000 Btu/lb. Coal costs $1.5 - 2/million Btu, or about $30/Ton. A typical coal plant consumes 6,000 tons per day. For a coal-fired plant, fuel is by far the largest expense item, representing about 55-75% of total plant expenses. Accordingly, reducing a power plant's heat rate can significantly lower fuel consumption and costs, directly benefitting power producers and their customers. For example, at a typical 500-megawatt (MW) plant operating at 80% capacity factor and firing $2.00/MBtu bituminous coal, a 1% heat rate reduction will save about $700,000 in annual fuel costs.

500,000kW x 10,200 Btu/kW/hr x 365 days/year x 24hr/day x 80% x 1% x $2/Mbtu =

~$700,000 annual fuel cost savings

Heat rate improvement is also the first obvious step to reduce carbon dioxide (CO_2) and all other emissions. It is commercially proven and is the most cost-effective and immediately available control process for lowering CO_2. The 1% heat rate reduction described in the example above corresponds to a 1% reduction in CO_2 emissions—about 40,000 tons/year—which could amount to significant savings if new regulations permit trading of CO_2 credits or impose a "fee" on CO_2 emissions.

Even assuming the eventual implementation of carbon capture and storage technologies, optimizing heat rate will still make sense as a first line of CO_2 reduction and could be a complementary activity with other control options.

Heat rate reductions will also result in decreases in other emissions, such as nitrogen oxides (NOx), sulfur dioxide (SO_2), particulates, and mercury, which can help plants meet other compliance requirements. Even for a constant emission rate in pounds per million Btu, an improvement in heat rate will result in fewer Btus fired, and consequentially, fewer total pounds of a given pollutant produced. In some cases, the benefit of emissions reduction may exceed the value of fuel savings.

Historical Heat Rates

Since the mid-1960s, the average heat rates of fossil-fueled electric power plants in the United States have gradually increased. Several factors have contributed to this slow degradation in unit performance. One early reason was the introduction of nuclear generating units to provide an increasing share of the baseload generation, and the anticipation of a large expanding nuclear construction program over the next several decades. With these low-cost generating units forecast to provide a large fraction of the baseload capacity, utilities devoted less attention to the maintenance and upkeep of their older fossil stations in anticipation of their retirement in the 1970s or 1980s.

This trend was exacerbated as nuclear construction costs escalated, reducing the funds available for maintaining fossil station performance, as well as diverting the attention of utility upper management from the operation of these stations. For those utilities that brought nuclear units on line, many of the fossil plants that formerly comprised their system's baseload capacity were changed to cycling duty. The thermal inefficiencies associated with start-ups, shut-downs, and swings in load, as well as extended periods of operation at less than full power, resulted in increased heat rates for these units. Generating units are designed and built to achieve their best heat rates when operated in steady state at full load.

In addition, environmental regulation was enacted that forced many utilities to retrofit energy-consuming pollution control equipment such as Flue Gas Desulfurization (FGD) systems. Refer to EPRI report 1019003, Survey of Impacts of Environmental Controls on Plant Heat Rate, 2009 on the effects of emission control devices on heat rate. The key deleterious effects caused by the addition of emission controls were the increase in auxiliary power consumption and the decrease in boiler efficiency. This adverse trend started many decades ago with the required addition of electro-static precipitators (ESPs) to remove particulate matter from the flue gas prior to exhausting it out the stack. Those new ESP created a pressure drop, forcing the fans to work harder and increased the consumption of auxiliary power.

At the same time, in some areas, decreasing coal quality and the use of higher-moisture-containing fuels such as Powder River Basin (PRB) contributed to a reduction in unit performance. Refer to EPRI report 1019703, Evaluation of Fuel Quality Impacts on Heat Rate, 2010 for the effects of fuel quality on heat rate. Most recently, the proliferation of renewable and gas generation, along with economic factors, has resulted in a need for more flexible operation (e.g., more frequent cycling and lower turndown) of the existing coal-fired fleet, which has a substantial negative effect on plant heat rate.

The problem of improving fossil plant heat rates in the 1980s was made more difficult by the penalties associated with retrofitting air emission control equipment, declining coal quality, and normal degradation associated with aging of the units. This latter concern continues today, as more units are operated beyond their expected operating lifetimes, with additional emission controls, and increased generation flexibility is required.

The hurdles to improving performance were further increased when site performance engineers were lost either to retirements or shrinking personnel levels in the wake of the deregulation movement of the 1990s.

Considering all these elements working against heat rate improvements in the electric generation industry, it should not be surprising that the current industry estimates suggest several percent of efficiency has been lost at many of the existing coal-fired power plants. A portion of it is potentially recoverable if the correct processes, procedures, and resources can be applied and maintained.

Assessing the Range and Applicability of Heat Rate Improvements

Coal-fired power plants were initially designed and built to achieve unit-specific heat rates. The typical coal-fired plant is now about 30-40 years old. As discussed in the previous section, the operating heat rates may be significantly different than initial design values.

Power plant owners and operators are unsure of the range of possible heat rate improvements for their existing fleets.

In recent years, several EPRI projects have explored different aspects of heat rate improvements. This report summarizes the findings of those projects to provide information on the range and applicability of heat rate improvements.

- Section 2 describes methodologies for assessing the costs and benefits of capital and maintenance projects for heat rate improvement in coal-fired power plants.
- Section 3 reviews the results of implementing heat rate optimization programs at five power plant sites, with summaries of the issues, recommendations, actions taken, and resultant heat rate improvements.
- Section 4 discusses a study conducted to identify potential heat rate improvements that could be implemented across all coal-fired power plants in a utility fleet.
- Section 5 presents several perspectives on heat rate improvement, including recovering plant efficiency lost during flexible operation, implementing a cycle alignment program, employing remote monitoring, making physical upgrades to steam turbine generators, designing and implementing a heat rate improvement program, and improving the effectiveness of steam turbine performance engineers.
- Section 6 contains a summary, conclusions, and recommendations for future work.
- Section 7 lists EPRI reports related to heat rate improvement referenced in this document.
- Appendix A lists additional resources on heat rate improvement.

2
HEAT RATE IMPROVEMENT—CAPITAL AND MAINTENANCE PROJECTS

Introduction

In 2008-2009, EPRI developed a methodology to assess the costs and benefits of potential maintenance improvements to coal-fired power plants, and refined the methodology to assess the net annual benefit of potential capital improvements to these plants.

