National Energy Technology Laboratory

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MERCURY SPECIE AND MULTI- POLLUTANT CONTROL

A DOE Assessment

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Starting in the mid 1980s, Congress created and funded a series of programs intended to demonstrate the market readiness of new coal-based technologies. These are the Clean Coal Technology (CCT) programs managed by the Department of Energy (DOE) at the National Energy Technology Laboratory (NETL). The first program, the Clean Coal Technology Demonstration Program (CCTDP), comprised five solicitations spanning the period from February 1986, when the first Program Opportunity Notice was issued, to February 2007, when the last Final Report was accepted. In 2001, a second program was introduced called the Power Plant Improvement Initiative (PPII), which consisted of a single solicitation. The current program is the Clean Coal Power Initiative (CCPI). To date, three rounds of CCPI program solicitations have been completed. These demonstrations are conducted on a commercial scale to assess the commercial readiness of the technologies and to provide technical and financial information for future applications.

The primary objective of Round 1 of the CCPI (CCPI-1) was to demonstrate technologies that reduce emissions and improve efficiency and maintainability while extending the asset life of coal-based generation, thus bolstering the long-term viability of the United States' abundant coal resources. The primary objectives of Round 2 of the CCPI (CCPI-2) were to demonstrate advances in coal gasification systems, technologies that permit improved management of carbon emissions, and advancements that reduce mercury (Hg) and other power plant emissions. Four projects were selected for negotiation from the proposals submitted for CCPI-2. One was withdrawn, two are still active, and one, the subject of this assessment, has been completed.

One of the projects selected for negotiation was "Mercury Specie and Multi-Pollutant Control" proposed by Pegasus Technologies of Chardon, OH. Early in the project, Pegasus Technologies was acquired by NeuCo, Inc. of Boston, MA, and the project was carried out by NeuCo under Cooperative Agreement Number DE-FC26-06NT42389. NRG provided the host site, operating personnel, and engineering support. The total project cost was approximately $15.56 million, of which the DOE share was $6.08 million (39.1 percent). The Participant contributed the remaining $9.48 million (60.9 percent). The project was conducted from April 12, 2006, to May 31, 2010, at Unit 2 of NRG Energy's Limestone Power Plant (formerly owned by Texas Genco) located in Jewett, TX. This unit is a nominal 890 megawatt (MW) plant that is fueled by a combination of Texas Lignite and Powder River Basin (PRB) sub-bituminous coal. Unit 2 is a dual-furnace; tangentially-fired unit equipped with a cold-side electrostatic precipitator (ESP) for particulate removal and a wet flue gas desulfurization (FGD) system for sulfur dioxide (SO_2) removal.

The broad objectives of the project were to install advanced instrumentation and optimization software to improve plant operations with respect to a variety of operational parameters. The project used advanced sensors coupled with neural networks and artificial intelligence to optimize the oxidation state of Hg, making downstream removal more effective. This suite of technologies was also expected to reduce the emission rates of other pollutants such as carbon dioxide (CO_2) and nitrogen oxides (NO_x) and reduce the net heat rate.

Specific goals were to:

- Optimize overall plant performance
- Reduce fuel consumption and net heat rate by 0.5–2.0 percent
- Reduce NO_X emissions by 10 percent
- Achieve 40 percent post combustion Hg capture
- Increase operating controllability and flexibility
- Reduce capital investment compared to alternative emission control technologies

In order to achieve these goals a number of optimization control systems consisting of the software and the necessary instrumentation and automated analysis equipment to support the optimization software were installed. The systems installed (or were to be developed) were:

- Intelligent Fuel Management System (FMS)
- Mercury Specie Control System
- Develop Advanced Electrostatic Precipitator (ESP) Optimization System

- Advanced Intelligent Soot Blowing (ISB) System
- Develop Advanced FGD Optimization System
- Intelligent Plant Optimization System

The project was carried out over three separate budget periods or phases. Phase I comprised sensor installation and software system design. Baseline operating metrics were also established in Phase I. Phase II included the installation of software and verification of data communications links from the sensors. Modifications to integrate the software system and the distributed control system DCS were also carried out in Phase II. Phase III demonstrated the performance of the control systems, including installation of the software, as well as the instrumentation and analyzers. The results of the tests were then compared to the performance goals established for the demonstration project.

Although difficult to precisely determine, the demonstration results indicated an availability improvement equivalent to an additional one or two days per year. The optimization system enabled the plant to reduce NO_X emissions by 16 percent and carbon monoxide (CO) emissions by 24 percent. Heat rate was reduced by 0.5 to 1.2 percent under various operating conditions. The optimization systems increased post combustion mercury removal by 4.9 percent. When combined with improved coal blending, the total reduction in mercury emissions was 22 percent. The Participant estimates the total benefits derived from the installed demonstration technologies to be over $3.5 million per year for Unit 2. These benefits could likely been obtained with some hardware improvements, but hardware modifications can be expected to be substantially more expensive than software. It does appear that an improvement in operability and flexibility resulted from the optimization software packages in that they regularly provided alerts to the operators allowing them to make corrections to an underperforming system or to remedy equipment problems before they became serious the FMS resulted in a more stable fuel HHV to the boiler. The ESP and FGD optimization systems were not developed and demonstrated for various reasons.

I. INTRODUCTION

The Clean Coal Technology Demonstration Program (CCTDP) and the two subsequent programs—the Power Plant Improvement Initiative (PPII) and the Clean Coal Power Initiative (CCPI)—are government and industry co-funded programs. The goal of these programs is to demonstrate a new generation of innovative coal-utilization technologies in a series of projects carried out across the country. These demonstrations are conducted on a commercial scale to prove the technical feasibility of the technologies and to provide technical and financial information for future applications.

A goal of these programs is to furnish the marketplace with a number of advanced, more efficient, coal-based technologies that meet increasingly strict environmental standards. These technologies will help mitigate the economic and environmental barriers that limit the full utilization of coal. Three rounds of solicitations have been completed as of the date of this assessment. The primary objective of Round 1 of the CCPI (CCPI-1) was to reduce emissions and improve efficiency and maintainability while extending asset life of coal-based generation, thus bolstering the long-term viability of the United States' abundant coal resources. The primary objectives of Round 2 of the CCPI (CCPI-2) were to demonstrate advances in coal gasification systems, technologies that permit improved management of carbon emissions, and advancements that reduce Hg and other power plant emissions.

The solicitation for CCPI-2 was issued in February 2004. Four projects were selected for negotiation in October 20004. One project was withdrawn before negotiations could be completed. One project, the subject of this assessment, has been completed. Two projects are currently active, with one in the construction phase and one in the negotiation phase.

