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CLEAN COAL TECHNOLOGY

Power Plant Optimization Demonstration Projects

A report on four projects conducted under separate cooperative agreements between the U.S. Department of Energy and:

- Great River Energy
- Tampa Electric Company
- Pegasus Technologies
- NeuCo. , Inc.

Cover Photos:

- Top left: Coal Creek Station
- Top right: Big Bend Power Station
- Bottom left: Baldwin Energy Complex
- Bottom right: Limestone Power Plant

CLEAN COAL TECHNOLOGY

Power Plant Optimization Demonstration Projects

Executive Summary

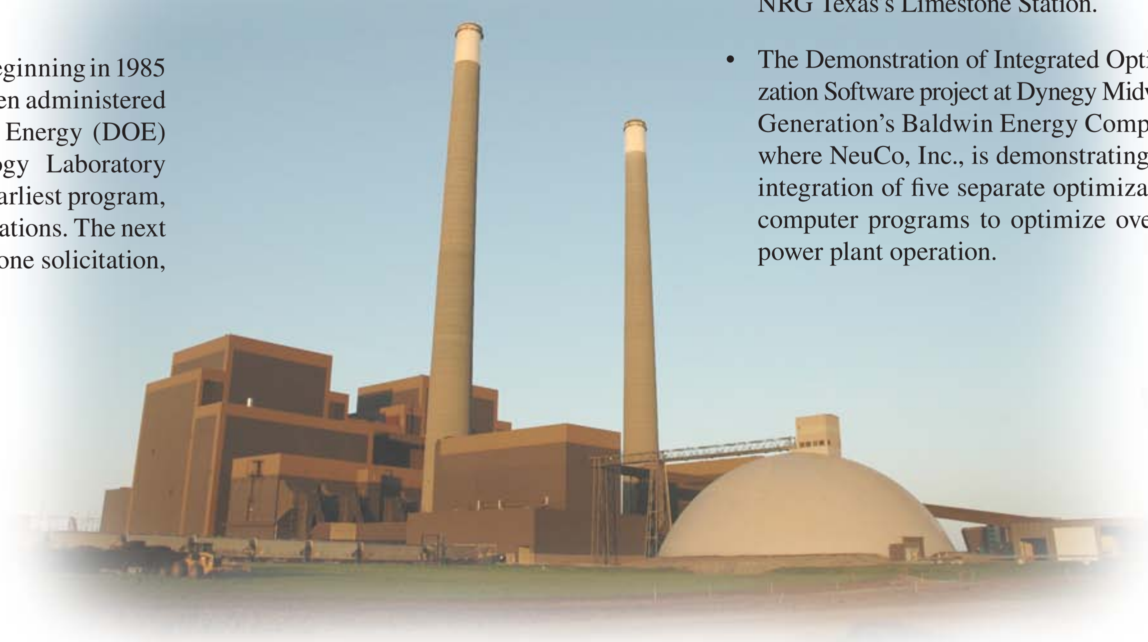
The Clean Coal Technology Demonstration Program (CCTDP) and the two following programs—the Power Plant Improvement Initiative (PPII) and the Clean Coal Power Initiative (CCPI)—are government and industry co-funded programs. The goal of these programs is to demonstrate a new generation of innovative coal-utilization 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 further 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.

To achieve these goals, beginning in 1985 a multi-phased effort has been administered by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). The CCTDP, the earliest program, initiated five separate solicitations. The next program, the PPII, sent out one solicitation, and the CCPI has had two solicitations to date. The projects selected through these solicitations have demonstrated technology options with the potential to meet the needs of the energy markets while satisfying relevant environmental requirements.

This report describes four projects aimed at improving or optimizing the performance of coal-fired power plants. All four projects are being conducted under the CCPI and PPII programs. The first project deals with upgrading high moisture lignite by partial drying to enhance its quality and improve overall plant performance. The remaining three projects involve the development of software that optimizes overall power plant performance or some aspect of performance by incorporating features of artificial intelligence (AI), a decision-making capability that simulates the human brain.

- The Lignite Fuel Enhancement project is demonstrating improved plant performance by using waste heat to partially dry lignite, which is normally high in moisture.
- The Neural Network-Intelligent Sootblowing (NN-ISB) project with the Tampa Electric Company (TECO) Big Bend Power Station was intended to demonstrate improved efficiency and lower emissions of nitrogen oxides (NO_X) by using a computer-based neural network to determine when sootblowing is needed.
- The Mercury Specie and Multi-Pollutant Control project with Pegasus Technologies is demonstrating the capability to optimize mercury speciation and control of emissions from an existing power plant using state-of-the art sensors and neural network-based optimization software at NRG Texas's Limestone Station.
- The Demonstration of Integrated Optimization Software project at Dynegy Midwest Generation's Baldwin Energy Complex, where NeuCo, Inc., is demonstrating the integration of five separate optimization computer programs to optimize overall power plant operation.



Great River Energy's Coal Creek Station

Power Plant Optimization Demonstration Projects

Topical Report Number 25

Background: Power Plant Optimization

Overall optimization of a coal-fired power plant is a highly complex process. One must first decide what constitutes optimal performance. Obvious answers include maximum thermal efficiency, lowest possible emissions, lowest possible cost, readily marketable by-products, and maximum system availability for power generation. In reality, these goals—and others—are interrelated. In some cases, however, these optimization goals are at odds with each other. For example, high excess air will result in better carbon burnout and less carbon monoxide but will also result in higher emissions of nitrogen oxides (NO_X). These interactions must be kept in mind and addressed with any optimization program.

There are a number of relatively fixed items that affect overall plant operation. These include boiler design, cooling water conditions, burner type, design steam conditions, and environmental control systems that capture and remove particulate matter, sulfur dioxide (SO_2), NO_X, and mercury. Coal quality is also a major factor that affects plant performance. High moisture and/or ash content decreases efficiency and increases wear and power requirements on the pulverizers. High sulfur content results in more reagent consumption and increased by-product generation.

The benefits of optimizing the overall process of generating power from coal are significant. Efficiency is increased, total maintenance costs are reduced, emissions are decreased, and reliability is improved. While the greatest benefit can be achieved by optimizing the overall operation, important benefits can also be achieved by optimizing one or more of the factors that contribute to the overall efficiency of the plant.

Many optimizations can yield substantial positive results. For instance, use of lignite and sub-bituminous coals, which are high in moisture, lowers the boiler efficiency, increases the load on the pulverizers, and increases flue gas volume. Drying the coal before it is fed to the preparation system is generally not practical due to the energy required. Switching to a higher quality coal, even if available, is often not practical either due to cost or to the fact that a boiler designed for a specific coal may not function as well with other coals. If such a switch is made, the unit may need to be de-rated. So, if drying the coal can be economically integrated into the overall power plant process, potential benefits are substantial.

There are several obvious systems that can be optimized independently and result in better performance. Some involve simply upgrading a specific piece of equipment.

For example, a refurbished steam turbine will improve heat rate and result in less fuel consumption per megawatt (MW). The cost of electricity is then reduced, as are the emission rates of some pollutants.

In some cases, optimizing one aspect of boiler operation can have several benefits. For example, during boiler operation, ash slowly builds up on boiler tubes. This causes reduced heat transfer to the boiler feed water and steam which results in lower efficiency and higher NO_X emissions. The buildup is removed by blowing it off the tubes with high-pressure steam. But when sootblowing occurs, the electrostatic precipitator (ESP), or baghouse, is temporarily overwhelmed by the high particulate load at the inlet. Sootblowing is traditionally done on a set schedule rather than as needed. This results in some boiler sections accumulating excessive ash on the tubes while others, having little ash buildup, are serviced when it is not required. Optimized sootblowing can solve these problems by using sensors and artificial intelligence (AI) software to determine when a particular section of the boiler needs to have the ash removed from the tubes, thus minimizing steam consumption (and improving heat rate), reducing the frequency of a high particulate load in the flue gas, and reducing NO_X formation.

As one would expect, optimizing the operation of multiple components normally gives better results than optimizing one aspect of the operation. Maximizing the overall performance of multiple pieces of equipment does not normally have an adverse effect on the other power plant components. However, when using AI/neural network systems to optimize multiple aspects of power plant operation, care must be taken to consider the possible negative impact on other parameters. This can best be accomplished by designing the software packages to communicate with each other through a management software package.

