NeuCo, Inc.
Prudential Tower
800 Boylston Street, Floor 30
Boston, MA 02199
Phone: (617) 587-3100
Fax: (617) 262-4186

The Financial Benefits of Flexibility with Real-Time Asset Optimization

Author: Peter Spinney, NeuCo, Inc.

This paper describes and quantifies the ability of real-time, integrated boiler optimization to dynamically manage power generation operating and financial tradeoffs in a manner responsive to uncertain and volatile fuel, NOx allowance and carbon markets. The paper also explains that for a typical 375 MW coal-fired generating unit, integrated boiler optimization with the flexibility to shift priorities in response to changing market conditions provides an additional $6.7 million in benefits beyond the $22.7 million ten-year benefits that would be achieved through an optimization system that uses fixed priorities to address tradeoffs between NOx and heat rate improvement.

Introduction

Optimization is broadly defined as extracting the best result from a complex process while working towards objectives and within constraints. Real-time optimization software within the power industry applies artificial intelligence (AI) methods to mimic the biological learning processes that the brain uses to transform data into knowledge. These intelligent systems have the ability to learn, remember, adapt, prioritize and optimize in a complex environment.

Combustion optimization is the most pervasive application of real-time optimization software for power generation. Combustion optimization manipulates the fuel and air biases within the furnace to streamline the process of burning fuel to produce steam, thereby reducing NOx emissions and improving heat rate and operational consistency. This boiler application has been recently broadened to encompass boiler cleaning, which impacts the same objectives as combustion optimization and has a significant impact on unit availability, since forced outages are often caused by cleanliness-related tube erosion and ruptures. Compared with hardware-based alternatives and physical retrofits, optimization preserves existing assets, requires significantly lower capital investment and maintenance costs, minimizes installation lead time, and delivers a flexible solution platform that can accommodate changes in the relative priorities among existing operating objectives, as well as new ones as they arise.

While boiler optimization has been demonstrating its value for NOx reduction, fuel efficiency and availability improvements for more than ten years, the financial value of the flexibility afforded by the technology to shift between objectives has never been quantified. The highly uncertain regulatory, emissions allowance and fuel markets are increasing the financial value of flexibility. This paper quantifies the value of flexible-priority optimization solutions versus fixed-priority applications.

Holistic Optimization

While the utility generating term “boiler” refers to a seemingly simple process of converting water to steam, the boiler process is complex. Combustion quality, fuel and air mixing, gas and steam temperatures, and emissions controls are just a few of the interrelated variables that need to be continually managed for successful boiler operations. Fluctuating constraints and changing objectives add to the complexity.

Optimizing combustion or sootblowing alone produces benefits, but can leave operational and economic benefits on the table. For example, boiler cleanliness significantly impacts combustion processes, and combustion stoichiometry and temperatures affect ash build-up, fouling, and slag formation. Both affect opacity formation.

Integrated boiler optimization addresses these complex interactions in a holistic fashion to consistently achieve the best boiler performance under changing operating conditions.

Boiler Optimization

NeuCo defines boiler optimization as the integrated and coordinated optimization of combustion and boiler cleanliness toward global unit performance objectives pertaining to efficiency, emissions, and availability. The result is an economically optimal combination of steam temperature control, improved capacity and heat rate, and lower emissions. Importantly, these benefits are typically achieved while reducing total boiler cleaning actions, with an associated reduction in water wall erosion and attendant tube rupture-related outages, which represent by far the largest source of forced outages. Integrated boiler optimization allows power generators to minimize operating costs while maximizing reliability, commercial availability, and profitability. Integrating and coordinating combustion processes and boiler cleanliness is a prerequisite for the dynamic tradeoff management that this paper focuses on.