One of the projects selected for negotiation was "Mercury Specie and Multi-Pollutant Control". The project was proposed by Pegasus Technologies (Pegasus) of Chardon, OH. Cooperative Agreement Number DE-FC26-06NT42389 was awarded on April 12, 2006. During the course of the project, Pegasus was acquired by NeuCo, Inc., (NeuCo) of Boston, MA, who completed the project as Pegasus' successor. The total project cost was approximately $15.56 million. NeuCo provided approximately $9.48 million (61 percent) of the total, while DOE provided $6.08 million (39 percent). NRG’s Limestone Power Plant (formerly owned by Texas Genco) contributed the host site, human resources, and engineering support to ensure the project’s success.

This report is DOE's assessment of that project.

II. PROJECT PROCESS DESCRIPTION

A. Project Site

The host site for this demonstration project was Unit 2, an 890-MW tangentially fired boiler at the NRG Limestone Plant in Jewett, Texas. It is a base-load plant equipped with a cold-side ESP rated at 99.8 percent particulate removal efficiency and a wet limestone FGD system rated at 90 to 95 percent sulfur dioxide (SO_2) removal efficiency. The wet FGD system is capable of high Hg capture efficiency if the Hg is in an oxidized rather than an elemental state. The plant burns a blend of Texas lignite and PRB subbituminous coal, both of which are known to contain relatively high levels of Hg emitted under normal combustion conditions.

B. Project Description

The project comprised three phases. Phase I primarily consisted of the installation of advanced instrumentation. The instrumentation was evaluated as part of the project and was needed to provide the input data for the optimization software that was demonstrated during the project. In Phase II the optimization software was installed, data and closed-loop control were integrated, and the instrumentation installed in Phase I was verified. Validation and demonstration of the optimization instrumentation and software was carried out in Phase III, as was analysis of test results.

The specific systems to be installed or developed generally included various instruments and analyzers along with the Participant's optimization software. The systems and components that were to be installed or developed include:

- Intelligent Fuel Management System (FMS)
  - Ready Engineering Corporation's Coal Fusion System
  - Sabia, Inc's (Sabia) elemental analyzer
- Mercury Specie Control System
  - Boiler area optimization
  - Sensors from Zolo Technologies, Inc. (Zolo), PS Analytical, Inc. (PSA), and Triple Five Industries
  - Mercury Continuous Emission Monitors (CEMS) by PSA

- Advanced Electrostatic Precipitator (ESP) Optimization System
  - Carbon-In-Ash (CIA) virtual online analyzer
  - CIA sensor from ABB
  - Optimization software developed during the project
- Advanced Intelligent Soot Blowing (ISB) System
  - SootOpt® Intelligent Sootblowing software
- Advanced FGD Optimization System
  - Optimization software developed during the project
- The Intelligent Plant Optimization System
  - Software to ensure that the other optimization software will work together effectively

The interrelationship between these systems is shown in Figure 1.

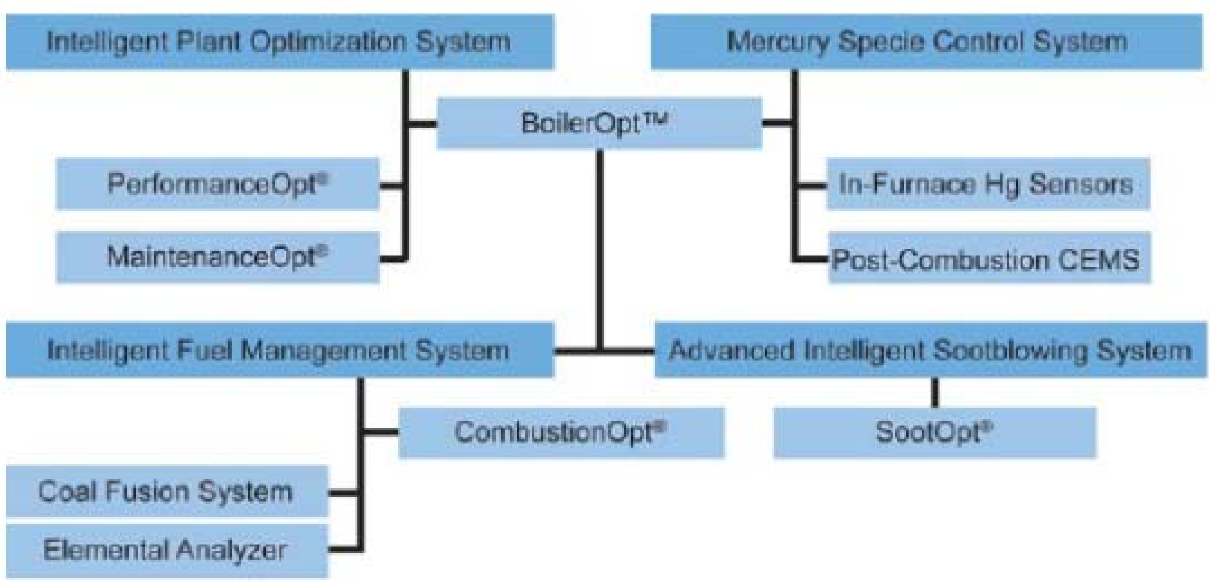

Figure 1. Relationships between Demonstration Technologies (Ref. 3)

In addition to the optimization systems, a number of instrumentation systems were needed to effectively utilize the software-based optimization systems. Figure 2 shows the locations of the major instrumentation systems with respect to their locations within Unit 2. These technologies will be described later in this report.

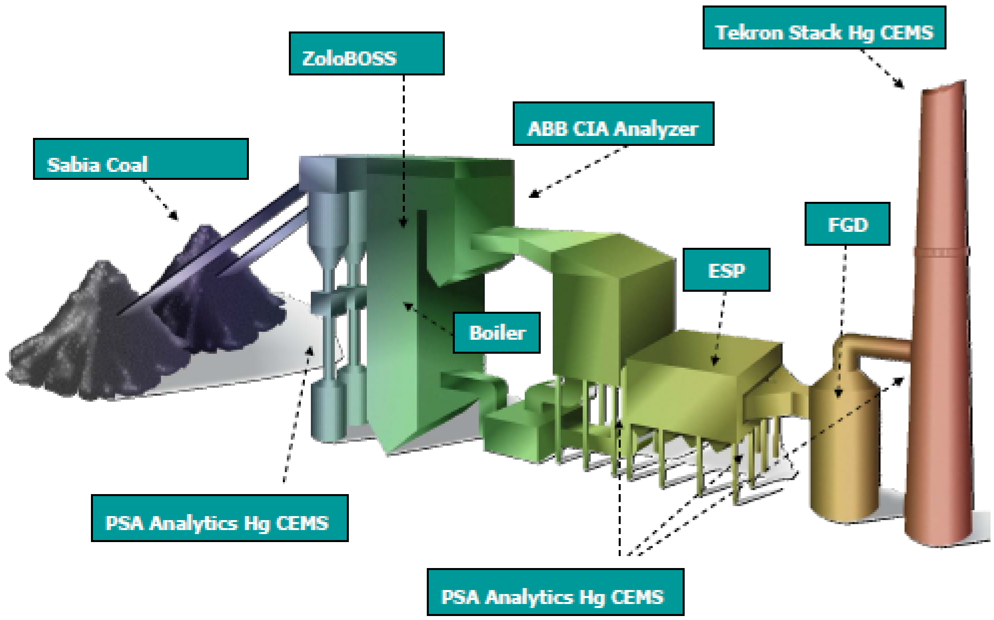

Figure 2. Location of Key Instrumentation (Ref. 1)

When the Cooperative Agreement was awarded to Pegasus Technologies, it was intended that Pegasus' optimization software would be used. Because Pegasus and NeuCo had been competitors, each company had developed several optimization software packages that were intended to accomplish similar results. Following Pegasus' acquisition by NeuCo, and with NeuCo becoming the Participant, NeuCo's optimization software was used. The plans to develop ESP and FGD optimization software were ultimately abandoned for reasons that will be described later.