This document describes four optimization projects within the PPII and CCPI programs. The following are brief descriptions of the four projects:

In the **Lignite Fuel Enhancement** project, Great River Energy has installed a full-scale prototype dryer module to supply one-sixth of the coal required for a 546 MW unit. Results to date have shown improved performance in overall operation of this unit. In the next phase of this project, Great River Energy will design, construct, and perform full-scale, long-term operational testing on a complete set of dryer modules to supply all the coal needed for the full operation of this unit.

The **Neural Network-Intelligent Sootblower** (NN-ISB) project with the Tampa Electric Company (TECO) Big Bend Power Station is complete. This project showed that the concept of using a neural network system to optimize the sootblowing process is sound but that additional development and better equipment are needed. Mechanical problems with sensors and water cannons were encountered and overall results were affected by these issues. However, some benefit was obtained with respect to stack opacity and nitrogen oxides reduction.

In the **Mercury Specie and Multi-Pollutant Control** project, Pegasus Technologies will utilize state-of-the-art sensors and neural-network-based optimization and control technologies to maximize the proportion of mercury species that are easy to remove from the boiler flue. This project will demonstrate how integrating sensors, controls, and advanced analysis techniques into multiple facets of plant operation can lead to improved economics and environmental compliance.

With the **Demonstration of Integrated Optimization Software** project at Dynegy Midwest Generation's Baldwin Energy Complex, NeuCo, Inc., is integrating and optimizing their software, SCR-Opt™, CombustionOpt®, SootOpt™, PerformanceOpt®, and MaintenanceOpt™. ProcessLink® is the integration software that coordinates these programs to achieve overall plant goals. The project is ongoing as of this time and results to date appear promising.

Artificial Intelligence

Artificial intelligence (AI) is commonly defined as the science and engineering of making intelligent machines, especially intelligent computer programs. Relative to applications with coal-fired power plants, AI consists of aspects or considerations that deal with the following:

- Neural networks, which mimic the capacity of the human brain to handle complex nonlinear relationships and "learn" new relationships in the plant environment
- Advanced algorithms or expert systems that follow a set of pre-established rules written in codes or computer language
- Fuzzy logic, which involves evaluation of process variables in accordance with approximate relationships that have been determined to be sufficiently accurate to meet the needs of plant control systems

Neural networks (NNs) are a class of algorithms that simulate the operation of biological neurons. The NN learns the relationships between operating conditions, emissions, and performance parameters by processing the test data. In the training process, the NN develops a complex nonlinear function that maps the system inputs to the corresponding outputs. This function is passed on to a mathematical minimization algorithm that finds optimum operating conditions.

NNs are composed of a large number of highly interconnected processing elements that work in parallel to solve a specific problem. These networks, with their extensive ability to derive meaning from complicated or imprecise data, can be used to extract patterns and detect trends that are too complex to be detected by either humans or other computer techniques. NNs are trainable systems that can "learn" to solve complex problems and generalize the acquired knowledge to solve unforeseen problems. A trained NN can be thought of as an expert in the category of information it has been given to analyze. NNs are considered by some to be best suited as advisors, i.e., advanced systems that make recommendations based on various types of data input. These recommendations, which will change as power plant operations change, suggest ways in which plant equipment or technologies can be optimized.

Advanced algorithms, on the other hand, are programmed to incorporate established relationships between input and output information based on detailed knowledge of a specific process. They are used by computers to process complex information or data using a step-by-step, problem-solving procedure. In particular, genetic algorithms provide a search technique to find true or approximate solutions to optimization problems. These algorithms must be rigorously defined for any computational process since an established procedure is required for solving a problem in a finite number of steps. Algorithms must tell the computer what specific steps to perform and in what specific order so that a specified task can be accomplished. Advanced algorithms are now part of the sophisticated computational techniques being successfully applied to power plants to increase plant efficiency and reduce unwanted emissions.

Fuzzy logic (FL), the least specific type of AI software, is equipped with a set of approximate rules used whenever "close enough is good enough." Fuzzy logic is a problem-solving control-system methodology that has been used successfully with large, networked, multi-channel computers or workstation-based data-acquisition and control systems. FL can be implemented via hardware, software, or a combination of both. Elevators and camera auto-focusing systems are primary examples of fuzzy logic systems. Fuzzy logic stops an elevator at a floor when it is within a certain range, not at a specific point.

FL has proven to be an excellent choice for many control system applications since it mimics human control logic. By using an imprecise but very descriptive language, FL deals with input data much like a human operator. FL is very robust and provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, or missing input information. However, while the FL approach to solving control problems mimics human decision-making, FL is much faster. The FL model is empirically based, relying on operator experience rather than technical understanding of the system.

Lignite Fuel Enhancement Project

Introduction

The use of low-rank coals (lignite and subbituminous) has seen a significant increase in recent years. Because of the low sulfur content of such coals, many units have adopted fuel switching to meet sulfur emissions specifications, and other units have been built specifically to burn low-rank coals. However, a major disadvantage of low-rank coals is their high moisture content, typically 25 to 40 percent. When such coal is burned, considerable energy is required to vaporize the moisture it contains, thus raising the heat rate of the power plant and lowering its efficiency.

Fuel moisture has many effects on unit operation, performance, and emissions. As fuel moisture decreases, the fuel's heating value increases so that less coal needs to be fired to produce the same electric power, thus reducing the burden on the coal-handling system. Drier coal is easier to convey as well, which reduces maintenance costs and increases availability of the coal to the handling system. When the crushed coal is gravity-fed into bunkers, the drier coal flows more readily than the wet coal, causing fewer feed hopper bridging and plugging problems. Drier coal is easier to pulverize as well so that less mill power is needed to achieve the same coal fineness. Finally, with less moisture in the fuel more complete drying of coal can be achieved in the mill, which results in an increased mill exit temperature, better conveying of coal in the coal pipes, and fewer coal pipe plugging problems.

The mixture of pulverized coal and air from the pulverizers is combusted in the burners. With drier coal, the flame temperature is higher since there is less moisture to evaporate. At the same time, heat transfer processes in the furnace are modified. The higher flame temperature results in a larger radiation heat flux to the furnace walls. Also, drier coal results in less moisture in the flue gas, which changes the radiation properties of the flame. The change in the flame emissivity also affects the radiation flux to the wall. With a higher flame temperature, the temperature of coal ash particles is correspondingly higher, which could increase furnace fouling and slagging, reducing heat transfer and resulting in a higher flue gas temperature at the furnace exit. However, the reduction in coal flow rate as fuel moisture is reduced also reduces the amount of ash entering the boiler, which leads to less solid-particle erosion in the boiler and decreased boiler maintenance cost.

The Clean Coal Technology Program

The DOE commitment to clean coal technology development has progressed through three phases. The first phase was the Clean Coal Technology Demonstration Program (CCTDP), a model of government and industry cooperation that advanced the DOE mission to foster a secure and reliable energy system. With 33 projects completed, the CCTDP has yielded technologies that provide a foundation for meeting future energy demands that utilize the vast U.S. reserves of coal in an environmentally sound manner. Begun in 1985, the CCTDP represents a total investment value of over $3.25 billion. The DOE share of the total cost is about $1.30 billion, or approximately 40 percent. The project industrial participants (non-DOE) have provided the remainder, nearly $2 billion.

Two programs have followed that have built on the successes of the CCTDP. The first is the Power Plant Improvement Initiative (PPII), a cost-shared program patterned after the CCTDP and directed toward improved reliability and environmental performance of the nation's coal-burning power plants. Authorized by the U.S. Congress in 2001, the PPII involves five projects that focus on technologies enabling coal-fired power plants to meet increasingly stringent environmental regulations at the lowest possible cost. Four projects have been completed and one is still active. The total value of these projects is $71.5 million, with DOE contributing $31.5 million or 44.6 percent.

The second program is the Clean Coal Power Initiative (CCPI), also patterned after the CCTDP. Authorized in 2002, the CCPI is a 10-year program having a goal of accelerating commercial deployment of advanced technologies to ensure that the nation has clean, reliable, and affordable electricity. Total Federal funding will be up to $2 billion, with a matching cost share by industrial participants of at least 50 percent. To date, two solicitations have been completed and nine projects have been awarded or are in negotiation. These projects have a total value of approximately $2.68 billion. The DOE share is $533 million or 19.9 percent.