An integrated optimization system that uses expert rules and inductive neural network models to optimize combustion and boiler cleanliness is one of the most cost-effective methods to reduce NOx, and can reduce this emission by 10-25 percent. Boiler optimization can help power generators realize fuel savings and/or reliability benefits even when the monetary value of NOx reduction is negligible. Optimization's flexibility and capacity to shift priorities make this technology an excellent solution for increasingly stringent NOx regulations with uncertain timing.

Flexibility in Response to Uncertain Regulations and Fluctuating Fuel Prices

There a several dimensions through which optimization technologies provide flexibility, all with substantial financial value, particularly when viewed through the lens NOx and CO_2 compliance strategies.

A Cost-Effective NOx Solution

While current and anticipated regulations will require substantial additional NOx reduction in all US states and most Canadian provinces, much of the "low-hanging fruit" for reducing NOx has already been picked. Generators have chosen compliance solutions such as fuel switching, pollution control hardware and software, and buying excess allowances from companies that have reduced their emissions under cap and trade provisions. Many generators will face a difficult choice between adding SCRs to units previously seen as too small to justify such and investment; or buying allowances in a costly, uncertain, and volatile allowance trading market.

Integrated boiler optimization is one of the most cost-effective methods to reduce NOx. These solutions can be implemented and producing benefits in as little as 10-14 weeks. Combustion optimization streamlines the combustion process, resulting in lower NOx emissions by between 7.5% and 20%. Optimal boiler cleanliness obtained by closed-loop condition-based actuation of soot blowers, water lances and other boiler cleaning devices can reduce NOx by another 2.5-5% by correctly proportioning heat transfer and reducing "hot spots" that result from ineffective cleaning. These software solutions let the end user view and manage interactions between combustion processes and soot blowing systems, thereby minimizing conflicts between complex goals such as low NOx and steam temperatures. The decision about whether to take a hardware or software approach to meet emissions standards is not a mutually exclusive one. In fact, in many cases the best approach is a hybrid one.

SCR systems reduce NOx emissions, but often do so at the expense of efficiency, combustion degradation, reagent costs, and increased complexity of operations. Units with these post-combustion control systems gain additional benefits from boiler optimization. Integrated boiler optimization enables boiler controls to more closely match boiler outlet temperatures and NOx profiles to catalyst effectiveness and reagent distribution as they change over time. Boiler optimization allows plants with SCR or SNCR systems to reduce reagent (ammonia or urea) usage by 10 – 20 percent, reduce ammonia slip, minimize sulfur trioxide conversion, and recover the heat rate degradation associated with such systems.

Unlike NOx control hardware, integrated boiler optimization systems not only reduce NOx, but also improve fuel efficiency and reliability. So even without the ability to change priorities between objectives, fuel savings and/or reliability benefits will be achieved though optimization even when the monetary value of NOx reduction is negligible.

Historically, this flexibility has provided value via fuel savings and/or improved reliability for generating units operating in the Clean Air Act Amendments of 1990 (CAAA) State Implementation Plan (SIP) protocol, where the “cap” in the “cap and trade” program created by this legislation only applied to the five month “ozone season” comprising the warm months of the year where NOx creates the most ground level ozone. Under these existing regulations, NOx reduction would typically be the highest optimization priority during ozone season, and heat rate could be the highest priority during the off season, with the constraint that NOx be kept below some limit.

CAIR: A Whole New Source of Uncertainty

The Clean Air Interstate Rule (CAIR) is a formal Environmental Protection Agency (EPA) Administrative Mandate that is intended to codify into law many provisions first proposed as part of President Bush’s Clear Skies legislation. In addition to the 5-month “Ozone Season” – during which NOx caps and associated allowance trading applied to the 19 states included in the Clean Air Act Amendments of 1990 – the CAIR rule imposes a 60% incremental NOx reduction, expands the geographic scope to cover nine additional states, and layers on top of the existing 5-month market a separate 12-month cap and associated trading market. To place CAIR in historical perspective, regulations between 1970 and 2006 decreased US NOx levels by 41 percent. CAIR by contrast, required a 60 percent reduction in just six years (2009-2015).