C. Project Goals

The systems that were deployed and evaluated at Unit 2 were used to achieve optimization objectives.

The demonstration objectives were:

- To optimize overall plant performance
- To reduce NO_X emissions by at least ten percent
- To improve heat rate by 0.5 to 2.0 percent normalized to fuel type and kWh generation
- To demonstrate 40 percent post combustion mercury capture

- To increase operating control and flexibility
- To demonstrate lower capital costs than other approaches for achieving comparable emission reductions
- To develop and demonstrate an FGD optimization system
- To develop and demonstrate an ESP optimization system

D. Technology Description

Intelligent Fuel Management System (FMS)

The technology installed at Limestone Unit 2 consisted of several optimization software packages and supporting analytic equipment, sensors, and controls designed to work synergistically to achieve the optimal performance in a given plant operation and overall plant performance. One such system is the Intelligent FMS. NeuCo's CombustionOpt® optimization, although not directly tied to the FMS, is supported by the FMS. The primary components that are strictly part of FMS are Sabia's elemental analyzer and the Ready Engineering Coal Fusion system.

As stated earlier, the Limestone plant fires a blend of Texas lignite and PRB coal. The Sabia coal analyzer provides regular analyses of the coal that will be fed to Unit 2. The operators use its signal to adjust the ratio of lignite to PRB in order to maintain a consistent HHV of the fuel that is fed to the boiler. They adjust the PRB portion upward if the Btu content of the blend dips below the desired range. Due to the location of the analyzer, the operators have an eight hour window to make the necessary adjustments.

The Ready Engineering system was specifically adapted to the coal transport system at the Limestone plant. Its function is to blend PRB and lignite to the desired percent of PRB. It utilizes linear programming to provide the desired blend and usually operates in the closed-loop mode. Feeding the proper blend of PRB and lignite to the boiler not only contributes to improved Hg and NO_X reduction, but allows for better overall plant performance.

Intelligent Soot Blowing (ISB)

The ISB system is composed of the SootOpt® intelligent sootblowing software. SootOpt is a closed-loop optimization system that aligns soot blowing actions with unit goals. It factors in heat rate, reliability, emissions, and operational constraints. SootOpt models the effect of soot blowing on heat transfer throughout the furnace and determines cleaning actions to best achieve improved boiler operation while minimizing the number of cleaning operations.

Traditionally, soot blowing has been operator-controlled based on a set schedule. This method is basically a hit-or-miss approach that has several disadvantages. If the operation is triggered when not needed, the steam (or other media) is wasted and efficiency suffers. In addition, sootblowing increases wear on the boiler parts being cleaned. When slagging and fouling are occurring, delay in sootblowing can result in lower furnace efficiency, increased NO_X production, and excessive flue gas exit temperatures.

SootOpt combines neural network and expert system optimization methods with direct measurements and local controls to optimize the soot blowing operation. It can be installed on top of existing control technologies and can use existing equipment. In addition to providing adaptive modeling techniques, SootOpt leverages customized operational constraints and control considerations, in the form of rules, to identify correct responses to different operating conditions. Some of these conditions include when soot blowing is required due to suboptimal steam temperatures or high sprays, when it should be suspended (due to the same conditions), or when soot-cleaning media limitations dictate coordination of activity. SootOpt also takes into account information received from CombustionOpt in determining optimal sootblowing in a total unit context. A sample SootOpt home page is shown in Figure 3.

Figure 3. SootOpt Home Page (Ref. 1)

At of the end of the demonstration project, closed-loop SootOpt was running with moderate utilization. Rules stabilized and its goals were integrated with those set for the MPC and neural combustion optimizers. Several sootblowers were the primary reason for limited closed-loop operation. Since these particular sootblowers have a very significant impact on unit performance, plant personnel have generally chosen to keep them under operator control.

<u>Mercury Specie Control System</u>

The Primary optimization software for this system is combustion optimization software (CombustionOpt). CombustionOpt uses input from several sensor packages. The sensor packages included in the Mercury Specie Control System include those from Zolo Technologies, PS Analytical (PSA), and Tekran. Mercury emissions were measured by Continuous Emission Monitors (CEMS) supplied by PSA and Tekran. The Tekran CEMS was not part of the project but installed by the plant during the project, but proved useful when problems occurred with the PSA sensors.

The Zolo laser sensors provide real-time information regarding conditions and compositions in the combustion zone. Unit 2 is a double furnace t-fired unit with a dividing wall between the two furnaces. Zolo uses a Tunable Diode Laser ("TDL") array and the normal crossing installation pattern of the array could not be used. Four crossing lasers were used instead and provided some useful data. Some problems did occur due to the high ash content of the lignite and the fact that Unit 2 is a particularly wide furnace. The high ash content interfered with the lasers by plugging the laser view ports, resulting in intermittent signals.

CombustionOpt uses neural networks to develop relationships that enable it to understand how to change input variables to achieve the performance objectives determined by the plant operators. These relationships are based on real-time and recent data that relate input variables to the objectives set by plant personnel. Important relationships for this model include heat rate and NO_X formation.

In normal operation, operators usually make only occasional adjustments to the various controls based on their understanding of how they will affect unit performance. These adjustments are usually made when an operating condition is at or approaching an unacceptable level. While this method has worked well for keeping the overall operation within acceptable limits, it does not provide optimal operation. CombustionOpt calculates, in real-time, the control settings that improve the mixing of the fuel and air in the furnace, leading to reduced NO_X production in the furnace.

While operators generally make few changes, CombustionOpt makes numerous changes based on current boiler conditions. These changes are based on the model's understanding of the changes required to meet established performance objectives.

CombustionOpt strives to improve the mixing of fuel and air in the furnace to reduce furnace NO_X production while maintaining critical combustion parameters, such as combustion efficiency. CombustionOpt can address a variety of operating situations and can anticipate as far ahead as necessary for dynamic situations, thus rapidly accommodating changing conditions, inputs, controls, and objectives. The optimizer can be modified or expanded to incorporate new controls and objectives or to address additional optimization goals. For example, Hg emission reduction using the Tekran stack Hg CEMS data was added as an optimization objective during Phase III. When the courts vacated the Clean Air Mercury Rule (CAMR), plant personnel decided to reduce the emphasis on Mercury removal and place greater emphasis on NO_X reduction. The Participant analyzed the process and concluded that Hg emission reductions and removal improvements would be coincident with NO_X reductions, which were a significant priority for Limestone personnel.