The flue-gas flow rate from a furnace firing dry coal is lower than one firing wet fuel, and the specific heat of the flue gas is lower due to its lower moisture content. A lower flue gas flow rate also results in a lower rate of convective heat transfer. Therefore, despite an increase in initial flue gas temperature with drier fuel, less heat will be transferred to the water or steam in the boiler convective pass.

Drier coal is expected to lower the temperature of flue gas leaving the economizer and air preheater (APH). APH performance will also be affected by changes in the ratio of air and flue gas flows through the APH and changes in specific heat. Improved overall process efficiency will result from drier coal as the auxiliary power decreases due to decrease in forced draft, induced draft, and primary air fan power as well as decrease in mill power.

Previously, a number of proposals have been advanced to dry low-rank coals prior to combustion, but none of these efforts has resulted in a successful commercial operation. The two major problems with drying schemes before this have been the cost of the energy required and the fact that low-rank coals become pyrophoric when dried beyond a certain point. The Great River Energy Lignite Fuel Enhancement Project overcomes these problems by using waste heat to dry the coal and removing only about 25 percent of the moisture, enough to appreciably improve plant performance but not enough to cause handling problems.

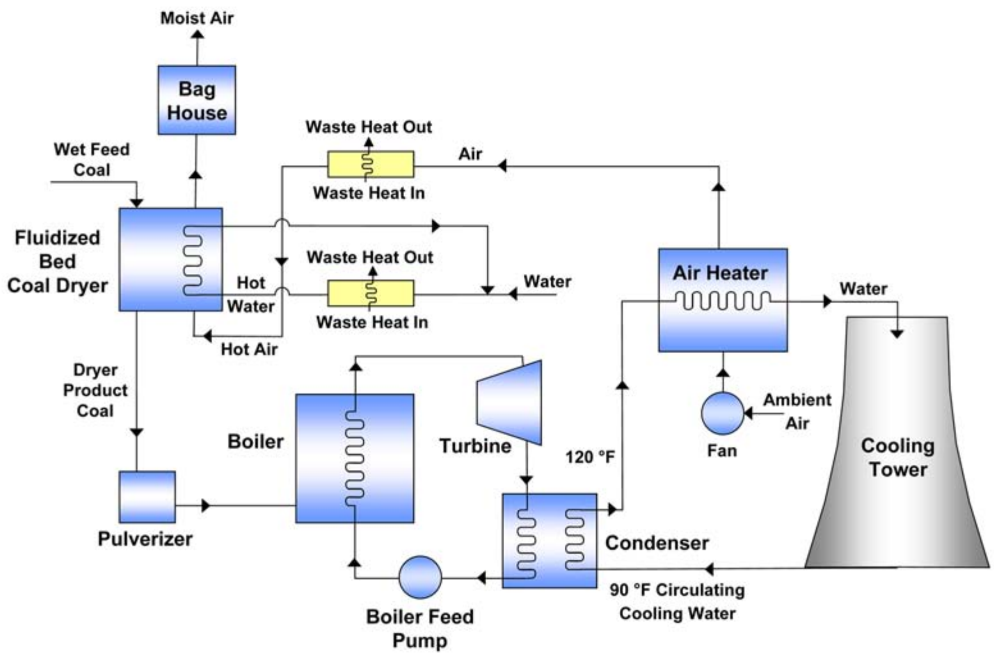
Aerial view of Great River Energy's Coal Creek Station lignite power plant

Project Objectives

The objective of this project is to demonstrate an economic process of moisture reduction of lignite, thereby increasing its value as a fuel in power plants. The project is being conducted at the Great River Energy's Coal Creek Station in Underwood, North Dakota. The demonstration activities focus on using low grade condenser waste heat and flue gas in the plant to lower the moisture content of the coal by about 10 percentage points (e.g., reduce the lignite moisture from 40 to 30 percent). A phased implementation is planned: In the first phase, a full-scale prototype dryer module was designed for operation of one of the pulverizers on one of the two 546 MW units at the Coal Creek Station.

The objectives of prototype testing were to gain operating experience, confirm pilot results, and determine the effect of air flow rate, bed coils, bed depth, and coal feed rate on dryer operation in order to optimize performance. The lessons learned from the prototype were incorporated into the design of the dryers being installed in the second phase. A total of four dryers will be built for Unit 2. Although operating with wet lignite requires seven pulverizers, six will provide all the dried lignite required by the boiler.

Following successful demonstration in the first phase, Great River Energy is designing and constructing a full-scale, long-term operational test on a complete set of dryer modules needed for full power



Schematic of Lignite Coal Drying Using Waste Heat From Condenser Water and Flue Gas

operation of one 546 MW unit (four dryers). The coal will be dried to a number of different moisture levels. The effect of coal drying on plant performance will be measured with respect to increase in plant efficiency and availability, reduction in emissions, and improvements in plant economics. The dryer design and operating conditions will be determined for optimal plant performance.

Project Description

In response to the first round of the Clean Coal Power Initiative, Great River Energy (GRE) submitted a proposal for a full-scale test of a lignite-drying technology that they had been developing since the 1990s. The previous work included bench-scale research and development, field trials, and preliminary drying studies. These studies convinced GRE of the technical feasibility and economic benefits of lignite drying and prompted the submittal of their proposal. The Department of Energy evaluated and selected their proposal, and a cooperative agreement was awarded on July 9, 2004.

The project team for the Lignite Fuel Enhancement Project consists of GRE, participant and site provider; the Electric Power Research Institute, collaborator; Lehigh University, collaborator; Barr Engineering, lignite handling; and Falkirk Mining and Couteau Properties, lignite supplier. The project is sited at GRE's Coal Creek Station in Underwood, North Dakota. Coal Creek Station is a mine-mouth plant, burning approximately seven million tons of lignite per year and consisting of two 546 MW, tangentially fired Combustion Engineering boilers. Steam is produced at 2,400 psig and 1,000 ºF with a 1,000 ºF reheat temperature. The Coal Creek station has eight pulverizers per unit (seven active and one spare). The station has two single reheat General Electric G-2 turbines.

The figure at left provides a simplified flow diagram of the lignite drying process. Warm cooling water from the turbine exhaust condenser goes to an air heater where ambient air is heated before being sent to the fluidized bed-coal dryer. The cooling water leaving the air heater is returned to the cooling tower. A separate water stream is passed through coils in the fluidized bed-coal dryer (a two-stage dryer is used to enhance heat transfer). The purpose of these coils is to provide additional heat to the fluidized bed to reduce the amount of air required. The dried coal leaving the fluidized bed is sent to a pulverizer and then to the boiler. Air leaving the fluidized bed is filtered before being vented to the atmosphere.

The technical aspects of the project are being implemented in two phases. The first phase involved the construction and operation of a prototype dryer, a full-sized dryer with a maximum capacity of 112.5 tons/hour (225,000 lb/hour). It was designed to reduce the moisture content of lignite from 38 percent to 29.5 percent and improve the higher heating value from 6,200 Btu/lb to 7,045 Btu/lb. The prototype unit was fully automated and integrated into the plant control system. The first coal was introduced into the prototype dryer on January 30, 2006, and performance testing was carried out in March and April 2006.

Benefits

Firing drier coal results in improved boiler efficiency and unit heat rate, primarily due to lower stack loss and lower auxiliary power (lower fan, pulverizer, cooling tower, and coal handling power). This performance improvement will allow greater electrical output with existing equipment. Performance of back-end environmental control systems (scrubbers and electrostatic precipitators) will also improve with drier coal due to the lower flue gas flow rate and longer residence time. The reduction in required coal-flow rate and modified temperature profile will directly translate into lower emissions of NO_X, carbon dioxide (CO_2), SO_2, and particulates. For units equipped with wet scrubbers, mercury emissions resulting from firing drier coal would also be reduced. This is due to reduced APH gas outlet temperature, which favors the formation of mercuric oxide and mercuric chloride at the expense of elemental mercury. These oxidized forms of mercury are water-soluble and can therefore be removed in a scrubber.

During testing of the prototype coal dryer in 2006, at a feed rate of 75 tons/hour (14 percent of total fuel rate to the 546 MW unit), there were no major operating problems. The moisture of the total coal was reduced by only about 1.1 percentage points. Yet there were significant benefits in the prototype dryer operation for the 546 MW unit.