The assessment methodologies were then applied to a hypothetical 500-MW plant to calculate the potential benefits of potential capital improvements and maintenance projects, including the heat rate reduction benefit, reduction in auxiliary load, capacity increase, equivalent forced outage rate (EFOR) improvement, and emissions benefits. The calculations were captured in two spreadsheets—one for capital projects and the other for maintenance projects. Inputs could be modified according to plant-specific circumstances, thus making it possible for individual utilities to use the methodology for scoping studies. The magnitude of the actual heat rate improvements are site specific, as are the drivers and economic benefits.

The methodologies and the calculations were described in the EPRI report 1019002, *Capital and Maintenance Projects for Efficiency Improvements*, published in 2009.

Although the specific data presented in this report were conceptual in nature, this screening guide for capital and maintenance projects was developed based on experience with actual projects. The information did not represent any actual plant or facility, but was intended to be representative. The projects depicted represented capital and maintenance projects that improve plant efficiency and appear to be economically justified. The list of potential power plant capital improvements and maintenance-related projects assessed in this report was not exhaustive, and not all of the improvements will result in a net positive annualized benefit for every situation.

The information provided in this report is intended for use as a screening tool to compare the potential for different capital and major maintenance projects that may prove to be beneficial to a specific generating unit. The methodology is not intended as a rigorous project analysis. The values provided are reasonable order-of-magnitude estimates, but they reflect circumstances that are hypothetical and do not represent any specific plant. Values for a specific facility may be different. A project that appears to deliver value in this analysis may, in fact, be marginal or not cost-justified under different real-world circumstances. The opposite may also be true.

The following sections describe the approach used by the assessment methodologies and provide an overview of the capital and maintenance projects.

Methodologies

The assessment methodologies followed a six-step approach that divides the effort into logical steps designed to ensure a reasonably comprehensive and technically accurate analysis. The six steps are as follows:

1. **Identify major systems in a typical plant.** The purpose of this task is to ensure all applicable plant systems were considered. The classification focuses on major systems and does not address every nuance of plant design.
2. **Identify typical or potential projects for each system.** For each of the systems noted above, a number of different options were identified for capital and maintenance projects that could conceivably improve performance if implemented. This initial list was based on industry experience with similar efforts and knowledge of the respective systems.
3. **Obtain input data and values.** A significant number of assumptions are necessary to effectively characterize the options and economics for a given plant. To make this reference useful to most power plant operators and other companies, those specific required metrics, configurations, and other inputs were identified and used to populate example calculations.
4. **Characterize typical or potential projects for each system.** For each of the systems identified in Task 1, the guide includes a list of capital and maintenance projects that could, in theory, be economically attractive efficiency improvements. This list was selected based on potential applicability and does not address all the issues that affect the feasibility of a specific project at an actual plant, especially with respect to economics and plant configuration.
5. **Summarize uncertainty and potential findings.** Even with the screening used to characterize the potential project list, uncertainty will remain for a number of issues for any project. For this reason, the resultant list of projects has been further characterized with a brief discussion of those issues that could significantly affect the value of the project but are beyond the scope of this screening activity.
6. **Conduct a reasonability check of results and input data.** The results were reviewed internally by EPRI, comparing the values stated to those in other EPRI documents and validating the logic behind the spreadsheet calculations. The spreadsheets were also reviewed by an EPRI member working in this field to ensure the input and results were representative and current for power plant projects.

Capital Projects

The report contained spreadsheets, listing 32 capital projects. For each project, the spreadsheets identify the estimated capital cost, added O&M cost per year, heat rate reduction (% and Btu/kWh), estimated auxiliary load benefit, capacity increase, EFOR improvement benefit, heat rate benefit, emissions benefit, added power sales benefits, and net annual benefit. At the time this project was completed and report written, the emissions benefit related only to NOx and SO_2, but the equations could easily be adapted to include CO_2 and mercury.

Example projects included: turbine steam seal upgrades, turbine section replacements, intelligent sootblowing systems, automated boiler drains, coal drying systems, air heater baskets, and combustion optimization. The results represent a wide range. Not all projects generated net benefits with a positive payback. Heat rate reductions range from 0.10% to 2.50%. Project positive net benefits range from $30,000/year to $2.9 million/year. The spreadsheets can be used by plant engineers and planners to develop a realistic case for making a specific capital investment.

Maintenance Projects

The report contained spreadsheets, listing 25 maintenance projects and practices. For each, the spreadsheets identify the estimated initial maintenance cost, additional O&M costs per year, heat rate reduction (% and Btu/kWh), estimated auxiliary load benefit, capacity increase, EFOR improvement benefit, heat rate benefit, emissions benefit, added power sales benefits, maintenance annual benefit-cost ratio, useful life, and payback (years).

Example projects included: replacing feed pump turbine steam seals, repairing steam and water leaks, boiler chemical cleaning, repairing boiler air in-leakage, cleaning air preheater coils, repairing condensate pumps, and repairing flue gas desulfurization (FGD) systems. The results represent a wide range. Heat rate reductions range from 0.03% to 1.50%. Maintenance annual benefit-cost ratios range from about 1 to over 100.

3
HEAT RATE IMPROVEMENT—FIVE SITES

Introduction

The EPRI Production Cost Optimization (PCO) project assisted participating members in implementing or enhancing heat rate optimization programs to reduce production costs through sustainable performance improvements.

The PCO assessment process consisted of benchmarking plant thermal performance, using historical plant data, along with an on-site performance appraisal, to identify potential areas for performance improvement. In some instances, a significant heat rate improvement can be achieved with a recommitment to best operating practices, and without the need for capital expenditures on new technology.

In 2010, EPRI report 1019704 *Production Cost Optimization Project 2010*, summarized the status of the project and presented results for five sites that had completed initial and follow-up assessments.

This section summarizes improvement recommendations for the five sites, provides brief descriptions of the actions taken by participating plants, and identifies the resultant heat rate improvements based on the original benchmarked performance.

Overview

Unit heat rate improved at four of the five plants. While most plants had estimates of the improvement expected with the actions taken, it was not always possible to reconcile observed improvements with estimated improvements. Recommendations resulting from the PCO appraisal process were typically a combination of plant-specific items and common, general recommendations, such as establishing or expanding routine plant monitoring through testing or on-line means, establishing a cycle isolation procedure, and conducting heat rate awareness training for plant staff.