Intelligent Plant Optimization

The NeuCo Intelligent Plant Optimization uses BoilerOpt™, which links the optimization of the combustion and heat transfer processes. It also coordinates PerformanceOpt® and MaintenanceOpt® monitor performance to provide early detection of operating and equipment anomalies.

BoilerOpt

BoilerOpt integrates the combustion and sootblowing optimization systems (CombustionOpt and SootOpt). The scheme leverages the non-adaptive features of Model Predictive Control (MPC) technology to manage major dynamic controls first. MPC consists of a set of fixed relationships between large control manipulated variables (MVs) and objectives. These relationships can be adaptively developed although expectations exist as to what they should look like. Often, a good guess based on similar units is an adequate starting point. Neural technology is then used to search the secondary control response relationships for useful sensitivity relationships and try them.

PerformanceOpt

PerformanceOpt is a predictive performance management system that identifies efficiency and capacity losses so that operators can take actions to reduce losses and operating costs. PerformanceOpt performs mass and energy balances for thousands of variables and calculates the results on a minute-by-minute basis. These variables include process flow rates and conditions, heat transfer rates, and subsystem and unit performance results. PerformanceOpt uses these results to identify problems that cause non-optimum performance and determines their efficiency and capacity impacts.

PerformanceOpt ensures model accuracy and reliability by making use of sophisticated sensor validation techniques. PerformanceOpt continuously monitors key equipment- and unit-level performance factors and detects (in real-time) when performance deviates from optimum operating conditions. The optimum operating conditions are determined through "what-if" scenarios that are run with the full-scale model of the unit. PerformanceOpt runs predictive simulations to determine the potential improvement in efficiency and capacity that would result from resolving each problem. Problem identification workflow is shown in Figure 4.

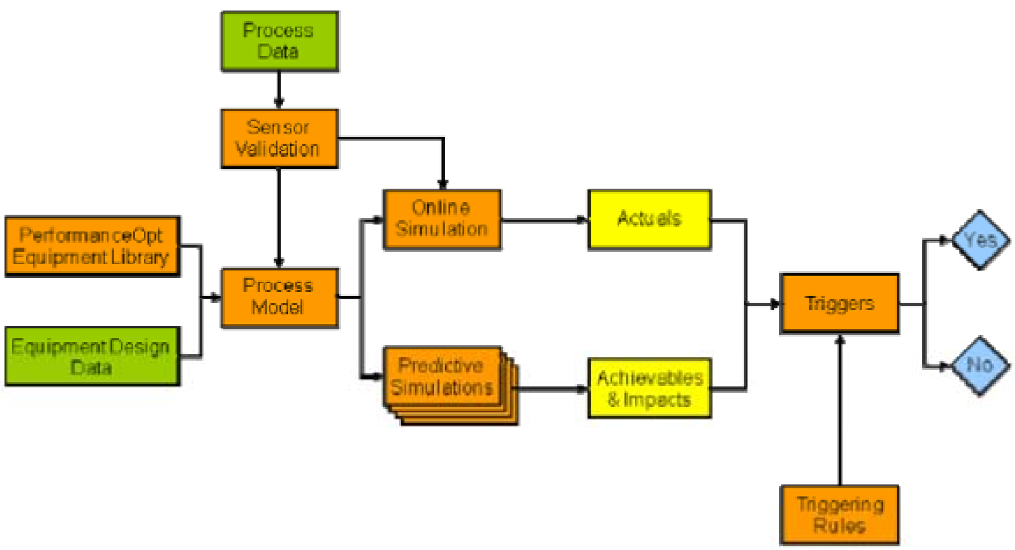

Figure 4. PerformanceOpt Components in Problem Identification (Ref. 1)

The PerformanceOpt model of integrated plant processes typically comprises several interconnected flow sheets that represent all of the plant equipment, the equipments' interconnecting streams, instrumentation, source streams, and products. This model is used both for monitoring and predicting performance. It calculates both actual and achievable plant performance as well as the efficiency and capacity impacts associated with the deviations between actual and achievable performance.

Once problems are identified, PerformanceOpt prioritizes them based on their impacts to plant operation. PerformanceOpt then facilitates the analysis needed to determine the root cause of the problem and identify appropriate action by providing the user with grouped, detailed information. The operator can review this information as well as other data, diagnose the problem, and take corrective action.

All data received from the PerformanceOpt data acquisition system are processed through a sophisticated set of data validation and substitution algorithms to ensure the integrity of the data being fed into the PerformanceOpt model.

PerformanceOpt uses an engineering library that consists of heat and mass balance models of all individual equipment and subsystems comprising a power generation unit. The library also includes various stream types that connect the equipment blocks in a flow sheet representation of the process. The model supports the major equipment and systems as well as all important process conditions. In addition, PerformanceOpt contains a library of engineering and physical property functions that include:

- American Society of Mechanical Engineers (ASME) 1967 and 1997 Steam Tables
- Psychrometric functions
- The Health Effects Institute, 8th edition
- The National Institute of Standards and Technology gas property tables

Calculation modules in PerformanceOpt include those for boiler efficiency, boiler cleanliness, ASME turbine performance, and heat rate. Equipment-level performance results are also generated during the model simulation and made available to the user. These results include boiler efficiency and performance parameters for the high-, intermediate-, and low-pressure turbine sections. Performance parameters are also available for the deaerator, condenser, any other heat exchanger, pumps, fans, and the cooling tower.

Like the other home pages, the PerformanceOpt home page (Figure 5) provides information that enables users to obtain maximum results. The upper left section shows current advice for how to further optimize the unit base, and the lower left section provides access to information that describes how the unit is currently operating and facilitates understanding of PerformanceOpt's advice. The right-hand section shows how the unit has performed in the recent past, comparing actual heat rate and capacity factors to a baseline and an achievable performance determined from what-if simulations of the rigorous PerformanceOpt model.