Performance measures showed that the lignite flow rate was reduced by 2 percent, pulverizer power was reduced by 3.3 percent, boiler efficiency improved 0.5 percent (absolute), net unit heat rate improved 0.5 percent, NO_X emissions decreased 7.5 percent, and SO_2 emissions decreased 1.9 percent. These results indicate that there will be significant improvements in operations once the project is fully implemented.

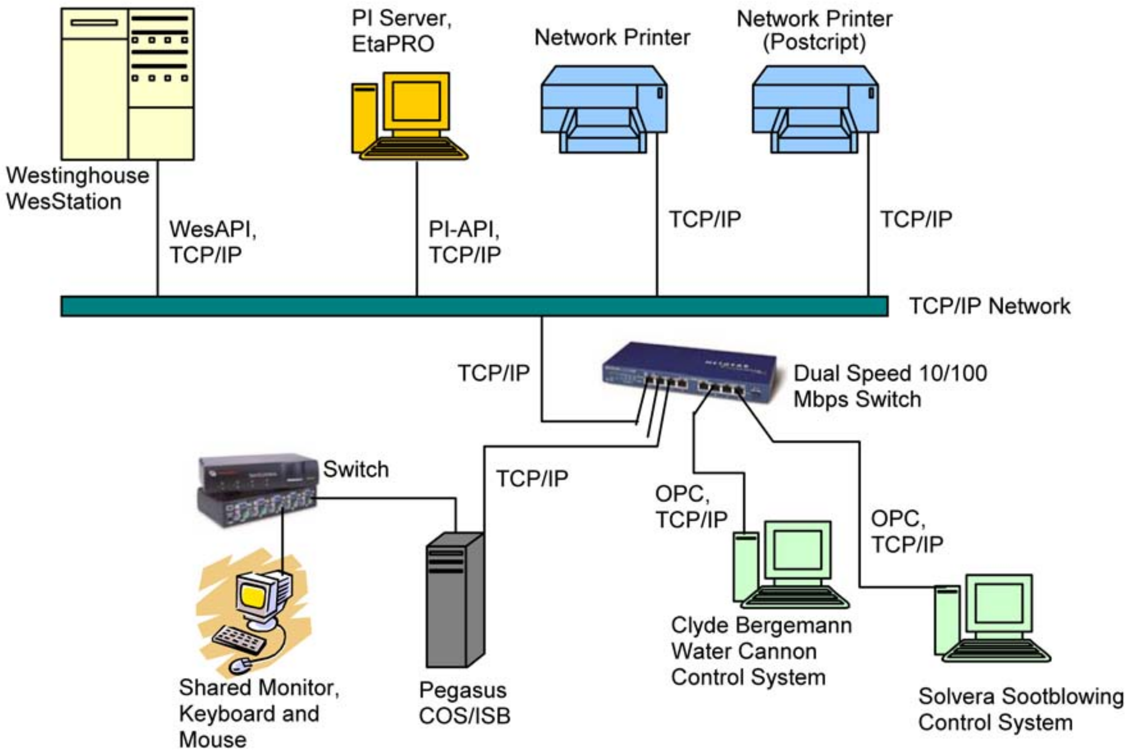
The potential market for GRE's coal-drying technology is quite sizeable. There are 29 units with a total capacity of 15.3 gigawatts (GW) that are burning lignite directly, and another 250 units with a total capacity of over 100 GW burning Powder River Basin coal. If all these units were to adopt coal drying, the economic and environmental benefits would be quite large.

Neural Network Intelligent-Sootblower Optimization Project

Introduction

A neural-network-driven computer system offers the potential to optimize sootblowing in coal plant boilers, reduce NO_X emissions, improve heat rate and unit efficiency, and reduce particulate matter emissions. Installed at the Tampa Electric Company (TECO) Big Bend Power Station in Hillsborough County, Florida, the Pegasus Technologies neural network-intelligent sootblowing (NN-ISB) system was designed to be used in conjunction with advanced instrumentation and water cannons to prevent soot from building up in a boiler. Of the four coal-fired units at the power station, Unit No. 2 was selected for installation of the NN-ISB control system. Fired with bituminous coal, this wet bottom pressurized Riley Stoker single-drum radiant boiler has a total of 48 coal nozzles on a single elevation, 24 on each side, firing toward the center line of the furnace. The final project cost for the NN-ISB control system (equipment/instrumentation, software, testing, and reporting included) was $3.4 million, including a 27 percent Department of Energy (DOE) cost share. Software costs of a few hundred thousand dollars were a small part of the total cost. Project testing of the NN-ISB was completed in December 2004, and the final report on the system was issued in September 2005.

Tampa Electric Big Bend Power Station



Communications Architecture at Big Bend Power Station

Project Objectives

The project objective at the Big Bend plant was to develop a neural-network-driven system that could initiate, control, and optimize sootblowing in response to real-time events or conditions within the coal-plant boiler rather than relying on general rule-based protocols. The project demonstrated and assessed a range of technical and economic issues associated with the sensing, management, display, and human interface of sootblowing goals as they relate to emissions and efficiency of a coal-fired utility boiler. Specifically, this optimization process targeted reducing baseline NO_X emissions by up to 30 percent, increasing unit efficiency by 2 percent, and reducing particulate matter (stack opacity) by 5 percent.

Project Description

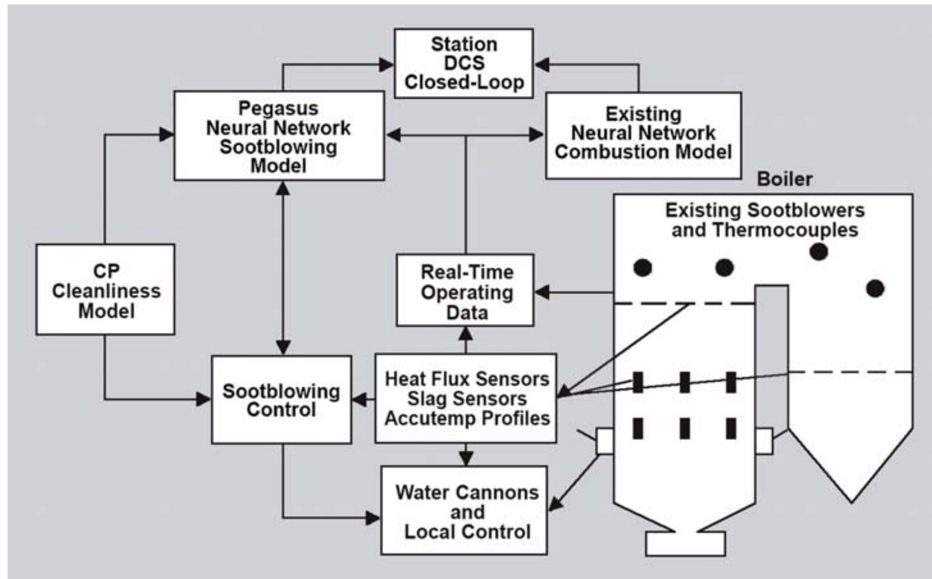
This neural network project was implemented under the Power Plant Improvement Initiative (PPII), a DOE program designed to demonstrate plant improvement technologies and processes in commercial settings. At the time of the award, this installation was the first domestic project to use neural network technology to optimize the sootblowing process within a boiler. Started in 2001 after a series of brownouts and blackouts had plagued major regions of the country, the initiative targeted new technologies that could help coal plants boost their output and improve their environmental performance. The Big Bend project was designed to be a full-scale demonstration of the neural-network-driven technology on a large commercial boiler, using state-of-the-art controls and instruments to optimize boiler operation and systematically control boiler slagging and fouling.

In a coal-fired boiler, the continuing buildup of ash and soot on the boiler tubes leads to reduced boiler efficiency. If periodic ash and soot removal (sootblowing) is not performed, this leads in turn to higher flue gas temperatures and ultimately to higher NO_X formation and reduced efficiency. Therefore, cleaning the heat-absorbing surfaces is one of the most important boiler auxiliary operations. Typically, sootblowing uses mechanical devices for online cleaning of fireside boiler ash and slag deposits on a periodic basis. Sootblowers clean by directing steam or water through nozzles against the accumulated soot and ash on the heat-transfer surfaces in order to remove the deposits and maintain heat-transfer efficiency. Basically, sootblowers consist of four components: a tube or lance that is inserted into the boiler and carries the cleaning medium, nozzles in the tip of the lance to accelerate and direct the cleaning medium, a mechanical system to insert or rotate the lance, and a control system.