The plant participants were not always able to implement all recommendations and often had their own initiatives for outage work that resulted in decreased heat rate. Performance improvements were significant and ranged from 3-5%. This level represents an equal percentage of each plant's annual fuel bill and demonstrates that making heat rate an integral part of maintenance and operations activities can yield real and lasting financial savings as well as a significant reduction in CO_2 and other emissions.

Plant Profiles

For the five units, which follow-up analyses were prepared, net unit capacities range from 95 MW to 650 MW. All five plants burn coal as their primary fuel. The service ages of the plants range from 30 to 55 years, with the average service age being 40 years. Three plants burn Powder River Basin sub-bituminous coal and the others burn bituminous coal. Three boilers are drum-type units by Combustion Engineering, Riley, and Babcock and Wilcox; the remaining two are supercritical units by Combustion Engineering and Foster Wheeler. All plants, but one, are single reheat units. Three plants have once through cooling source, another has a mechanical-draft cooling tower, and the fifth has a natural-draft cooling tower.

Common Issues

Of the five plants with completed analyses and reports, the common issues include:

- Combustion problems and high air heater/stack exit gas temperatures
- Limited heat rate information availability
- Need for heat rate awareness training, including controllable losses understanding
- Need for unit and equipment performance testing
- Feedwater heater train performance problems
- Need for sootblowing optimization

Common Recommendations

The following recommendations are common to the five units covered by follow-up analyses:

- Provide heat rate awareness training to operations staff
- Make heat rate information readily available to more plant personnel
- Improve utilization of controllable losses information by operations staff
- Optimize sootblower operation
- Initiate a routine testing program
- Increase routine feedwater heater performance monitoring

These recommendations are described below:

- **Provide Heat Rate Awareness Training to Operations Staff.** Provide the entire plant staff with heat rate awareness training focused on the basics of heat rate, the cost of heat rate deviations, and actionable heat rate information for operations. Such training will help to enhance a positive work culture and provide staff with the tools to optimize heat rate on an on-going basis.
- **Make Heat Rate Information Readily Available to More Plant Personnel.** Sharing heat rate-related information with a broader segment of plant personnel can result in earlier identification and resolution of heat rate problems. Incorporating heat rate “thinking” into day-to-day operational decision making can reduce overall plant heat rate.
- **Improve Utilization of Controllable Losses Information by Operations Staff.** Incentivize operations staff to monitor and minimize controllable losses. Maintain controllable losses targets to be achievable within constraints of equipment and operating conditions. This may require the site(s) to enhance, upgrade, or initiate real-time controllable losses displays.
- **Optimize Sootblower Operation.** Sootblower optimization can help to improve steam temperature control, normalize heat absorption patterns, and improve precipitator performance. Additional benefits such as reduced air heater /stack exit gas temperature, a decline in circumferential cracking of boiler tubes, and NOx emissions reduction may also

result. Automated sootblowing optimization can be effective but expensive to implement. A lower-cost alternative is to conduct parametric testing to provide insight into the effectiveness of sootblowing patterns and guide operators in achieving best unit performance.

- **Initiate a Routine Testing Program.** A periodic testing program should be established to aid in early detection of changes in equipment performance and/or unit operation to improve maintenance scheduling efforts and reduce unscheduled outages. By utilizing station instrumentation, a reliable, repeatable trend of unit performance could be developed. Guidelines to conduct such testing are contained in EPRI reports 1019004, Routine Performance Test Guidelines, 2009 and 1019705, Routine Performance Test Guidelines, Volume 2, 2010.
- **Increase Routine Feedwater Heater Performance Monitoring.** Heater Terminal Temperature Difference (TTD) and Drain Cooler Approach (DCA) should be monitored on a daily basis along with heater levels to maintain best performance. In particular, the DCA should be checked to ensure that steam is not entering the drain cooler. If this happens for an extended period of time, the drain cooler will be damaged, resulting in tube leaks, heaters out of service, and higher unit heat rate.

Plant-specific Recommendations

The following recommendations, grouped by plant equipment/area, were specific to individual plants:

Cycle Isolation

- A site-specific cycle isolation checklist should be developed for operations use to ensure continued cycle isolation maintenance.
- Perform periodic cycle water loss tests.

Instrumentation

- As transmitters are replaced or upgraded, they should be replaced with high-accuracy, “smart” transmitters.
- Plant calibration standards should be set up on a periodic schedule to be calibrated.
- Set up and use an electronic database for tracking of instrument calibrations.
- Redundant instruments should be of sufficient accuracy to provide the same readings. If two instruments are measuring the same parameter and provide different readings, they do not provide value to operations.

Boiler

- Utilize the plant performance calculations to trend boiler efficiency and individual boiler losses so that changes in performance can be identified quickly, and action can be taken to restore boiler efficiency.
- Resolve coal distribution problems, and inspect diffusers and riffle distributors.
- Review boiler optimization after coal distribution problem is addressed.
- Perform unit diagnostic testing to determine the O_2, CO, and NOx distribution at the economizer outlet duct where the present in-situ O_2 analyzers are located. With some

additional effort, these tests could be used to assess the degree of air in-leakage between this location and the furnace exit to verify that most, if not all, of the casing leakage has been satisfactorily repaired. This information can be used to fix the leaks and may help to recover the induced-draft (ID) fan capacity, especially during warmer summer months. These tests will also identify the minimum O_2 operating level for best efficiency without excessive CO and unburned carbon. Other potential benefits of these efforts are reduced back-end temperature, improved precipitator performance, and reduced NOx and mercury emissions.

- Maintenance efforts should be given a priority to:
  - Restore burner tilt functionality
  - Restore burner corner secondary air damper functionality
  - Inspect coal nozzle condition and replace as necessary
  - Repair furnace casing leaks
  - Repair leaking valves

Turbine

- Use turbine performance data to help determine when a turbine overhaul is necessary.
- Trend the high-pressure (HP) and intermediate pressure (IP) turbine efficiency periodically with the unit at a consistent operating point (typically full load, valves-wide-open is best).
- Continue to monitor the following performance using the performance monitoring system:
  - High-pressure section efficiency
  - Intermediate-pressure section efficiency
- Conduct temperature variation tests prior to the next turbine outage to determine the benefit of replacing turbine seals and/or snout rings.