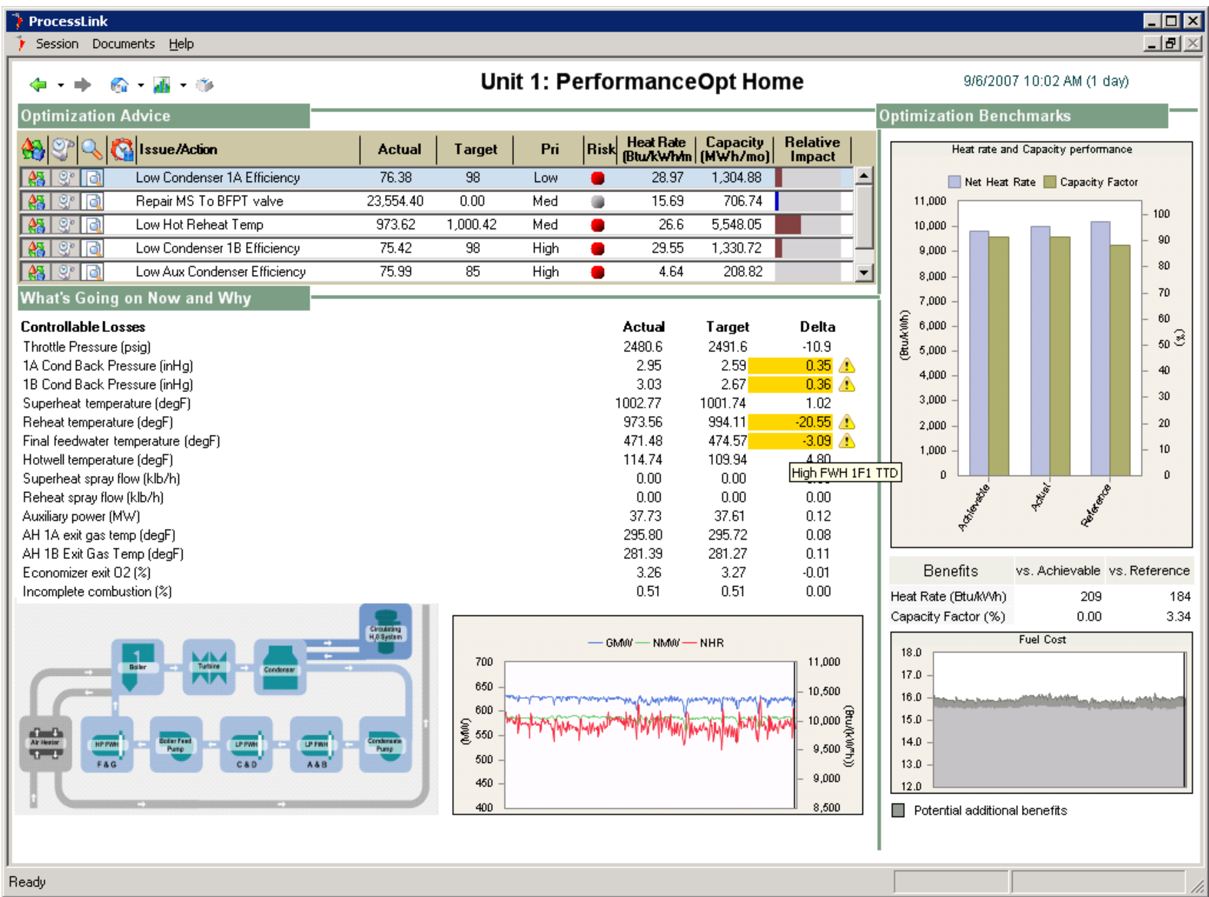

Figure 5. Performance Opt Home Page (Ref. 1)

<u>MaintenanceOpt</u>

MaintenanceOpt continuously monitors process and equipment data to identify anomalies that might indicate reliability, capacity, or efficiency problems. When anomalies are detected, MaintenanceOpt identifies the most likely causes, estimates the impacts on efficiency, reliability, and capacity, and prioritizes the order in which problems should be addressed.

MaintenanceOpt presents the maintenance problems, their diagnoses, required actions, and impacts and risks, which help engineers manage the process of correcting these problems more effectively. MaintenanceOpt displays all the information required to determine whether the detected anomaly points to a real problem or is the result of sensor malfunction.

If engineers decide the problem is real, they use MaintenanceOpt's diagnostics database to identify possible causes. Plant engineers assign a priority to the problem based on the projected impacts and put it on their action list. The workflow supported by MaintenanceOpt is shown in Figure 6 below.

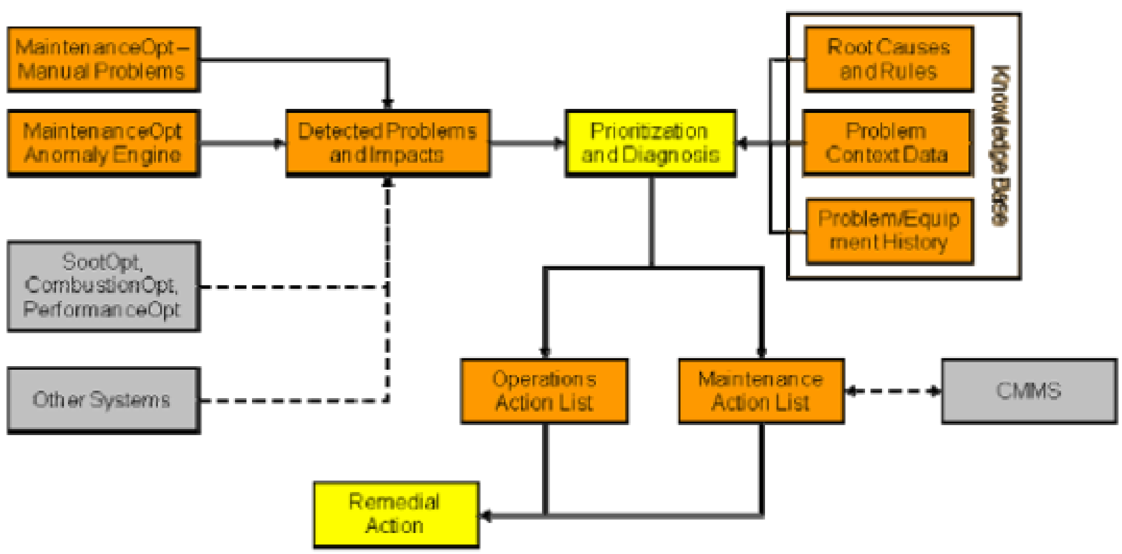

Figure 6. MaintenanceOpt Workflow for Problem Detection, Diagnosis, and Resolution (Ref. 1)

MaintenanceOpt can detect slowly developing problems that have an increasingly negative impact on capacity and efficiency as well as problems that could have a critical near-term reliability impact. In addition to supporting the diagnosis and resolution of problems it detects, MaintenanceOpt also supports the diagnosis and resolution of problems found by other optimizers such as PerformanceOpt, CombustionOpt, and SootOpt, thus serving as a clearing house for all problems that are impacting plant performance to be addressed by appropriate plant personnel. Maintenance tasks are also categorized into activities that do not require a derate, require a derate, or require an outage.

The MaintenanceOpt home page, shown in Figure 7, also provides several types of information that enable users to obtain the maximum benefit from the technology. The top left section displays a summary of all issues currently managed in MaintenanceOpt and provides an overview of the reliability risks and impacts associated with the current problem lifecycle. The bottom left section shows a summary view of current problems managed in MaintenanceOpt based on affected equipment and priority. In addition, the user is also presented with a consolidated list of instrumentation-related problems. The section on the right shows recent unit performance compared to baseline and target performance standards. This section also benchmarks the efficiency of problem lifecycle management over that period based on the average time problems remained in various states (e.g., not yet screened, undiagnosed).