Because it either uses steam that would otherwise be used to generate electric power or it requires energy for pumps or compressors, sootblowing has a direct impact on plant efficiency. Thus, optimizing sootblower operation is important in maximizing unit efficiency. Typically, sootblowers operate on a specified timed cycle or, alternatively, operation is initiated by an operator who believes sootblowing is needed. The purpose of an "intelligent" sootblowing system is to decide when to sootblow based on information from boiler instruments. The overall objective is to sootblow when, and only when, necessary.

The Pegasus Technologies NN-ISB control system uses a neural network to model the characteristics of the boiler. Designed to recognize patterns in input data, this network must be "trained" using historical data before it can associate a particular pattern with a corresponding plant state. Once this training has been completed, the system can respond rapidly to new inputs. An advantage of a neural network is that if any inputs are faulty the prediction capability degrades only gradually compared to most other modeling techniques.

The project installed at Big Bend Unit No. 2 includes 16 heat flux sensors, 8 slag sensors, a heat transfer advisor, acoustic pyrometers, a sootblower control system, an online performance monitor (OPM), and an advanced calibration monitor (ACM). For the communications layout, the combustion optimizing system and intelligent sootblowing (ISB) software were loaded into one computer. For this application, the models were partitioned so they could function separately or work interactively. This approach was important since it permits upgrades to existing power plants as well as applications to new boilers. Although the demonstration was carried out on the hardware and software systems developed for this project, the equipment (including the distributed control system) could be obtained from any manufacturer.



Pegasus Technologies NN-ISB Control System

After verification that the core elements of the NN-ISB system were satisfactorily installed and operational, detailed model tuning was completed. During this task, the unit was operated under a variety of conditions, including some non-ideal variations. This helped to define acceptable operating limits and constraints used by the neural network while optimizing the system.

During system optimization, appropriate adjustments were made to allow the system to "learn" and to make recommendations on Unit 2 operation, including both manual or advisory (open-loop) and automatic (closed-loop) operation. The advisory mode provided recommendations to the operators and engineers, who used those results to further tune the system. This activity also proved very valuable in assessing and recording the performance and status of the new sensors and systems.

NRG Texas's Limestone Power Plant in Jewett, Texas

Results

The automated closed-loop activation of the sootblowers during this project confirmed that neural-network, adaptive sootblowing can benefit efficiency. There was a clear improvement at low loads, with the benefit decreasing as the load increased. During closed-loop operation of the NN-ISB, Pegasus reported that efficiency gains were in the range of 0.1 to 0.4 percentage points compared to baseline. Results with open-loop operation were slightly lower. With more operating experience, gains at the high end of the load range should be achievable.

NN-ISB closed-loop (automatic) operation was shown to be better than open-loop (non-neural network baseline) operation. Other Pegasus results indicated an improvement of 1.0 to 1.5 percent in opacity for closed-loop compared to open-loop operation during certain tests.

While it is reasonable to expect that optimizing sootblowing would be beneficial for NO_X reduction (due to an improved temperature profile in the furnace), the Big Bend project was unable to clearly demonstrate this. Supporting equipment and material issues (e.g., unavailability of the water cannons during the NN-ISB tests, underperformance of much of the instrumentation) greatly limited the optimization software from performing as expected.

Prior to this project, sensors and controls related to sootblowing were usually treated as isolated systems. In contrast, the Big Bend NN-ISB system had the ability to understand, evaluate, and optimize the process as an entire system with multiple, real-time objectives. Integration of the sensors went well and communication was established to the neural network system with all sensors and elements of the project. The project demonstrated that such systems can be linked together despite the use of proprietary networks. Further, it confirmed that the sensors can provide data that can be correlated to achieve a set of objectives. Generally, the NN-ISB system appears to have merit and can improve boiler performance.

Conclusions

The major conclusion from this project is that the Pegasus Technologies NN-ISB control system is a sound idea with significant potential. The Big Bend project successfully demonstrated a neural network, closed-loop operation on a full-scale boiler without causing unit upsets or violating any constraints—and it also achieved operator acceptance. The NN-ISB appears to provide generating companies with an integrated solution that will assist in optimal economic and environmental real-time, online operation of a unit.

The NN-ISB is modular in design and can be readily applied to a variety of power generating units. The solution architecture and infrastructure are designed to allow full or staged deployment, depending on the needs of the generating company. The technology applied throughout allows unit flexibility (i.e., existing systems can be integrated within the overall solution) and is extendible (new modules/new equipment can be readily modeled and incorporated).

In general, the project provided a testing ground for several innovative measurement devices and feedback on their operation that may also lead to improved instruments. Since some equipment and instrumentation (e.g., water cannons, heat flux sensors, slag sensors, and acoustic pyrometers) did not fully operate as expected during this testing, an additional project with improved equipment and instrumentation may be needed in order to fully quantify all the benefits. Other project goals were also achieved:

- Promoted the use of coal by making coal more fuel-efficient automatically, reducing all pollutants on a per megawatt-hour basis. In addition, reducing NO_X emissions should lower the resistance to coal use for electrical generation.
- Enabled rapid deployment into the market. All coal-fired boilers employ sootblowers which, in turn, require control systems. Since current systems cannot achieve the desired results in sootblowing operations, a neural network control system appears to offer significant advantages. Further, no new hardware needs to be developed since the hardware is "off the shelf" and readily available.
- Expanded U.S. revenues through world-wide market acceptance. The same rapid deployment capability and acceptance by domestic plants should apply to offshore coal-fired boilers. Since the United States is presently the world leader in AI (of which the neural network system is a subset) there should be minimal competition from offshore suppliers.

In summary, the project provided valuable information on neural networks and the positive results should encourage other power plants to install these systems to control sootblowing, improve boiler efficiency, reduce NO_X emissions, and improve other aspects of their operations. Although equipment and instrumentation issues may have precluded the NN-ISB project from achieving all of its goals, the project clearly demonstrated the validity of using AI to control a major aspect of boiler operation.

NRG's Limestone Power Plant

Mercury Specie and Multi-Pollutant Control Project

Introduction

Implemented under the CCPI, the project at the NRG Texas (formerly Texas Genco) Limestone Power Plant in Jewett, Texas, is designed to demonstrate the capability to optimize mercury speciation and control emissions from an existing power plant. NRG Texas, with a generating capacity of more than 14,000 MW, has plants primarily based on fossil fuels and is an important producer of electricity in Texas.

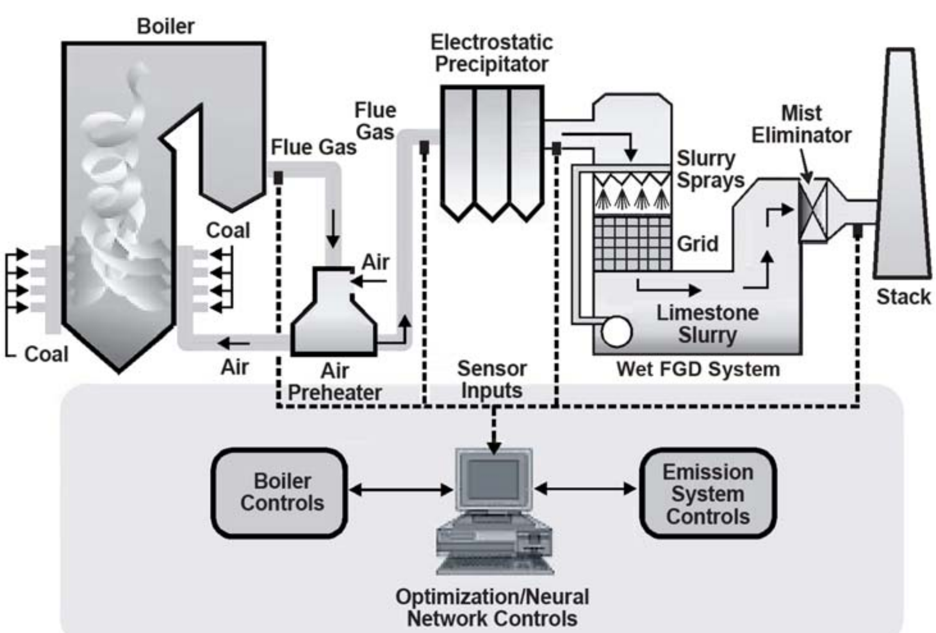
Performed by Pegasus Technologies, Inc., a division of NeuCo, Inc., this demonstration is occurring on an 890 MW utility boiler that uses 14,500 tons of coal per day. The Pegasus technology provides plant operators with the ability to assess detailed plant operating parameters that affect mercury capture efficiency, overall heat rate, particulate removal, and flue gas desulfurization (FGD) efficiencies. These data are also provided to a neural network optimization system that controls plant subsystems to provide the lowest possible pollutant emissions, highest heat rate, and least risk of environmental non-compliance, all with minimal capital expenditure.