In July 2008 The US Circuit Court vacated CAIR. This ruling was both a surprise and a problem for the industry, environmental interests, and emissions control suppliers alike. In late December, the Court decided to stay the overturn, which preserved CAIR regulations and the original Phase 1 implementation starting January 1, 2009, until a final ruling is made.

Despite CAIR's first phase being preserved, virtually all observers agree that Phase 2 requirements will be substantially more stringent than the original CAIR, and may well add CO2 and/or mercury as additional affected pollutants. By moving quickly to adopt optimization, generators can inform their near- and longer-term plans for meeting the new stricter regulations in the most cost-effective manner possible. In using optimization to learn how low NOx can go given each unit's existing hardware configuration, future plant or fleet-wide NOx control investments – such as the quantity and size of SCR, SCRs, and other low-NOx hardware – can be more effectively planned.

The Future of Carbon Regulations

Congress is considering several bills to regulate CO2 , but no federal legislation for CO2 presently exists in the US. Instead, individual states and areas of the country are governed by a patchwork of CO2 policies, with at least 29 states being covered under voluntary, regional, and/or state-level regulations. Many generators are already operating in liquid CO2 trading markets via the Regional Greenhouse Gas Initiative and/or the Chicago Climate Exchange. Whether a power plant is currently affected by these initiatives or not, the seeming inevitability of nationwide CO2 legislation is causing almost all power generators to grapple with their options for addressing this emission.

Currently, the only commercially available and proven method for power plants to reduce CO2 emissions is through improved efficiency. Integrated optimization allows plants to lower CO2 through improved efficiency (improved heat rate) while simultaneously managing other, often competing plant objectives. CO2 reductions are already being realized at plants using optimization, particularly ones using integrated boiler optimization. These solutions can improve heat rate in the range of one-to-three percent, which results in less coal consumption and reduced CO2. On average, each ton of coal burned generates roughly 2.75 tons of CO2, so a 2.5% percent heat rate improvement at a 350 MW plant burning 1.7 million tons of coal each year will avoid approximately 108,000 tons of CO2.

The highly speculative future of carbon trading markets is a large additional source of uncertainty, one will makes the flexibility of being able to switch back and forth between NOx and heat rate priorities even more valuable as such markets are implemented.

Dynamic Tradeoff Management

While boiler optimization provides numerous emissions, efficiency, and availability benefits, we focus here on minimizing NOx and heat rate and managing the tradeoffs between the two, since these benefits are common to all units and are the most readily monetizable. With respect to NOx, boiler optimization is intrinsically more flexible than most approaches to NOx reduction, since it also provides simultaneous heat rate improvement, in addition to a variety of other benefits (e.g. reduced unnecessary boiler cleaning actions and associated tube failure outages, better control over opacity, avoided slagging, reduced process variability, etc.). Both NOx and heat rate are easily quantified, and the monetary value of both efficiency improvements (whether including CO2 or just fuel costs) and NOx reduction depends on commodity markets that are both uncertain and volatile.

Boiler optimization's ability to vary the priority accorded to different objectives based on their monetary value and/or operational importance compounds the total benefits by minimizing operating costs in the face of uncertain and volatile fuel and allowance markets.

Using Financial Theory to Monetize Flexibility

To illustrate this benefit, we apply a simple form of "real options" analysis to monetize the incremental benefits associated with an optimizer with the flexibility to manage the tradeoffs between NOx reduction and heat rate reduction as conditions evolve, as opposed to one employing a fixed relationship in the priority between these two objectives.

Real options analysis uses financial theory in the form of decision analysis and/or stochastic simulation to quantify the benefits of flexibility in the face of uncertainty and volatility. The ability to respond to unknown future market conditions in securities transactions sometimes takes the form of a "put" or a "call" based on some pre-specified price threshold; more sophisticated mechanisms index the return on an investment related to an index (such as inflation or commodities prices) thought to correlate with the future value of the investment instrument itself.