Condenser

- Monitor condenser pressure and compare to target daily to ensure proper condenser performance.
- Consider using or installing an on-line air in-leakage monitor.

Feedwater Heaters

- Monitor heater TTDs and DCAs on a daily basis, along with heater levels, to maintain best performance.
- For heaters with off-design TTDs and temperature rises (TRs) that are close to design, verify that extraction pressure water legs are properly accounted for.
- Repair or replace the high-pressure feedwater heater.
- Check first-point heater outlet temperature as compared to economizer inlet temperature to ensure feedwater is not bypassing the top heater(s).

Cooling Tower

- Consider accelerating the fill replacement schedule to reduce cold water temperature and condenser pressure.
- Perform an annual inspection of the cooling tower with a focus on performance.
- For mechanical-draft towers, as fan blades require replacement, consider upgrading to high-efficiency fans. There is not a sufficient justification for upgrading the fans until there is a mechanical reason for replacement.
- As replacement stacks are needed, upgrade to high-performance stacks to improve air flow and cooling.

Technology Review

- Maintain controls tuning and responsiveness in addressing controls issues.
- Review plant historian, and consider removing points that are no longer valid or no longer used.
- Distribute key performance information to commonly used operator screens. If the controllable loss information is on the common screens, there is more of a chance that it will be used.
- Increase the visibility of heat rate and performance information throughout the plant. Taking this step will help improve heat rate awareness.
- Ensure that the design or target values on the controllable loss screens are realistic, achievable values over the load range.
- Input periodic fuel analysis into on-line monitoring system so that better values of heat rate and boiler efficiency can be calculated.
- Input periodic carbon-in-ash loss values into on-line performance monitoring system so that better values of heat rate and boiler efficiency can be calculated.
- Provide heat rate awareness training, primarily for operations.
- Have operations start monitoring controllable losses.
- Ensure that critical performance-related data are being properly stored in plant historian.
- Consider upgrading to a more robust performance monitoring system that will run reliably without significant upkeep.
- Ensure that the design or target values are realistic, achievable values over the load range.

Potential Heat Rate Improvements

Actual heat rate improvement for the plants participating in the PCO follow-up assessments ranged from 3 to 5%. Potential heat rate improvements for some of the common recommendations were estimated to be:

- Provide Heat Rate Awareness Training to Operations Staff (50 to 100 Btu/kWh).
- Make Heat Rate Information Readily Available to More Plant Personnel (50 to 150 Btu/kWh).

- Improve Utilization of Controllable Losses Information by Operations Staff (75 to 100 Btu/kWh).
- Optimize Sootblower Operation (70 Btu/kWh).
- Initiate a Routine Testing Program (75 to 200 Btu/kWh).
- Increase Routine Feedwater Heater Monitoring (30 to 60 Btu/kWh).

Boiler

Potential heat rate improvement from recommendations to improve boiler heat transfer and combustion were estimated to be 100 Btu/kWh or better. Sootblowing optimization was estimated to have a potential improvement of 70 Btu/kWh.

Turbine

Potential heat rate improvement from recommendations to improve turbine cycle performance was estimated to be 100 Btu/kWh or better. Losses due to worn internal seals and snout rings were estimated to be 20 to 50 Btu/kWh or higher.

Feedwater Heaters

Potential heat rate improvement from replacing the first point heater was estimated to be 150 Btu/kWh.

Quantified Benefits of Implementation of Recommendations

Plant heat rates were trended for one-month periods during the original PCO assessment and then again during the follow-up assessment. The time elapsed between the original and follow-up assessments ranged from 20 to 24 months. Heat rates were calculated using two different methods: 1) input/output method; and 2) energy balance method.

Some plants reported expected heat rate improvements from actions that they had taken or planned to take, which ranged from 200 to 400 Btu/kWh, approximately 2 to 4%. While it was difficult to correlate specific improvements with measured data, it was clear from the assessments that plant efficiency improved significantly at four of the five plants completing follow-up assessments. The magnitude of the heat rate improvements ranged from 279 to 557 Btu/kWh at or near full-load operation (see Figure 3-1) which represents an approximate 3 to 5 percent improvement in heat rate. The results of this project are site specific and are not universally applicable to all coal fired power plants.

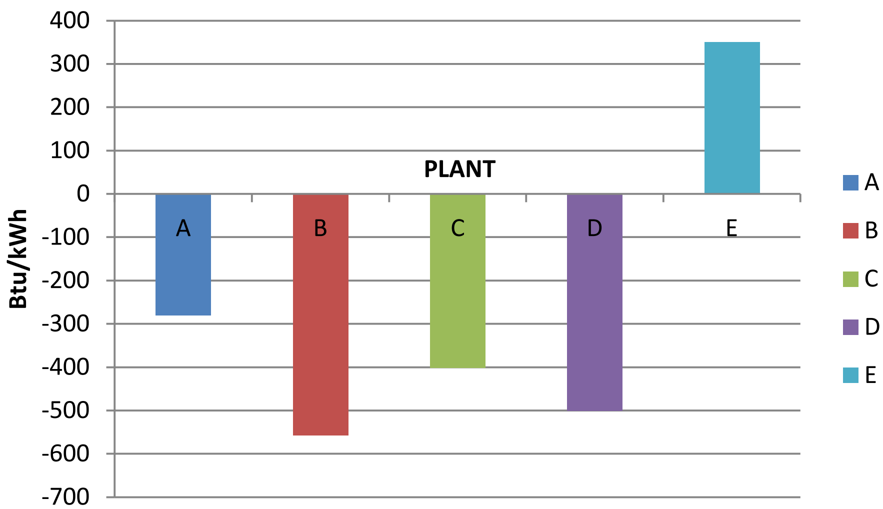

Figure 3-1
Plant Heat Rate Changes

Plant “A” improved its heat rate by 279 Btu/kWh through comprehensive organizational focus of multi-level heat rate teams, training of operations staff, and close attention to minimizing boiler excess air. With a 557 Btu/kWh improvement, Plant “B” decreased its heat rate by the largest margin. This improvement was accomplished through diligent cycle isolation, reduction of boiler casing air in-leakage, a turbine chemical cleaning, and reduced condenser air in-leakage.