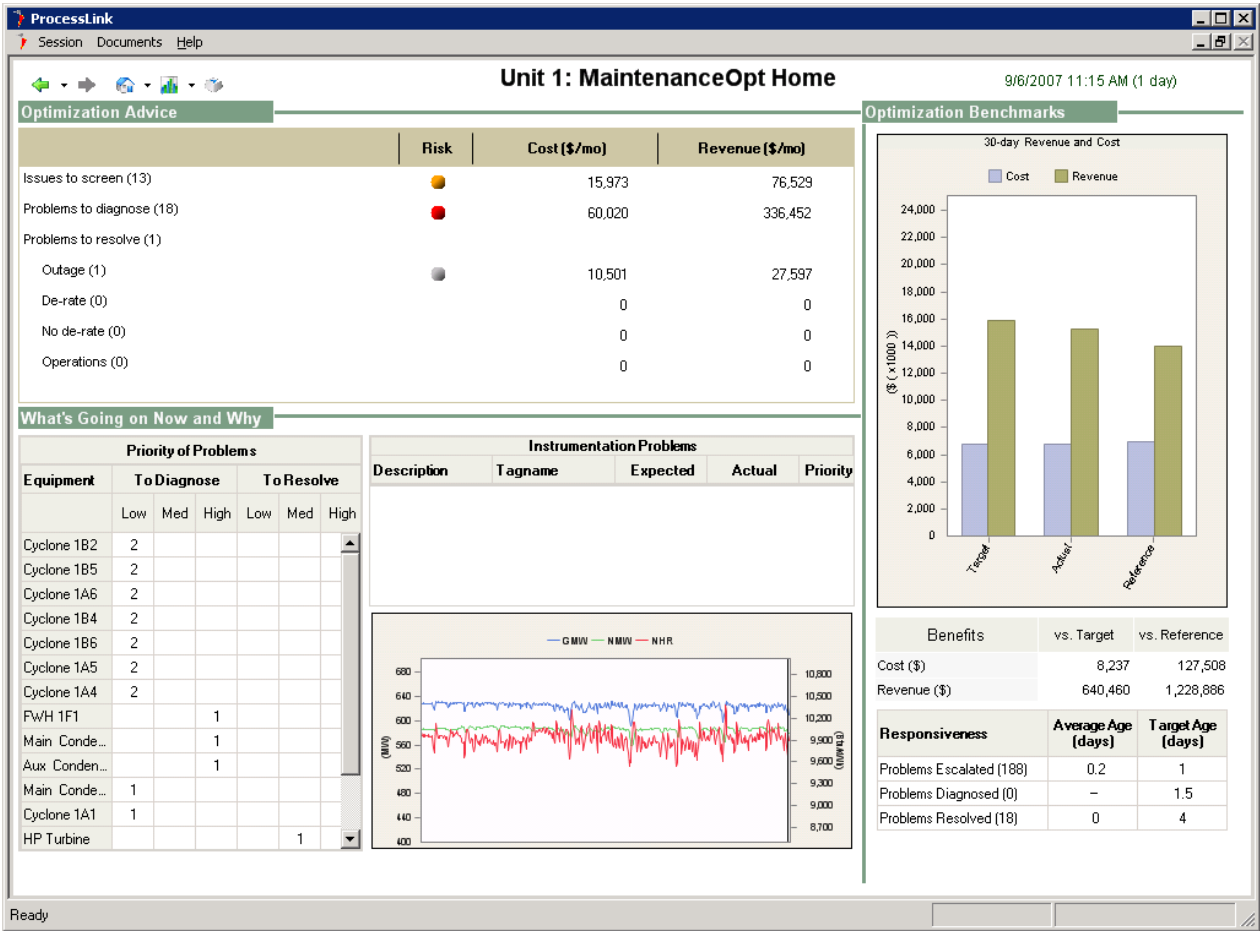

Figure 7. MaintenanceOpt Home Page (Ref. 1)

As described in Section III, virtual on-line analyzers were used to obtain some Hg data. The Participant (Reference 1) describes a virtual on-line analyzer (VOA) as " …a regression based model, trained on measured data to match a target measured value as a function of other observed values. The model can be used to estimate what the target measurement would have been in situations where a measurement was not taken based on the values of the other variables". The Hg removal VOA inputs were amount of O_2 measured, burner tilts, and unit load. The VOA for total stack Hg used amount of O_2 measured, burner tilts, fuel blend, and unit load.

III. RESULTS

Personnel were faced with several challenges throughout the course of the project that impacted the project results. The most significant were:

- Maintenance of good Hg CEMS data at the ESP and FGD inlets and FGD outlet
- Changing regulatory and market conditions
- Installation and maintenance of a wide array of instrumentation from multiple vendors

These challenges were responsible, at least to some degree, for the failure to achieve some project goals. Other goals were successfully met.

The FMS generally worked well. After the resolution of some issues the Ready Engineering system has operated reliably in providing the desired blend of lignite and PRB. While the system is an important part of the NO_X and Hg reduction strategy, plant personnel have also found it useful in maintaining a reasonably constant HHV in the coal fed to Unit 2. The Sabia coal analyzer also performed well but requires regular calibration to provide accurate data to the operators so that they can adjust the coal blend. The Participant and plant personnel consider the Coal Fusion system and Sabia analyzer to be cost-effective systems.

As of the end of the project, the SootOpt was running in the closed-loop mode with only moderate utilization. Its goals were integrated with those set for the MPC and neural combustion optimizers. Plant personnel limit closed-loop operation since the long, retractable sootblowers that clean certain sections have a major effect on unit performance and are kept under operator control.

Mercury Specie Control System

The Zolo laser sensors were installed during Phase I. These sensors are intended to provide real-time information on conditions and chemical species within the combustion zone. Unit 2 is a double furnace that has a dividing wall between the two furnaces. The typical cross-firing TDL array could not be used; therefore, a different laser pattern was used in an effort provide useful data. Unit 2 was also the first application of Zolo laser sensors on a unit burning lignite. The high ash content of lignite and slagging issues on Unit 2 resulted in only intermittent signals being obtained since the slag tended to plug the view ports. Longer port rodders (devices that can be inserted through the view port to clear it) were installed and resulted in the collection of more consistent data. Various issues limited the value of this improved data flow.

The PSA CEMS suffered from numerous reliability problems throughout the project. The Tekran stack Hg CEMS were installed by the plant in Phase III. Since the stack Hg level and the Hg level at the FGD outlet are essentially the same, the Tekran CEMS basically replaced the PSA CEMS at the FGD outlet. Other Hg measurements had to be estimated by the VOA. Eventually, the use of the PSA CEMS was discontinued due to the high maintenance costs and low reliability. Mercury removal was de-emphasized during the course of the project when the courts vacated the Clean Air Mercury Rule (CAMR).

Throughout the project different problems conspired to limit the ability of the participant to obtain valid Hg data. Figure 8 demonstrates the degree to which Hg data was limited. No shading indicates valid data, gray shading indicates that Unit 2 was off-line or operating at a significantly reduced capacity, yellow shading indicates bad values due to sensor/communication problems, and pink shading indicates obviously bad values determined by inconsistency between two measurements.