In the same manner that financial instruments (often referred to as "options") can hedge risks in securities or other financial markets, real options theory allows the inherent flexibility of certain capital assets to be monetized. Recent developments have revealed some severe shortcomings in some of the financial instruments formerly believed to manage risk, but these issues have more to do with the lack of transparency in the complex, layered, multi-party transactions that obscured underlying risks associated with providing mortgages to people that could not afford them and/or based on the premise that housing prices would continue increasing over the life of the mortgages.

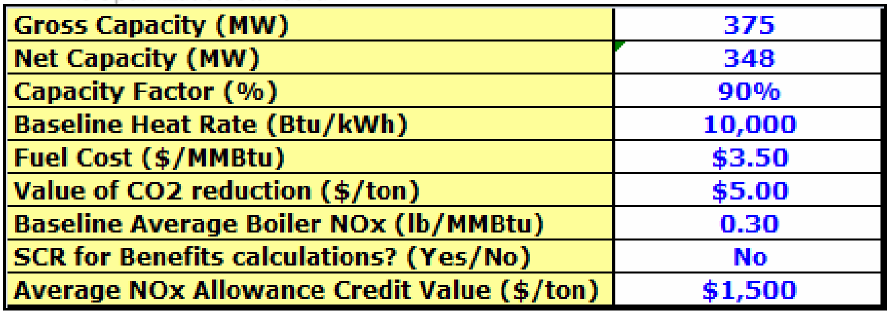
The risk management approach discussed here is much simpler and more fundamental, embodying the ability for integrated optimization of the processes that together have the biggest impact on NOx and heat rate, i.e. combustion and boiler cleanliness.

For the simple analysis, we examine the heat rate and NOx reduction benefits for a 375 MW coal-fired unit over 10 years where both applicable coal and NOx allowance prices vary stochastically and independently of one another, with levels of volatility for each roughly approximating historical price behavior in both spot coal and SIP NOx allowance markets.

Illustrative Case Study: Fixed vs. Dynamic Tradeoffs

Two cases are compared: one with a boiler optimization system that uses a fixed priority where reducing NOx and heat rate are of equal importance; the second where such an optimization system can dynamically alter the relative priority between these two objectives on the basis of their respective value in any given year.

The basic assumptions describing the operating characteristics of this illustrative coal-fired generating unit are shown below in Table 1.



Gross Capacity (MW)	375
Net Capacity (MW)	348
Capacity Factor (%)	90%
Baseline Heat Rate (Btu/kWh)	10,000
Fuel Cost ($/MMBtu)	$3.50
Value of CO2 reduction ($/ton)	$5.00
Baseline Average Boiler NOx (lb/MMBtu)	0.30
SCR for Benefits calculations? (Yes/No)	No
Average NOx Allowance Credit Value ($/ton)	$1,500

Table 1. Illustrative 375 MW Coal-Fired Generating Unit

Note that this generating unit has a heat rate, baseline boiler NOx, and fuel costs typical of a medium-sized coal-fired boiler burning eastern bituminous coal. We assume that the unit is not equipped with an SCR, in which case the primary NOx benefits would take the form of required ammonia as opposed to NOx allowances. Note that ammonia prices have undergone steep price increases in recent years. While the level of uncertainty is not likely to be as great as that associated with NOx allowance markets, the same principles apply.

The expected performance improvements, expressed in percentage change, for heat rate and average boiler NOx, as well as the associated annual savings for fuel, CO_2 (reduced proportionally to heat rate) and NOx allowances are shown in Table 2. Some of the operating assumptions from Table 1 are repeated in order to make the calculated benefits more obvious.