Plant “C” improved its heat rate by 400 Btu/kWh, 100 Btu/kWh of which plant staff attributed to boiler improvements and 250 Btu/kWh to steam path maintenance and a feedwater heater replacement. Plant “D” improved heat rate by 500 Btu/kWh with substantial maintenance work, including reducing boiler casing air in-leakage, replacing a feedwater heater, and cleaning condenser and feedwater tubes.

Unlike the other four plants in the follow-up studies, heat rate for Plant “E” increased unexpectedly by 350 Btu/kWh. This result was thought to be due in part to increased cycling and extended operation at lower loads.

Fuel Savings and CO_2 Benefits

With heat rate improvements ranging from 3 to 5%, the results of the PCO follow-up studies clearly demonstrate that plant heat rate can be favorably affected by operational and maintenance activities undertaken by plant owners.

Figure 3-2 shows the range of equivalent fuel savings for a 5% reduction in heat rate for generating units of three different sizes and for a range of fuel costs. Not all participants actively quantify return on investment of activities in terms of fuel savings; however, Figure 3-2 clearly demonstrates that these savings are very significant. For example, a 5% improvement in the heat rate of an 500-MW (net) power plant can be worth over $3,500,000 in annual fuel savings and reduce CO_2 emissions over 180,000 tons annually.

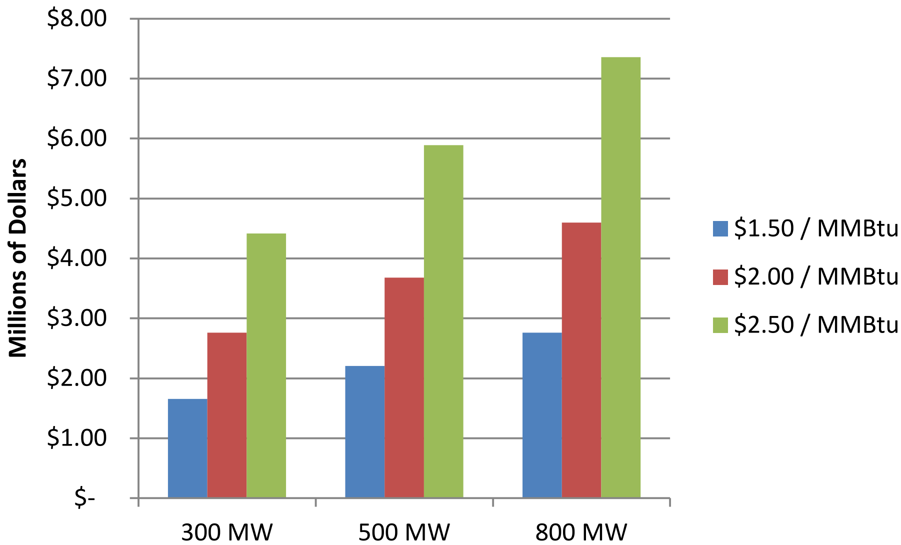

Figure 3-2
Typical Fuel Savings for 5% Heat Rate Improvement

4
HEAT RATE IMPROVEMENT—FLEETWIDE ASSESSMENT CASE STUDY

Introduction

In 2010, EPRI conducted a study with a member utility to identify power plant efficiency improvements that could be implemented across all 12 coal-fired plants in their fleet to reduce carbon dioxide (CO_2) emissions.

The study and its findings are described in the EPRI report 1021206, *Methodology for Fleetwide Energy Efficiency Analysis,* 2010.

This section briefly summarizes the study.

Approach

This project was undertaken to show how coal plant energy efficiency improvements could be used to reduce carbon dioxide (CO_2) emissions. The utility established a Plant Energy Efficiency Team (PEET) to explore their company's options for improving coal plant efficiency. The PEET results are focused on tons of CO_2 avoided or reduced and the cost per ton of CO_2 avoided or reduced ($/ton). The estimated cost per ton of CO_2 avoided or reduced for each technology can be used to determine which projects are potentially viable based on the price of CO_2 credits.

For the study, the project team applied a standardized methodology previously developed for evaluating efficiency improving projects in a single power plant, described in the EPRI report 1019002, *Capital and Maintenance Projects for Efficiency Improvements*, published in 2009.

The most powerful use of this approach is to apply the method to an entire fleet, where a set of potential projects can be evaluated for a group of specific coal-fired units. In this project, the project team compiled a list of feasible efficiency improvement options and conducted analyses to determine project-specific net annual benefits in relation to reduction of CO_2 emissions. Researchers compiled information from various internal sources and then added more projects from the EPRI capital projects report (1019002). All projects were listed in a spreadsheet and normalized to match each unit within their current operating system.

This study covered only projects for existing coal-fired power plants. This was not an Integrated Resource Plan (IRP) study; the PEET was not trying to determine how best to increase generation. The assumption was made that net plant output remains constant. If the proposed project happened to increase capacity along with efficiency, the fuel burn was reduced to hold net output constant. CO_2 emissions reduced or avoided were then calculated and summarized.

The following steps were used to evaluate potential energy efficiency improvement projects for that fleet:

- Assemble a team of experts within the utility with collective knowledge covering all of the units being investigated and all the projects being considered.
- Identify the potential projects, using the spreadsheet in EPRI Report 1019002 as the starting point.
- Identify the coal-fired units to be included in the analysis.
- Screen projects for feasibility of application to each unit in the fleet.
- Determine project attributes for each application.
- Evaluate the applicable projects for each unit.
- Develop project ranking based on the cost-benefit analysis for each application.
- Prepare Pareto curves to provide management with a decision-making tool to prepare for any future carbon-related charges.
- Issue fleet-specific report.

The technology feasibility screening process identified more than 40 candidate projects, organized by six major plant systems (Table 4-1).

Using the project list shown in Table 4-1, the project team conducted a fatal flaw analysis to determine the feasibility of the efficiency projects on a unit-by-unit basis at the 12 coal-fired power plants. Many potential projects may not be feasible for a particular plant or unit based on the configuration of the plant. For example, LP turbine replacement is not a potential project for a unit that just replaced its LP turbine. Numerous energy efficiency projects have already been completed in advance of this study. This list is not all inclusive of potential heat rate improvement projects, but that used by the utility conducting this analysis.