Once demonstrated, this technology is anticipated to have broad application to existing coal-fired boilers and a positive impact on the quality of saleable by-products such as fly ash. The project began in April 2006, with performance testing targeted for December 2008. This estimated $15.6 million project will be 38 months in duration, with a DOE cost share of 39 percent.

Project Objectives

On a large utility coal-fired boiler, Pegasus Technologies is demonstrating the ability to affect and optimize mercury speciation and multi-pollutant control using non-intrusive advanced sensor and optimization technologies. Plant-wide advanced control and optimization systems are being integrated into a coal-fired, steam electric power plant in order to minimize emissions while maximizing the efficiency and by-products of the plant. Advanced solutions utilizing state-of-the-art sensors and neural-network-based optimization and control technologies are being used to maximize the portion of the mercury vapor in the boiler flue gas that is oxidized or captured in particle and chemical bonds, resulting in lower uncontrolled releases of mercury.

This neural-network-based control and optimization system gathers data from coal composition, combustion gas composition, mercury species, feed rates, etc., and uses this information to optimize power plant operations. The greatest advantage of neural networks in power plants is their ability to generalize from previous information and develop possible similar patterns for future use. Such intelligent control is expected to improve mercury capture by over 40 percent, reduce NO_X emissions by 10 percent, reduce fuel consumption by 0.5 to 2.0 percent, and improve operating flexibility.

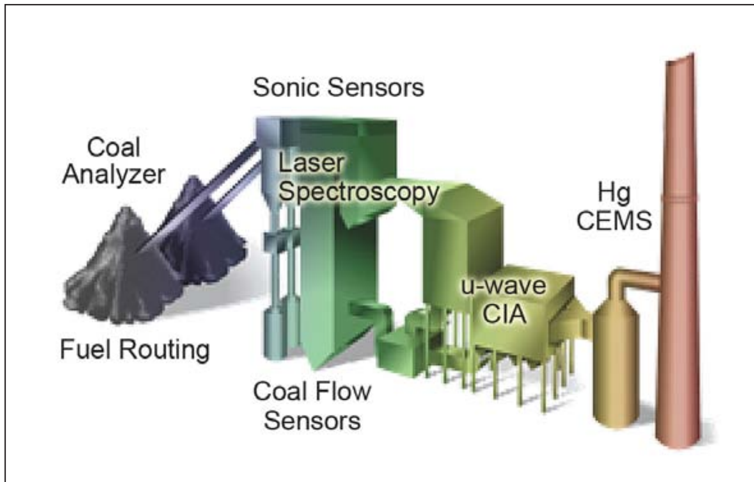


Control System Schematic for NRG Texas Limestone Power Plant

Project Description

The estimated 48 tons of mercury emitted annually by domestic coal-fired power plants is about one-third of the total amount of mercury released annually from all human activities in the United States. Mercury emissions take a number of chemical forms—or species—including the pure element, as part of a gaseous compound, or bound to particulates in flue gas. Certain mercury species, such as mercury that is adsorbed onto fly-ash particles or bound in the FGD, are relatively easy to remove from flue gas. Adjusting certain parameters during combustion can optimize the speciation process and maximize the mercury captured in particle bonds. This results in greater capture of mercury and lower uncontrolled releases.

The NRG Texas demonstration power plant is equipped with a tangentially-fired boiler that uses a blend of 70 percent Texas lignite and 30 percent Powder River Basin subbituminous coal, which are known to emit relatively high levels of elemental mercury under routine combustion conditions. Pegasus Technologies will apply sensors at key locations to evaluate the mercury species (elemental and oxidized mercury), develop optimization software that will result in the best plant conditions to promote mercury oxidation and minimize emissions in general, and use neural networks to determine the optimization conditions.



Key locations where sensors will be applied to evaluate mercury species

The unit is equipped with a cold-side ESP rated at approximately 99.8 percent particulate removal efficiency and a wet limestone FGD system rated at approximately 90 percent SO_2 removal efficiency. Both devices are capable of high mercury-capture efficiency, especially when the mercury is in an oxidized state rather than an elemental vapor state.

Using a neural network to affect and optimize mercury speciation and multi-pollutant control, the non-intrusive advanced sensor and optimization technologies will act as a highly trained operator, making decisions on inputs to the process by measuring and learning the outputs. By using AI and simulation technologies, Pegasus will minimize the use of raw material resources and pollutant emissions while simultaneously optimizing the operating capabilities of the plant.

This project involves the installation and demonstration of sensors and optimization software in six separate technology packages. While the modular design is transparent to this project, it is important to the future marketing of this system because of the flexibility needed with utilities to include or exclude a particular module based on either the existing equipment or budget for a specific plant. Many of the sensors and optimizer technologies that will be installed are utilized across the modules; therefore, they have been included under the module in which they are most used. The technology packages for this project include the following:

- The intelligent fuel management system (FMS): The FMS is composed of the Pegasus Combustion Optimizer system, the Ready Engineering CoalFusion™ system, and a Sabia elemental analyzer.
- The mercury specie control system: This system includes the boiler area optimization, Pegasus virtual online analyzers, and various sensors. Mercury emissions will be measured through continuous emission monitors.
- The advanced ESP optimization system: The ESP optimization system is composed of a carbon-in-ash virtual online analyzer, a carbon-in-ash sensor, and Pegasus ESP optimization software.
- The advanced ISB system: The ISB system is made up of Pegasus ISB software. This module has been previously demonstrated.
- The advanced FGD optimization system: The FGD System is composed of Pegasus FGD optimization software.

- The intelligent plant (unit optimization): This is the Pegasus i-Plant Optimization System that will contain a simulator and will arbitrate among the solutions for the above systems. This system will interface with users through a commercially available computer.

Each technology package includes non-intrusive sensors and the appropriate software needed for data acquisition, optimization, and integration with the overall neural network. In using this approach, all facets of coal-fired power plant operation will be optimized by balancing the inputs and outputs of the plant within a realm of multiple constraints. The intended result is to improve the efficiency of plant operations while operating within regulatory and commercial constraints.

During the first of three performance phases, sensor installation, software system design, and baseline operating metric testing will be completed. Instruments or instrument technology packages to be installed include a coal elemental analyzer (part of the fuel management system), mercury sensors, coal flow sensors, laser-based furnace gas speciation sensors, online carbon-in-ash sensor (located in the ESP), communications links for data acquisition and control, and related computers, controllers, and Pegasus optimization products.

Baseline testing will be performed to establish comparative data for the operational testing that will follow in Phase 3. After initial baseline testing, parametric testing will be performed to exercise various combinations of control variables to determine their effect on mercury speciation and by-product generation and to determine overall plant performance. These data will be used in Phase 2 to adjust the neural network for optimization control.

During Phase 2, software installation, data communications modification, and distributed control system modification will be achieved. The test plan data and historical data (if applicable) will be evaluated to confirm that no irregularities exist prior to model development. After extraneous data (e.g., calibrations) are eliminated from the data set, operating issues and constraints will be reviewed as part of further model development. Control models will be developed to characterize the effect of control variables on the operational characteristics of the boiler, mercury speciation, and by-product generation. Models will be created that accurately and robustly represent the effects that changes in the unit have on the outputs to be optimized. Before the control models are implemented in an online system, offline simulation will be performed. The models will then be evaluated and demonstrated to Limestone Power Plant operators and engineers so their input can be used to finalize the behavior of the models.

Pegasus uses pre-designed and custom methods for constraining the models under various design and operational limitations. These are dynamic constraints that fluctuate with load, number of burners in service, rate of change, etc. After the initial modeling is completed, a shorter series of tests will be conducted. These will involve setting up operational parameters to verify the predictive capabilities of the neural network model and to assure that the model has been properly trained. During this period, the models will be coarse-tuned. Control loops will first be tested one at a time and then as groups to deal with the individual loop characteristics before dealing with the interactive characteristics.