1	Gross Capacity (MW)	**375**
2	Net Capacity (MW)	**348**
3	Capacity Factor (%)	**90%**
4	Annual Output (MWh/y)	2,740,676
5	Baseline Heat Rate (Btu/kWh)	**10,000**
6	Annual Heat Input (mmBtu/yr)	27,406,755
7	Fuel Cost ($/MMBtu)	**$3.50**
8	CO2 Output (tons/yr)	2,898,791
9	Annual Fuel Cost ($/yr)	$103,477,500
10	Heat Rate Improvement (-%)	**-0.675%**
11	Annual Fuel Savings	**$699,637**
12	Value of CO2 reduction ($/ton)	**$5.00**
13	Annual CO2 Reduction (tons/year)	21,143
14	Annual CO2 Reduction Benefits	**$97,997**
15	Baseline Average Boiler NOx (lb/MMBtu)	**0.30**
16	Baseline Annual NOx (tons/yr)	4,435
17	Average ProcessLink NOx Reduction, at boiler (-%)	**-15.00%**
18	Average NOx Allowance Credit Value ($/ton)	**$1,500**
19	NOx Reduction Allowance Benefits ($/yr)	**$1,018,607**
20	Annual Availability Increase (%)	**0.50%**
21	Increased Availability Value ($/MWh)	**$55.00**
22	Increased Availability Value ($/yr)	**$236,298**
	Total BoilerOpt Savings ($/yr)	**$2,052,539**

Table 2. Assumed Heat Rate and Boiler NOx Reduction and Associated Annual Benefits

These percentage delta improvements are relatively typical for a properly implemented boiler optimization system that adapts to process changes over time. While the delta performance improvements do vary across units, the illustrative values used here represent the average obtained across more than 150 installations.

Uncertainty and Volatility in Coal and NOx Allowance Markets

While performance improvements as a percentage change applied to physical rates of fuel consumption and/or emissions rates are relatively predictable, the annual dollar savings that result from these improvements are subject to the vagaries of fuel and NOx allowance markets, both of which are uncertain and known to be volatile (i.e. rapidly changing over time).

Price behavior in coal markets also exhibits both long-term uncertainty and short-term volatility. While coal prices are less volatile than either natural gas or fuel oil markets, in the last decade there has emerged a robust spot and futures markets for coal. The advent of a futures market indicates uncertainty and price volatility, as well as the desire of market participants to manage both. In the last few years a variety of factors have placed strong upward pressure on coal prices, including increased domestic and international demand. Growth in both domestic usage and international markets has strained the US coal transportation infrastructure, adding another source of volatility. The impacts of future emissions control also heighten the uncertainty around future price behavior, since their impacts on the relative costs of different fuels affects associated demand and prices.

Note that due to the relative lack of historical experience with CO_2 allowance trading markets in the U.S. this analysis focuses on fuel and NOx allowance price volatility only. The introduction of federal cap & trade legislation for CO_2 however, will introduce a new source of uncertainty, and given the experience in European Economic Market (EU) in recent years, also substantial volatility. Consider, for example the range between the approximately $3.00/ton of CO_2 allowance “clearing price” for the intitial RGGI auction held in late 2008 and the $25.00/ton price seen through much of 2008 in the mandatory Kyoto-based EU CO2 allowance trading market . In the former case the annual CO_2 costs for the illustrative 375 MW coal-fired plant used for the analysis in this paper would be approximately $60,000 per year. With the $25.00/ton value faced by generators in the EU, annual CO_2 costs for the same 375 MW plant would be nearly a half million dollars per year.

With respect to NOx, note importantly that with the restoration of CAIR Phase 1, the annual market for NOx allowances has recovered rapidly and appears headed for the $5000/ton price point seen just before the U.S. Circuit Court initially overturned the rule in July, 2008. Given that these year-round prices are layered on top of the existing five-month seasonal market, itself which has been trading around $900/ton, the $1500/ton total annualized value of NOx reduction can be viewed as an extremely conservative assumption.