Table 4-1
List of Generation Efficiency Projects by Major Plant Systems

Boilers (10 projects)	**Turbines and Generators (15 projects)**
Intelligent Sootblowing System (ISB) Economizer retrofit Water cannons Automate boiler drains On-site fuel drying Blowdown recovery tank Air heater seals Air heater baskets Heat rate/performance monitoring Combustion/optimization monitoring system	HP/IP/LP steam seal upgrade (3) HP/IP/LP steam path upgrade (3) HP/IP/LP turbine replacement (3) LP turbine last-stage buckets Exhaust hood steam guide modification Rewind generator Increase hydrogen purity Partial-arc admission Sliding pressure
Condensers (8)	**Fans and Motors (4)**
Run with one circulation pump when temperatures are favorable Condenser ball cleaning system Re-tube condensers Water box vacuum priming system Circulating water strainers Circulating water turbine Supplemental cooling towers Deep lake water intake	Fan variable frequency drive (VFD) Forced draft fan VFD Induced draft fan VFD High-efficiency motors/boiler feed pump drives
Air Quality Control System (AQCS) **Precipitators (2)**	**Balance of Plant (2)**
Variable power input Power supply upgrade	Upgrade air compressors Plant lighting upgrade

HP = High Pressure
IP = Intermediate Pressure
LP = Low Pressure

Top Projects

Over 490 individual potential projects were identified and screened for feasibility. Of these, 174 projects were identified by PEET as potentially feasible projects.

Analysis determined that several project types may be justified, independent of the project's economic life. The top projects shown in Table 4-2 may be justified without any CO_2 credits and should be given further consideration.

Table 4-2
Top Projects

Automate Boiler Drains (12 units)
Air Heater Seals (8 units)
Station Air System (2 units)
Circulating Water Strainers (8 units)
Air Heater Baskets (4 units)
Condenser Ball Cleaning System (8 units)

Key Observations

There are many potential projects to improve plant energy efficiency and reduce CO_2 emissions. The PEET analysis provides a tool that will allow for numerous potential projects that improve plant energy efficiency and reduce CO_2 emissions to be evaluated and ranked easily. Based on a 30-year economic life, the PEET analysis estimated that if all 174 projects were implemented, the upper limit for fleet wide coal plant CO_2 reductions through efficiency improvement would be about two million tons a year (approximately a 5.3% reduction of their current operating fleet CO_2 emissions) at an estimated capital cost of over $800,000,000. However, initial evaluation indicates there may be some projects that should be investigated further regardless of the value of CO_2, yielding about one million tons a year in reduction of CO_2 emissions (approximately a 2.7% reduction of the fleet's CO_2 emissions).

Figure 4-1 is a Pareto-type supply curve that represents the cumulative CO_2 reduction and cost per ton of CO_2 reduced that is based on the PEET Analysis – Project Ranking List. The x-axis represents the projects that were ranked in order of cost per ton of CO_2 from Project Numbers 1-174. The y-axis represent the cumulative tons of CO_2 reduced per year by all projects (green bars) and the cost per ton of CO_2 reduced by each project (blue line). The red line separates out the projects that may be justified with a net annual benefit that is ≤$0/ton of CO_2. Projects with a negative cost per ton of CO_2 may be justified without credit for CO_2 (i.e., projects with the blue line below the red line, including project numbers 1-58).

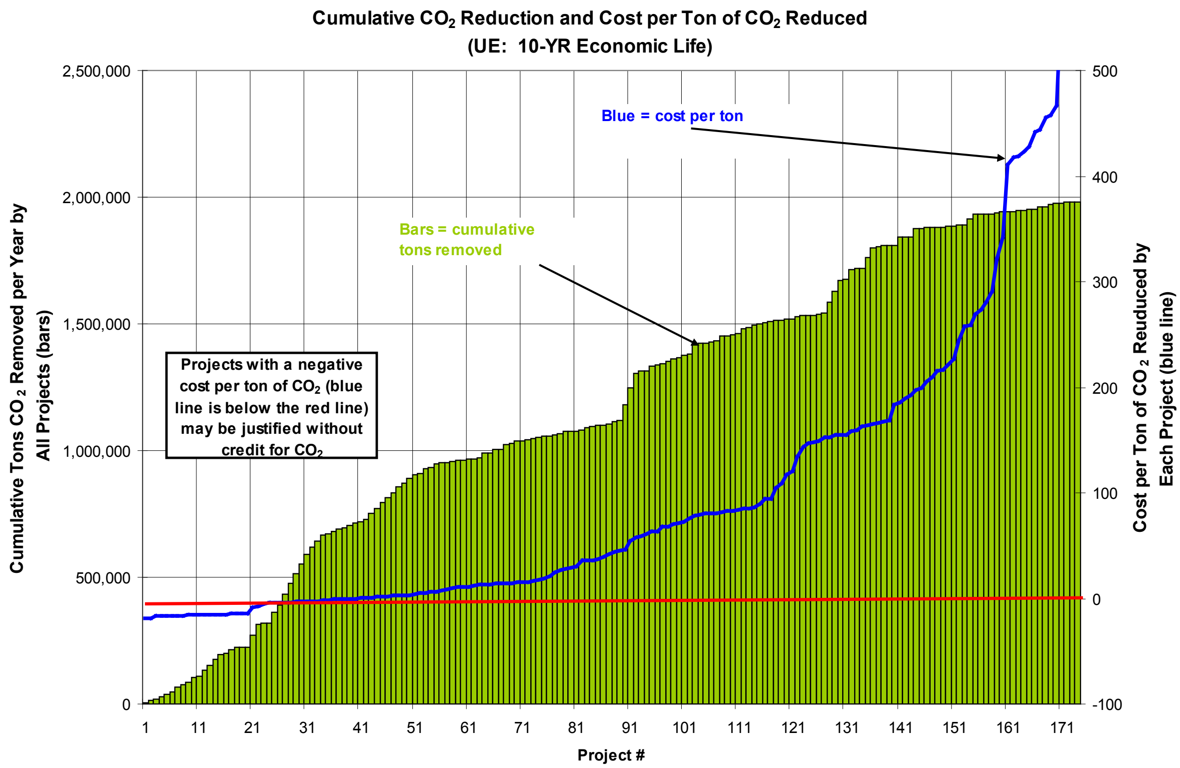

Figure 4-1
Cumulative CO_2 Reduction and Cost per Ton of CO_2 Reduced

5
HEAT RATE IMPROVEMENT—ISSUES AND PERSPECTIVES

Introduction

This section describes issues and perspectives on improving power plant heat rate—including recovering plant efficiency lost during flexible operation, implementing a cycle alignment program, employing remote monitoring, making physical upgrades to steam turbine generators, designing and implementing a heat rate improvement program, and improving the effectiveness of steam turbine performance engineers. The values of heat rate improvements stated for each of these projects may not be additive, as some overlap could exist and each of these projects were focused the results of site specific actions.