At the end of Phase 2, a decision will be made whether to initiate work under Phase 3 or to conclude the project after the successful demonstration of closed-loop operability for neural networks and controllers.

Phase 3 plans include demonstration and validation of all systems as well as a comparison of the test results with the project objectives. Extended mercury and multi-pollutant testing will be conducted. The technology packages—the fuel management system, combustion and mercury control system, ESP system, ISB system, FGD system, and intelligent plant (i-Plant) system—will all be demonstrated during closed-loop operation. Operator and engineering training will also be conducted during Phase 3.

Anticipated Benefits

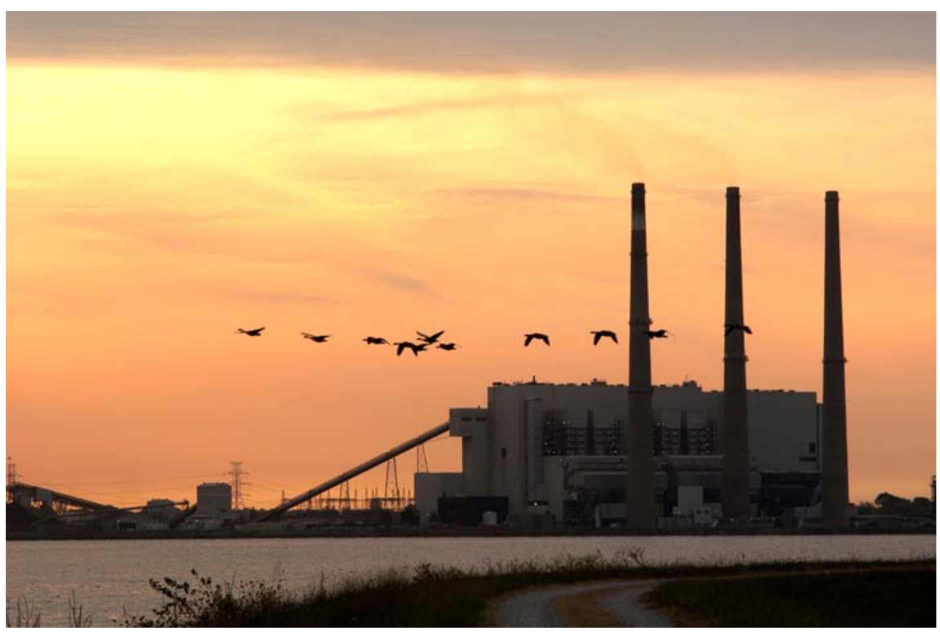
In this project, Pegasus Technologies and NRG Texas are attempting to put together all of the required best-of-class artificial intelligence and simulation technologies to prove that mercury speciation and multi-pollutant reduction benefits can be measured, optimized, and controlled. If successful, Pegasus will demonstrate the capability of sophisticated control processes and advanced sensor technologies to simultaneously reduce harmful emissions of mercury and increase plant efficiency. Increased control of SO_2, NO_X, and particulate matter should also result, along with a reduction in water usage. Since these technologies are designed to control and optimize all major facets of power plant operations, the demonstration is expected to provide the capability to maximize plant efficiency for electricity production while reducing mercury emissions. This project is also expected to address concerns that higher mercury concentrations in existing by-products, such as ash, may adversely affect the commercial value of those by-products.

This project should demonstrate an operating environment that simultaneously offers higher-than-average compliance with environmental requirements and better control of emissions, resulting in both a smaller risk of non-compliance to the utility and minimization of capital expenditures. In general, the project is expected to demonstrate how integrating sensors and advanced controls into a total plant solution can lead to improved economics while being environmentally compliant. The technologies being demonstrated are expected to have widespread application since they can be directly retrofitted to the existing coal fleet or integrated into future new plant designs.

Demonstration of Integrated Optimization Software at the Baldwin Energy Complex Project

Introduction

As part of the CCPI, sophisticated computational techniques are being applied to an Illinois coal-fired power plant to show how new technology can increase power plant efficiency and reliability and reduce air emissions. NeuCo, Inc., of Boston, MA, is designing and demonstrating an integrated online optimization system at the Dynegy Midwest Generation power plant located in Baldwin, IL. The Baldwin Energy Complex (BEC) consists of two 585 MW cyclone-fired boilers with selective catalytic reduction (SCR) and a 595 MW tangentially fired boiler with low NO_X burners.



Dynegy Midwest Generation's Baldwin Energy Complex

The five system optimization modules being developed include cyclone combustion, sootblowing, SCR operations, overall unit thermal performance, and maintenance optimization. This project builds on the NeuCo proprietary ProcessLink® technology platform. Power plants operate in many different conditions and plant processes are highly complex and interrelated. The goal of optimization is to continuously assess and adjust (or provide actionable advice about) the settings of the many variables affecting plant performance so that the optimal balance of plant emissions, fuel efficiency, capacity, and reliability is achieved. The total cost of this 45-month project is estimated at $19 million, including a 45 percent DOE cost share.

The Baldwin Energy Power Plant at sunset

Project Objectives

The overall objective of applying integrated optimization software is to improve the emissions profile, efficiency, maintenance requirements, and plant asset life for coal-based power generation in order to extend the use of abundant coal resources in the United States in an environmentally sound manner. In general, software optimization offers several advantages to power plants, including the ability to control key parameters on a consistent basis, compensate for changes in coal quality, optimize controls to meet specific plant objectives, and help in understanding the available data and its use for improved operations. The project at BEC will demonstrate and quantify the environmental and emissions benefits associated with deployment of a fully integrated set of software solutions for optimization of plant performance for coal-fired power generation.

Because retrofits, repowering, modifications, and new technologies are steadily increasing the complexity of modern power plants, an integrated process-optimization approach is required to maximize equipment performance and minimize operating costs. Optimization solutions are now available for a variety of power plant control systems; linking these systems together will provide overall plant-level optimization that is expected to yield additional benefits.

Therefore, the primary objective of this project is to demonstrate integration of existing controls and control systems, sensors, and computer hardware with advanced optimization techniques at BEC and to link the individual optimization modules through the NeuCo ProcessLink® platform. Collectively, these modules are expected to provide optimization solutions for this 1,765 MW coal-fired power plant by reducing emissions, increasing plant efficiency, and increasing the availability of the plant for power generation.

Project Description

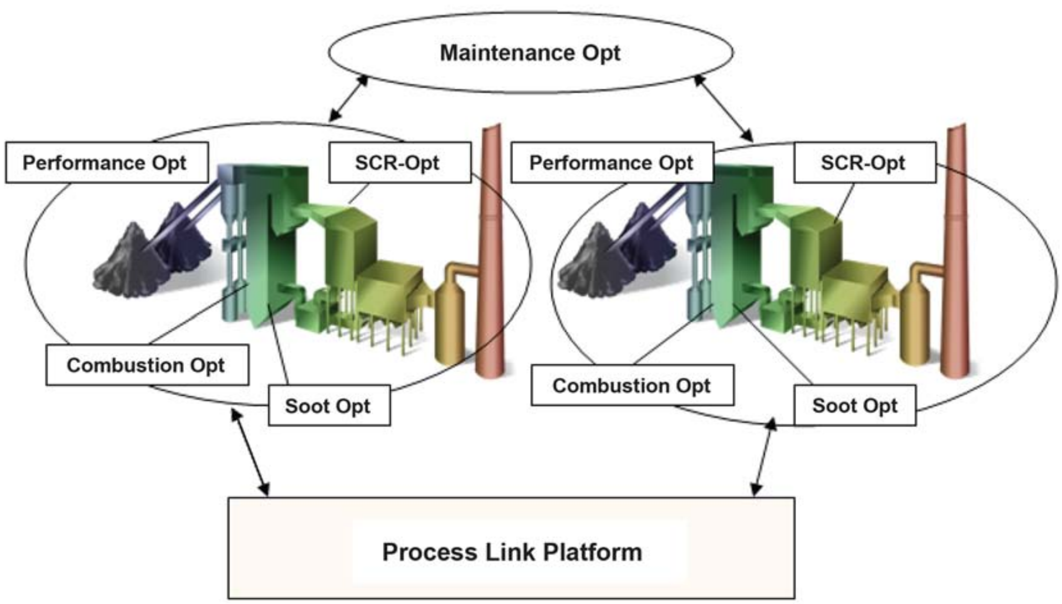
NeuCo is designing and demonstrating an integrated online optimization software system for the Dynegy Midwest Generation power plant using advanced computational techniques that are expected to achieve peak performance from the three coal-fired units at the energy complex. NeuCo is using its ProcessLink® technology platform of neural networks, expert systems (heuristics), first principle models, advanced algorithms, and fuzzy logic to maximize performances from the power plant combustor, soot removal system, and emission controls—the first time that all of these modules have been integrated into a computerized process network.