Methodology

There are two methods of representing uncertainty and volatility and monetizing the benefits of flexibility in responding to both. One is to employ a decision tree where the probability of price behavior following any given path from period to period is represented probabilistically, with an “expected value” determined by weighting the monetary values associated with each potential path by their respective probabilities.

A second approach entails a stochastic simulation whereby prices for any given period (e.g. year) are “drawn” from a “deck of potential outcomes” represented by some probability distribution thought to best reflect the actual distribution of outcomes based on the underlying determinants of price behavior. For example, if coal prices were expected to be equally likely to vary from the expected average (mean) up and down in a symmetrical manner, a “normal” probability distribution would be employed. The variance from the mean would be described in the form of a standard deviation, and 95 percent of all potential outcomes would be within two standard deviations below or above the mean.

Many probability distributions can be employed, most describing the likelihood of asymmetric distributions where for example, coal prices could increase to very high levels, but be much less likely to be significantly less than current or average expected levels. One such probability distribution, for example, would be a log-normal distribution.

For this article however, we are not trying to forecast either the mean or the variability of fuel and NOx allowance costs *per se*; but rather provide a simple illustrative example of how the flexibility to change priorities between reduced NOx and improved heat rate can provide financial benefits in addition to those that would be obtained by an optimizer with fixed priorities.

Accordingly, we employ a combination of scenario analysis and stochastic simulation, segmenting the possibility of price outcomes during any given year into medium, low, and high scenarios for both coal and NOx allowance prices.

A discrete probability distribution is employed such that the probability of each scenario for any given year is represented as 40 percent for the expected, and 30 percent each for the low and high price scenarios, respectively. This distribution is shown in Figure 1 below as follows.

Figure 1. Discrete Distribution for Coal and NOx Allowance Prices

The coal and NOx allowance prices are then determined for each sample for every year by either subtracting (for the “Low” case) from the “Base” case or adding to it (for the “High” case) a randomly drawn amount which is the product of the “volatility factor” for coal prices and NOx allowance value respectively, times a coefficient that varies for each “draw” between 0 and 1. For NOx allowances, for example, sampled prices can be drawn above or below the base case by as little as zero or as great as 50 percent. For coal, prices can vary around the “Base” anywhere between zero and +/-25%.

This combination of price scenarios determined probabilistically through a discrete distribution and stochastic variation around the expected prices for each scenario can approximate a Monte Carlo simulation using a normal distribution. While the resulting combined annual variability does not exhibit exactly the same statistical properties as a normal distribution (i.e. 95 percent of potential outcomes being within +/- two standard deviations from the mean and 68 percent being within +/- one standard deviation), it nonetheless suffices to portray the general principles at hand, i.e. the value of flexibility in the face of uncertain future outcomes.

The nature of the problem is such that we cannot know in advance the shape or the variance of the actual distribution for either NOx allowance or coal prices. There are sufficient historical discontinuities in both coal and allowance markets that there is no good reason to believe that historical price behavior would serve as precedent for future behavior.

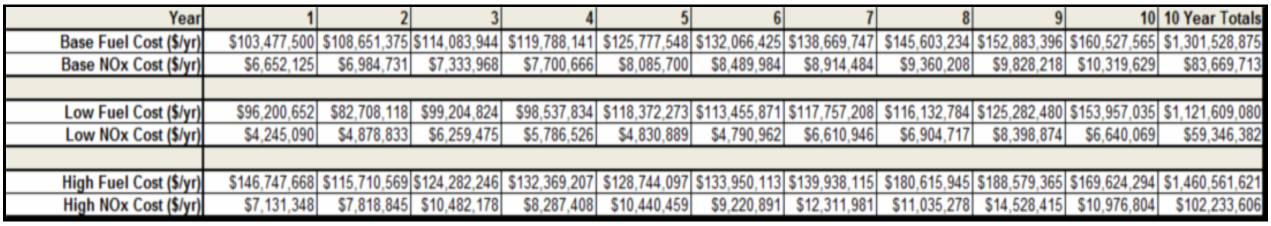
Determination of Price Paths, Associated Annual Fuel Costs, and NOx Allowance Values

The probabilistically determined scenarios and the variation around the expected value for determining coal and allowance process scenarios vary independently of one another and from one year to the next. The assumed independence between years is sometimes referred to as a "random walk," and the resulting level of year-to-year volatility is generally consistent with that observed for both coal spot prices and NOx allowance market values in recent years.