Flexible Operation

Flexible operation refers to the ability of a plant to operate at part load, load following, and cycling (on and off) modes, in response to economic conditions and increased utilization of non-coal based generation (e.g., renewable, gas). Operating conditions under flexible operation can result in reductions in plant efficiency and increased degradation and/or maintenance on components due to constant swings in operating temperature and pressure.

An EPRI study in 2010 identified cost-effective capital modifications and adjustments to plant operating procedures to improve heat rate during cycling operation. The study and its findings are described in the EPRI report 1021205, *Efficiency Improvement for Cycling*.

The study identified 10 upgrade options; the practicality of each is site dependent:

- **Sliding pressure operation.** With sliding pressure operation, the plant efficiency is increased by reducing turbine throttling losses. This option was further analyzed in a follow-up project and found to provide a heat rate improvement at part load in the range of 2%. For additional information refer to EPRI Report 1023912, *Methods to Mitigate the Effects of Increased Cycling and Load Following on Heat Rate*.
- **Variable-speed drives for main cycle and auxiliary equipment.** Variable-speed drives reduce auxiliary power consumption of rotating equipment, thus increasing plant net output. The amount of savings available with variable-speed operation can vary widely. Variable-speed drives are expensive and can be difficult to justify for older plants with limited remaining life.
- **Boiler draft system control schemes and operating philosophy.** Where multiple fans are operating in parallel, plant efficiency at low loads and under ramping conditions can be maintained and improved by the proper selection of startup/shutdown procedures. Depending on the load scenario, this measure will allow auxiliary load reductions by operating fewer fans, but can increase maintenance and reliability risks.

- **Automated pulverizer supervisory controls and variations with mill design.** Firing systems and operating procedures can be optimized for each load level. The goal is to operate the least number of pulverizers to maintain stable coal only flames while following load.
- **Optimum partial load operation of air quality control systems.** For a wet flue gas desulfurization (FGD) application, the number of operating recycle pumps can be reduced with load reductions, resulting in reduced plant parasitic loads. With electrostatic precipitators (ESPs), once the unit load has stabilized at the lower load, it may be possible to reduce ESP power consumption by turning off specific electrical fields while maintaining opacity and particulate emission rates at the regulated levels.
- **Feedwater heater drain system modifications for cycling**. Typically, cycling efficiency losses occur at low loads when heater drains are routed to the condenser as opposed to the deaerator. Plant efficiency at part load will be improved by ensuring that drains are directed to their proper destination, when possible.
- **Cooling system optimization.** Where multiple cooling water pumps and cooling tower fans are operated in parallel, proper selection of component startup/shutdown schemes (dependent on the load scenarios and ambient conditions) will allow auxiliary power reduction by removing pumps and /or fans from service, but can increase maintenance and reliability risks.
- **Performance monitoring.** Several tools are available to display relevant parameters with respect to plant efficiency at various loads. These tools can be optimized to enable operators to prioritize corrective actions, thereby improving cycling efficiency.
- **Reducing warm-up flow for idle boiler feed pumps.** Heat rate improvement can be achieved by reducing warm-up water flow rates from operating pumps to idle pumps. Less warm-up water flow will reduce the auxiliary power of the operating pumps.
- **Minimizing flow, pressure, and temperature oscillations during cycling operation.** Some oscillations of temperature, pressure, and flow typically occur when plants are operating at steady-state loads, but can be amplified during cyclic operation and result in a reduction in plant efficiency. Commercially available optimizers contain a forward-looking feature that minimizes the time that steam temperature strays from design, reducing attemperation spray flow and the heat rate effect of load following.

Cycle Alignment

Cycle alignment, also known as *cycle isolation*, refers to the alignment of the cycle by isolating all, or as much as possible, of the high-energy fluid leakage from the steam cycle at a power plant. Certain leaking valves will cause a direct loss in generation or an increase in fuel costs.

When used as part of an overall plant performance improvement program, cycle alignment programs have provided large gains at low costs. Implementing a cycle alignment program can jump-start a plant performance program and result in substantial heat rate improvements that lead to fuel cost savings and emissions reductions. With improved cycle alignment, heat rate improvements in the range of 50 Btu/kWh or about 0.5% are common. Units with problematic valves or no history of maintaining cycle alignment may experience a large one-time heat rate improvement upon this program's implementation.

Various methods have been used to ensure proper cycle alignment; but an application's success and costs vary depending upon the specific valves and unit designs involved. In 2011, an EPRI project assessed cycle alignment activities and identified their costs and benefits in order to permit power generation companies to optimize their applications of cycle alignment. The study and its findings are described in the EPRI report 1024640, *Cost-Benefit Assessment of Cycle Alignment*, 2011.

The study identified methods in use in the field to estimate or determine the leakage rate through leaking valves and used several real-life examples from operating power plants to illustrate how cycle alignment programs have been implemented.

Remote Monitoring Centers

Remote monitoring centers (RMCs) have been used for many years to track and improve equipment reliability, and in many cases, these same RMCs have thermal performance software installed for monitoring heat rate. The value of finding and fixing reliability issues can often be quantified, but placing a value on heat rate monitoring is not so easy.

In 2011, an EPRI study evaluated the use of remote monitoring systems and personnel as it relates specifically to heat rate improvement. The study and its results are described in the EPRI report 1023075, *Evaluation of Remote Monitoring for Heat Rate Improvement, 2011*.

The project team visited RMCs at three power generating companies. The main priority of these RMCs was to improve reliability, but they also monitored for heat rate improvement to varying degrees. All of the companies visited were able to verify heat rate improvements based on the activities of the monitoring centers in addition to improvement in equipment reliability. In many cases, the heat rate improvements were significant and well surpassed the incremental costs for monitoring heat rate in addition to reliability. Heat rate improvements in the range of 2.5 to 4% have been reported attributed to the actions resulting from these remote monitoring centers.