Figure 8. Total Mercury at the FGD Inlet (solid blue line) and other variables of interest. 1/1/2009 – 5/31/2009 (Ref. 1)

CombustionOpt generally performed well in adjusting dampers, burner tilts, pulverizer settings, over-fire air, and other controllable parameters to their optimal levels for a given set of conditions, objectives, and constraints. During Phase III, CombustionOpt operated in closed-loop mode to optimize NO_X, CO, O_2, burner tilt, and reheat temperatures. NO_X reduction was a high priority throughout the project while reducing Hg was added as an objective during Phase III. As stated earlier, CombustionOpt works with SootOpt to optimize boiler operation. The key results for these optimizers are shown below in Tables 1 and 2.

Table 1. Key Short Term Results (3/31/2010 – 7/9/2010)

	Optimizers Off	Optimizers On	Percent Change
NO_X, lb/MMBtu	0.218	0.182	-10.8
CO, ppm	33.08	25.15	-24.0
Unit Heat Rate, Btu/kWh	10,323.46	10,202.99	-1.17%
Total Stack Hg, µg/m3	5.48	5.21	-4.9%
Mercury Removal, %	62.18	63.63	+2.3

Table 2. Key Long Term Results (1/20/2009 - 6/25/2010).

	Optimizers Off	Optimizers On	Percent Change
NO_X, lb/MMBtu	0.212	0.189	-16.5
CO, ppm	26.98	26.79	-0.7
Unit Heat Rate, Btu/kWh	Not available	Not available	-.86
Total Stack Hg, µg/m3	6.07	6.58	-8.1
Mercury Removal, %	57.97	56.92	+3.4

PerformanceOpt and MaintenanceOpt

The Participant reports that both PerformanceOpt and MaintenanceOpt have performed as expected. Plant personnel have been alerted to both performance and equipment anomalies, typically generating around five alerts per day. These alerts have included such issues as bearing temperature and vibration performance and equipment health anomalies that need attention. Although the quantity of alerts varies, on a typical day PerformanceOpt and MaintenanceOpt will generate between five and ten alerts for Unit 2. These alerts have been for a variety of issues and symptoms including main turbine bearing vibrations, pump turbine temperature, economizer gas outlet temperature stratification, and feedwater heater drain cooler approach issues. These alerts have allowed plant personnel to make repairs or corrections in a timely manner, thus avoiding more serious problems that could lead to reduced load or an outage. In short, these systems performed as intended.

The original scope of work called for the development of ESP optimization (ESPOpt) and FGD optimization (FGDOpt) neural net-based software packages. Neither was developed.
The ESP Optimization System was to be composed of a Carbon-In-Ash (CIA) virtual online analyzer, a CIA sensor from ABB, and ESP Optimization software developed by the Participant. Prior to the start of Phase III, the ABB CIA instruments failed due to mirror erosion. ABB discontinued support shortly thereafter and replacement parts were not available. The loss of the CIA instrument reduced the degree to which CIA could be directly correlated with ESP Hg oxidation. In addition, it was discovered that a power optimization system had already been installed. Power consumed in the ESP was controlled by monitoring the opacity in the stack. Since the unit already had a power optimization system, no advanced ESP optimization system was implemented.

During the project, the Unit 2 FGD underwent a major modification that allowed it to produce byproduct gypsum instead of calcium sulfite. The revamped FGD upgrade was completed early in Phase III but startup issues persisted into June when it was (later) discovered that good Hg removal data was available. During Phase II changes in the regulatory context as well as the overall economy dramatically affected SO_2 credit prices. The low cost of SO_2 credits reduced the value of an FGD optimization product. By the summer of 2009, SO_2 credit prices had dropped to the point that plant management was no longer interested in increasing SO_2 removal; they were interested only in minimizing cost. This was accomplished primarily by bypassing flue gas around the FGDs, which required no optimization system. Thus, the effort to implement an FGD optimization system was abandoned. In addition, analysis of Hg removal indicated that the interaction between pre-project scrubber conditions and combustion and optimization actions taken by CombustionOpt and SootOpt to increase Hg oxidation were still important since most Hg removal was occurring, as expected, in the FGD.

IV. DISCUSSION OF RESULTS

As stated earlier, the demonstration project objectives were to:

1. Optimize overall plant performance
2. Reduce NO_X emissions by at least ten percent
3. Improve heat rate by 0.5 to 2.0 percent normalized to fuel type and kWh generation
4. Demonstrate 40 percent post combustion Hg capture
5. Increase operating control and flexibility
6. Demonstrate lower capital costs than other approaches for achieving comparable emission reductions
7. Develop and demonstrate an FGD optimization system
8. Develop and demonstrate an ESP optimization system

Although objectives 1 and 5 are difficult to quantify it does appear that they were met. The FMS resulted in a more stable fuel HHV to the boiler. PerformanceOpt and MaintenanceOpt regularly provided alerts to the operators allowing them to make corrections to an underperforming system or to remedy equipment problems before they became serious.

Objective 2 was clearly met. NO_X was reduced by more than ten percent over the long term, increasing to over sixteen percent over the shorter term at the end of the demonstration period. Objective 3 was also clearly met with heat rate improvements ranging from 0.86 to 1.17 percent during the demonstration.

Objective 4 was technically met. While it was met even when the optimization systems were not active, it should be noted that, according to the VOA estimates, the systems did show a slight increase in Hg removal. The actual optimizer impacts on Hg oxidation and removal could not be effectively determined due to several factors: During Phase III ABB's CIA analyzer and the PSA Hg CEMS were unable to provide reliable data and were essentially abandoned. The ability of the optimizers to reduce Hg emissions was difficult or impossible to determine given the problems in measuring Hg at all points except the stack and the plant decision to bypass the FGD system.

The participant provided insufficient data to allow assessment of objective 6. However, the participant estimated a benefit to the demonstration unit of approximately $3.5 million per year. Had these benefits been derived from equipment additions or modifications, the cost would almost certainly have been significantly higher. The payback time for the software-based optimization packages is in the order of a few months rather than the years one would expect for equipment improvements. Objectives 7 and 8 were not listed as performance objectives but were part of the project plan. Neither was accomplished, as discussed in the previous section. These efforts were abandoned due to failed instruments, a changing regulatory background, and plant priorities.

The limited benefit demonstrated with respect to Hg removal was due to bad CEMS and shifting plant preferences, which changed when SO_2 credit prices fell and the CAMR was vacated. The optimization systems also effectively lowered CO emissions by 24 percent although the goal was simply to keep them below 40 ppm. It appears that the various optimization software packages operated as expected, but their impact was limited by sensors and plant operating decisions.