Annual fuel costs and NOx allowance values (which could take the form of a cost or revenue stream depending on a generator's NOx position relative to their cap) for the Base Case are derived by taking the current year values (based on heat rate, NOx emissions rate, and the current cost of coal and value of NOx allowances). These values are then escalated at a 5 percent compounding rate (a proxy for some combination of upward prices pressures for fuel and allowance costs, and general inflation) for the remaining 9 years in the ten year analysis horizon, which sum to the $1.3 billion total fuel cost and $83.7 million total allowance value shown in the first two rows of Table 4 below.

The low and high fuel and NOx scenarios over this same period are generated by subtracting from or adding to the base values in each year a stochastically generated dollar amount reflecting both random variation (using Excel's RAND function) and a coefficient reflecting the estimated volatility in coal and NOx allowance markets, respectively. For coal prices, a "volatility factor" of 25 percent was used; and for NOx allowance values a 50 percent factor. Note that while recent coal prices have exhibited both steep escalation and substantial volatility, fuel oil and natural gas markets exhibit even greater volatility. The benefits of flexibility in managing uncertainty for generating units burning either or both of these fuels would be even larger.

As a result, coal prices for the Low scenario during any particular year could be less that the Base Case by anywhere between 0-25 percent with the actual percentage randomly varying. Similarly, NOx allowance values for the Low Scenario during any particular year could be less that the Base Case by anywhere between 0-50 percent with the actual percentage also randomly varying. Coal costs and NOx allowance values for the High Scenario were derived in the same manner, except the resulting "deltas" from the Base Case Scenario were added, as opposed to subtracted. The annual dollar values from one randomly drawn probabilistically determined sample as well as the ten-year total for that particular sample are shown in Table 3.



Year	1	2	3	4	5	6	7	8	9	10	10 Year Totals
Base Fuel Cost ($/yr)	$103,477,500	$108,651,375	$114,083,944	$119,788,141	$125,777,548	$132,066,425	$138,669,747	$145,603,234	$152,883,396	$160,527,565	$1,301,528,875
Base NOx Cost ($/yr)	$6,652,125	$6,984,731	$7,333,968	$7,700,666	$8,085,700	$8,489,984	$8,914,484	$9,360,208	$9,828,218	$10,319,629	$83,669,713
Low Fuel Cost ($/yr)	$96,200,652	$82,708,118	$99,204,824	$98,537,834	$118,372,273	$113,455,871	$117,757,208	$116,132,784	$125,282,480	$153,957,035	$1,121,609,080
Low NOx Cost ($/yr)	$4,245,090	$4,878,833	$6,259,475	$5,786,526	$4,830,889	$4,790,962	$6,610,946	$6,904,717	$8,398,874	$6,640,069	$59,346,382
High Fuel Cost ($/yr)	$146,747,668	$115,710,569	$124,282,246	$132,369,207	$128,744,097	$133,950,113	$139,938,115	$180,615,945	$188,579,365	$169,624,294	$1,460,561,621
High NOx Cost ($/yr)	$7,131,348	$7,818,845	$10,482,178	$8,287,408	$10,440,459	$9,220,891	$12,311,981	$11,035,278	$14,528,415	$10,976,804	$102,233,606

Table 3. Annual Fuel Costs and NOx Allowance Values for Ten-Year Analysis Timeframe

These values could be generated in a more statistically sophisticated manner using any form of underlying probability distribution and a standard deviation to denote variability/volatility, as well as any additional statistical parameters needed to describe asymmetries in the likelihood of high or low price excursions (e.g. log-normal, skewness, kurtosis, etc.). The purpose of this exercise however, is to illustrate the financial benefits associated with the flexibility for responding to uncertain markets, rather than to prognosticate on the probabilities associated with actual market price behavior, which – as recent developments have demonstrated – is a guessing game at best.