Five separate modules are being designed and demonstrated by NeuCo at BEC and then integrated to provide unified plant optimization.

- CombustionOpt® uses neural network-based optimization, model predictive control, and other technologies to extract knowledge about the combustion process, determine the optimal balance of fuel and air flows in the furnace, and respond to changing conditions. CombustionOpt directly adjusts the distributed control system to more consistently position the dampers, burner tilts, overfire air, and other controllable parameters at their optimal settings for given sets of conditions, objectives, and constraints. This module should reduce fuel consumption and NO_X emissions; it should also improve carbon monoxide control, reduce opacity, and improve loss on ignition.

Control Room at the Baldwin Energy Complex

- SootOpt® optimizes sootblowing to reduce adverse fouling conditions and unplanned outages that soot and sootblowing can cause. It also expands efficiency improvements, reduces emissions, and drives boiler-cleaning actions toward optimal plant heat rate, emissions, and reliability goals. The SootOpt adaptive neural network models identify the equipment and actions most effective for achieving plant efficiency, reliability, and emissions objectives, and then bias control activity toward those objectives. The neural models work within boundaries defined by expert rules to ensure all applicable unit-specific constraints are considered.
- SCR-Opt® uses neural-network-based optimization, model predictive control, and other technologies to make the operation of the SCR as efficient as possible. SCR-Opt is expected to minimize ammonia usage and reduce NO_X emissions.
- PerformanceOpt® uses a rigorous, first-principles-based thermodynamic model of the boiler and steam cycle to conduct both “what is” and “what if” simulations of unit operations. Continuously monitoring the actual versus the expected performance levels of key equipment and process



Planned Integration Concept for the Baldwin Energy Complex conditions, PerformanceOpt detects when performance deviates from what is achievable under current operating conditions and calculates the impact of that deviation so that remedial actions can be prioritized. PerformanceOpt is expected to improve heat rate, steam temperatures, and generating capacity.

- MaintenanceOpt™ helps engineers manage the entire life-cycle of reliability, capacity, and efficiency problems more efficiently and effectively. It uses neural network technology to constantly search for gaps between actual and expected behavior across a broad range of process and equipment health variables. Its powerful diagnostics knowledge base also helps to filter false alarms, determine the root causes and corrective actions of identified problems, and aid in problem resolution and tracking. MaintenanceOpt is expected to increase annual power output and assist in providing lower costs of electricity to the consumer.

These advanced computational capabilities will be used to comprehensively optimize a variety of systems within BEC by using existing control technologies and then linking these systems to each other. This innovative project will provide solutions that use system-specific optimization applications as data sources and actuators. In general, the overall architecture of this control platform is designed to permit flexible deployment strategies. Rather than requiring that all data and logic reside on a single computer, the service model allows applications to leverage networked computational resources. The application architecture is built around interoperable services that should result in more efficient plant operations. The planned integration concept is shown below.

This integrated optimization software project at BEC consists of two phases. Phase I, which has been completed, entailed the development and installation of initial versions of each of the five optimization modules, as well as their integration through the ProcessLink platform to address the full scope of plant operations and relevant system interactions.

Extensive operating experience will be required to quantify the benefits associated with control system optimization. The goal during Phase I was to establish each system and demonstrate its role in unified plant optimization. Phase I activities focused on developing, deploying, integrating, and testing prototypes for each of the five optimization modules; identifying and addressing issues required for the modules to integrate with plant operations; and systematically collecting and assimilating feedback to improve subsequent module releases.

The goal of Phase II is to improve upon the software installed and tested in Phase I and to perform rigorous analysis of operating data in order to quantify the benefits of the integrated system. Phase II entails quantification of results at BEC; refinement of the software installed and demonstrated in Phase I to support additional commercial releases of the five products; installation and beta testing at BEC; and commercialization of the solutions, taking into account both what is learned at BEC and feedback systematically incorporated from other operators of U.S. coal-fired power generation plants.

During both phases, best practices iterative software development methods will be applied toward integration, full-scale demonstration, and eventual commercialization of these five solutions. All system software engineering, applications engineering, and systems integration will proceed through a multi-step, iterative process that supports a structured, modular approach to determining software and hardware requirements and functional definitions along with various design, development, test, installation, and startup activities. This iterative development process is specifically designed to deploy a commercially viable product as soon as possible, while at the same time applying host-site feedback and what is learned toward maximizing functionality and benefits in subsequent releases.

Anticipated Benefits

This optimization initiative is expected to reduce NO_X emissions by 5 percent and increase thermal efficiency by 1.5 percent. The increased thermal efficiency is expected to reduce emissions of CO_2, mercury, and particulates. Ammonia consumption is expected to be reduced by 15 percent, accompanied by a one-year extension of the SCR catalyst. The optimization initiative is expected to also result in improved power plant capacity and reliability which, in turn, is expected to increase net annual electrical power production by 1.5 percent. Consumers should benefit through lower electricity costs.

The NeuCo ProcessLink® architecture offers plant operators a highly flexible control system platform. Optimization modules can be designed and applied to individual subsystems in a plant, leveraging existing sensors, actuators, and networked computational resources—and then linking them to other individual subsystems to provide overall plant-level integration of controls responsive to plant operator and corporate criteria. This integrated process optimization approach will likely be an important tool for plant operators as plant complexity increases through retrofit and repowering applications, installation of new technologies, and plant modifications.

Conclusions

The U.S. Department of Energy Clean Coal Technology programs continue to sponsor projects that develop technologies for optimizing power plant operation. These technologies help keep the cost of electricity low, reduce emissions, and conserve our fuel supply.

The **Lignite Fuel Enhancement** project demonstrates a technology that reduces the moisture content of low-rank coals, which results in a number of benefits to power plant operation. Coal consumption is reduced, thereby reducing CO_2 and other emissions. Parasitic power requirements are also reduced. When the technology is applied to new plants, capital costs will be reduced in several major subsystems, such as SO_2 removal, pulverizers, and cooling towers. This technology achieves these benefits using only waste heat to remove the moisture from the fuel.

While the **Neural Network-Intelligent Sootblower** project did not reach all of its goals, the NN-ISB control system was found to be a sound idea with significant potential. The project successfully demonstrated a neural network, closed-loop operation on a full-scale boiler without causing unit upsets or violating any constraints—and also achieved operator acceptance.

Although not yet completed, the **Mercury Specie and Multi-Pollutant Control** project and the **Demonstration of Integrated Optimization Software** project have demonstrated the ability of NN and AI technologies to provide significant economic, operational, and environmental benefits to power plant operation. The demonstrated technologies are applicable to all types of coal-fired boilers and do not require the purchase of major equipment. Given the benefits and relatively low cost, these types of technologies are likely to find a ready market.

The continuing development of software to control overall power plant operation, or selected aspects of it, has shown substantial progress in optimizing power plant performance. These software packages allow operators to more easily stay within their emission limits while improving power plant efficiency and lowering the cost of power production. While doing so, the participants have produced products that are expected to find a substantial market both in the United States and abroad.

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Acronyms and Abbreviations

ACM	Advanced calibration monitor
AI	Artificial intelligence
APH	Air preheater
BEC	Baldwin Energy Complex
CCPI	Clean Coal Power Initiative
CCTDP	Clean Coal Technology Demonstration Program
CO_2	Carbon dioxide
DOE	Department of Energy
ESP	Electrostatic precipitator
FGD	Flue gas desulfurization
FL	Fuzzy logic
FMS	Fuel management system
GRE	Great River Energy
ISB	Intelligent sootblowing
MW	Megawatt
NETL	National Energy Technology Laboratory
NN	Neural network
NN-ISB	Neural network-intelligent sootblowing
NO_x	Nitrogen Oxides
OPM	Online performance monitor
PPII	Power Plant Improvement Initiative
SCR	Selective catalytic reduction
SO_2	Sulphur dioxide
TECO	Tampa Electric Company

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