Steam Turbine Steam Path Modifications

Over the past 20 years, an increased number of nuclear and fossil power plants have undertaken modifications to increase the power rating and/or improve the heat rate of selected units. Many of these actions have resulted from physical upgrades to steam turbine generators, as well as enhancements to auxiliary components.

EPRI conducted a survey to compile current results of performance upgrades to produce a single technical report summarizing the findings. Refer to EPRI Report 1018346, *Compilation of Results and Feedback Regarding Turbine Upgrades at Nuclear and Fossil Power Plants*, 2008 for additional information. Commonly reported heat rate improvements attributed to turbine modifications were in the range of 2-4%. These modifications were capital intensive (expensive), large consumers of time and resources, have a finite life, and not always 100% successful.

Heat Rate Improvement Program Guidelines

Power plant facilities with performance or heat rate improvement programs perform better than those that do not have those programs. A heat rate improvement program typically provides sufficient information for decision making with respect to timely maintenance actions, operational adjustments, and/or physical modifications.

Monitoring the performance of any power plant component includes the trending of parameters that also describe the performance of other plant components, providing insight and information on improving their operation as a whole. A performance program creates a culture centered on improving plant performance. The sharing of performance data with the entire plant staff strengthens their understanding of how each individual may contribute, ultimately making heat rate improvement a team effort.

A 1983 utility survey covering 129 fossil generation units concluded that a mean heat rate improvement of more than 4% could be achieved at existing power plants by implementing an effective heat rate improvement program.

A 2012 EPRI project sought to provide a single-source document on heat rate improvement that can be used for both training and application. The project produced the *Heat Rate Improvement Program Guidelines* (1023913). The *Guidelines* incorporated information from earlier editions of programmatic documents and produced a new report organized to facilitate the ability of a site performance engineer to justify, design, implement, and manage a new heat rate improvement program.

Steam Turbine Performance Engineer's Guide

The steam turbine is the workhorse of most power plants. Its performance and reliability relate directly to the performance and reliability of the power plant that it serves. The actions of the turbine performance engineer are crucial to its high level of performance. However, in many cases, that engineer is assigned many other duties and/or is an early career engineer placed into this position without previous experience.

The primary role of a steam turbine performance engineer is to improve and maintain the efficiency and power output of the steam turbine cycle. One of the measurements of success is improved turbine heat rate.

In 2010, EPRI published the *Steam Turbine Performance Engineer's Guide* (1019657), which describes the functions and responsibilities of a steam turbine performance engineer. The instructions and recommendations in this guide, when properly executed, will improve the effectiveness of steam turbine performance engineers, positively affecting both the performance and reliability of the steam turbines under their care. No specific heat rate improvement value was attributed to the role of a steam turbine performance engineer.

6 SUMMARY AND CONCLUSIONS

Power plants are designed for an optimal heat rate. While that heat rate may not be the lowest achievable at that point in time, trade-offs occur with respect to capital and O&M costs, siting, and fuel. The average age of operating coal-fired power plants is 40 years. Over the course of those four decades, the plants have been subject to physical modifications and repairs, and have suffered age-related degradation. Many of those modifications have been the addition of emissions controls, which typically have an adverse effect on heat rate. Since initial startup, many units have changed their fuel supply and reduced staffing size, creating additional potential adverse heat rate effects. In most recent times, these old coal plants have been called on for flexible operation, requiring load following and significant time at part load, again reducing plant efficiency.

Realized and Projected Heat Rate Improvements

This study identified examples—both demonstrated/realized and projected—of methods to improve heat rate or recover efficiency losses.

- **PCO Project.** In EPRI's Production Cost Optimization (PCO) project, the units evaluated realized 3-5% heat rate improvements through various means (refer to Section 3).
- **Sliding Pressure.** By employing sliding pressure over a several-month period, a 2% heat rate improvement was realized at part load (refer to Section 5).
- **Remote Monitoring.** The use of remote monitoring centers was documented to improve heat rate 2.5 to 4% (refer to Section 5).
- **Steam Turbine Steam Path Modifications.** EPRI members reported steam turbine steam path modifications were worth 2 to 4% heat rate improvements (refer to Section 5).
- **Cycle Alignment.** Implementing a cycle alignment (isolation) program was documented to be worth at least 0.5% improvement in heat rate (refer to Section 5).
- **Capital and Maintenance Projects.** A list of 57 potential actions and modifications to improve efficiency was made and evaluated in detail. While the amount of gains would be unit specific, the projected heat rate improvements ranged from less than 0.1% to over 2% for the various actions and modifications. One utility applied the methodology and analyzed a number of these potential projects for their own specific fleet, resulting in a projected 5% improvement in heat rate (refer to Sections 2 and 4).

Applicability

The numerical values presented in the previous section may not be additive. They also may not be achievable or justifiable at every coal-fired plant. The staff at many well-performing plants have been proactive and implemented some of the previously discussed improvements (e.g., steam turbine upgrades, remote monitoring centers, etc.), reducing their potential maximum heat rate improvement range.

The finances of power generating companies, both regulated and IPPs, are managed prudently, so any large expenditure must be justified and/or create a return on investment. Smaller units consume less fuel, making a reasonable return on investment difficult to achieve for expensive modifications. As discussed, these units are old and may have a limited remaining life. Some of these modifications and actions are quite costly and require a long period of operation to realize a return on investment. Those modifications may not be applicable for units with a few or unknown years of remaining projected lifetime.

The management of many coal-fired plants may be unwilling to attempt many of these proposed improvements in order to avoid the possibility of triggering a New Source Review, which may result in the requirement of millions of dollars of additional emissions controls.

Recommendation(s) for Future Studies

Many of the efficiency improvement projects have been done in parallel, so the individual effect of each is not well defined. Tests and analyses could be conducted before and after future individual modifications are made to refine the results and reduce the uncertainty when those modifications are proposed for other units.

Based on industry data and studies conducted by EPRI and others, the maximum achievable heat rate improvement for any given coal-fired plant is unknown. More detailed studies to characterize improvements, taking into consideration constraints like fuel changes, equipment degradation, design changes, new environmental controls, etc., are needed to determine the technical and economic feasibility of the options. Afterwards an estimate could be made of the maximum potential efficiency gains. While the cost may be high, one could attempt to implement as many of those modifications and actions possible on one unit and measure the gains realized to provide perhaps the upper cap of expected heat rate improvement.

7
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