V. MARKET ANALYSIS

A. Potential Market

The optimization systems that were demonstrated in this project are applicable to all power generation units (estimated as 1,950 units in the United States). This figure includes coal, oil, and gas units. Due to the adaptive nature of the optimizers, these units represent market potential if they are not equipped with some optimization technology. The Participant did not include foreign or industrial units in their analysis nor did they address potential markets for the fuel management system, although these would be limited to coal-fired units that blend fuels. The Zolo system market was likewise not addressed. It is clear that the market for the optimizer packages is extensive.

B. Economic Impact

An engineering-economics benefits analysis was conducted by NeuCo to estimate the financial implications of an integrated optimizer package and to project the potential financial impact on the entire U.S. fleet of fossil-fired generating units. The results obtained in the Limestone project are used as the basis for these estimates and conservative values are used throughout. The results are presented in Table 3.

Table 3. Economic Benefits as applied to U.S. fossil Generation (Ref. 1)

US Fossil Units	Typical PRB W/SCR	Typical PRB No/SCR	Typical Bitum W/SCR	Typical Bitum No/SCR	Oil/Gas (ST + CCCT)	Total (1950 Units) Industry Benefits
Gross Capacity (MW)	698	246	698	246	198	514,359
Net Capacity (MW)	645	227	645	228	192	475,782
Capacity Factor (%)	90%	80%	90%	80.0%	40.0%	82.7%
Annual Output (MWh/y)	5,089,038	1,592,075	5,089,038	1,594,670	672,768	3,446,769,199
Baseline Heat Rate (Btu/kWh)	10,000	10,000	10,000	10,000	10,000	10,000
Annual Heat Input (mmBtu/yr)	50,890,382	15,920,747	50,890,382	15,946,704	6,727,680	34,467,691,992
Fuel Cost ($/MMBtu)	$1.50	$1.50	$2.50	$2.50	$6.00	$2.19
CO2 Output (tons/yr)	7,683,450	2,403,721	5,382,637	1,686,671	1,076,429	6,379,454,175
Annual Fuel Cost ($/yr)	$82,524,944	$25,817,428	$137,541,573	$43,099,200	$40,366,080	$75,546,189,528
Heat Rate Improvement (-%)	-0.86%	-0.86%	-0.86%	-0.86%	-0.86%	-0.86%
Annual Fuel Savings	$709,715	$222,030	$1,182,858	$370,653	$347,148	$649,697,230
Value of CO2 reduction ($/ton)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Annual CO2 Reduction (tons/year)	71,435	22,348	50,044	15,681	9,257	54,863,306
Annual CO2 Reduction Benefits	$0	$0	$0	$0	$0	$0
Baseline Average Boiler NOx (lb/MMBtu)	0.25	0.20	0.30	0.28	0.25	0.27
Baseline Annual NOx (tons/yr)	6,877	1,721	8,252	2,370	865	4,942,773
Avg ProcessLink NOx Reduction, at boiler (-%)	-16.00%	-16.00%	-16.00%	-16.00%	-16.00%	-16.00%
NH3 Reduction (%)	-14.40%	0.00%	-14.40%	0.00%	0.00%	-14.40%
Average NOx Allowance Credit Value ($/ton)	$1,844	$1,844	$1,844	$1,844	$1,844	$1,844
NOx Reduction Allowance Benefits ($/yr)	$38,512	$507,743	$46,214	$699,285	$255,241	$183,420,330
NH3 Cost ($/ton NOx)	$350	$350	$350	$350	$0	$350
NH3 Reduction Value ($/yr)	$346,605	$0	$462,140	$0	$0	$181,001,022
SOx Reduction Allowance Benefits ($/yr)	$53,938	$16,874	$165,600	$51,891	$11,065	$40,511,589
Annual Availability Increase (%)	0.55%	0.55%	0.55%	0.55%	0.55%	0.55%
Increased Availability Value ($/MWh)	$45.00	$50.00	$45.00	$50.00	$100.00	$48.77
Increased Availability Value ($/yr)	$805,650	$295,825	$503,058	$201,489	$148,009	$659,012,936
Total ProcessLink Suite Savings ($/yr)	**$1,954,419**	**$1,042,472**	**$2,359,870**	**$1,323,318**	**$761,463**	**$1,713,643,106**

The Participant estimates the total benefits derived from the installed demonstration technologies to be over $3.5 million per year for Unit 2.

C. Capital Costs and Operating and Maintenance Costs

No such cost information was presented in the final report for this project. In a report prepared by the Participant for a project carried out at Dynegy's Baldwin Energy complex, they estimated that the cost of installing optimizer packages could be recovered in four to nine months, depending on plant configuration and specific equipment.

VI. CONCLUSIONS

While the optimizers performed well, resulting in some project objectives being met, not all performance goals were met. CombustionOpt and SootOpt were able to achieve the goals of lower NO_X emissions and reduced heat rate to the desired extent. BoilerOpt, PerformanceOpt and MaintenanceOpt performed well as did the FMS. The Zolo sensors also worked satisfactorily after some initial problems.

There were several issues with regard to Hg speciation and removal. Limited Hg data due to faulty CEMS led to the use of VOAs, which are basically estimates based on other, measurable parameters. Reduced plant emphasis on Hg and operating decisions (FGD bypass) was also an issue. While some small improvement in Hg removal was noted, the goal of 40 percent removal was exceeded without optimization.

ESPOpt and FGDOpt were never developed as planned. Again, faulty CEMS and shifting priorities were cited, as well as the expenses that would have been required to maintain or upgrade the CEMS.

CombustionOpt, SootOpt, BoilerOpt, PerformanceOpt, MaintenanceOpt, the Zolo sensors, and the FMS generally worked well. Their performance was countered by the Hg results, the CIA CEMS, and the inability to develop two planned optimizers. Although the majority of the technologies were successfully demonstrated, given these shortcomings, this project cannot be deemed an unqualified success.

ACRONYMS and ABBREVIATIONS

ASME	American Society of Mechanical Engineers
Btu	British thermal units
CAMR	Clean Air Mercury Rule
CCPI	Clean Coal Power Initiative
CCPI-1	Round 1 of the CCPI
CCPI-2	Round 1 of the CCPI
CCTDP	Clean Coal Technology Demonstration Program
CEMS	Continuous emission monitors
CIA	Carbon-in-ash
CO	Carbon monoxide
DCS	Distributed Control System
DOE	Department of Energy
ESP	Electrostatic precipitator
FGD	Flue gas desulfurization
FMS	Fuel Management System
Hg	Mercury
HHV	Higher heating value
ISB	Intelligent Sootblowing system
lb.	Pounds
mm	Million
MV's	Manipulated variables
MW	Megawatts
MPC	Model Predictive Control
NETL	National Energy Technology Laboratory
NO_X	Nitrogen oxides
O_2	Molecular oxygen
PPII	Power Plant Improvement Initiative
PSA	PS Analytical
PRB	Powder River Basin
SO_2	Sulfur dioxide

TDL	Tunable Diode Laser
VOA	Virtual on-line analyzer

REFERENCES

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3. U.S. Department of Energy, Clean Coal Technology Programs: Program Update 2009 As of June 2009, October 2009