The fuel cost and NOx allowance value in each year could be any of the Low, Base or High values shown in Table 4 from that year, sampled from the discrete probability distribution shown in Figure 1. While this value is randomly "drawn," the algorithm is set up so that there is a 30 percent chance that the value for any given year reflects either the Low of High scenario; with a 40 percent chance of reflecting the Base scenario. Coal costs and Allowance values vary independently of one another, and the value of each for any year is determined independently of prior years.

The "actual" values for annual coal costs and allowance values determined in the manner described above for a single sample are shown in Table 4.

Year	1	2	3	4	5	6	7	8	9	10	10 Year Totals
Actual Fuel Cost ($/yr)	$103,477,500	$108,651,375	$114,083,944	$119,788,141	$125,777,548	$132,066,425	$138,669,747	$145,603,234	$152,883,396	$160,527,565	$1,301,528,875
Actual NOx Cost ($/yr)	$6,549,074	$5,767,873	$6,225,872	$7,690,176	$5,829,396	$6,148,044	$6,682,244	$8,900,626	$8,476,222	$6,906,557	$69,176,086

Table 4. Sampled Annual Fuel Costs and NOx Allowance Values

Range of Heat Rate and NOx Reduction Deltas

Representative combined reductions in heat rate and NOx associated with the integrated boiler optimization are shown in Table 5.

	Low	Base	High
Fuel Delta	-0.35%	-0.68%	-1.00%
NOx Delta	-7.50%	-15.00%	-20.00%

Table 5. Range of Heat Rate and NOx Reduction Deltas

This illustrative range of benefits approximates the lower and upper ranges of the heat rate and NOx benefits that are typically achieved through the integrated boiler optimization (via whatever combination of soot blowers, water lances and/or “cross-furnace water cleaning devices are used for soot removal and slag prevention) when heat rate and NOx are the primary objectives.

The extent and severity of tradeoffs between these two objectives varies across units depending on unit design, controls, instrumentation, fuel sources, etc. While both combustion and sootblower optimization have been proven to reduce both NOx and heat rate – individually and together – when deployed at non-optimized units, once optimized there are generally tradeoffs between the two.

This is particularly the case with boiler cleanliness. For example, if the sole objective for sootblower activation was to minimize NOx, the strategy would be maximizing heat transfer in the furnace section by getting furnace water walls as clean as possible. Soon into this process however, the reduction in heat absorption in the convection region would cause steam temperatures to sag, with the attendant deterioration in heat rate and possibly available capacity. The net effect is that the integrated boiler optimization system will tend to embody a greater degree of tradeoffs between heat rate improvement and NOx reduction than combustion optimization alone. While it is always good to move global objectives in the desired direction, it is also true that a more comprehensive approach to boiler optimization will allow greater flexibility in managing tradeoffs as imposed by varying market dynamics.

Annual Fuel Savings and NOx Allowance Benefits: Fixed Priorities

For an optimization process unable to manage tradeoffs between NOx and annual fuel savings, monetized benefits were determined by multiplying the simulated fuel costs and NOx allowance values for each year by the base case delta improvement, i.e. a 0.68 percent reduction in heat rate and a 15 percent NOx reduction. In other words, the heat rate and NOx reductions for the "Fixed Priority" case assumed the same relative level of heat rate improvement and NOx reduction every year, regardless of actual fuel prices or NOx allowances and the associated monetary benefits associated with each. The resulting annual and ten-year total savings for a single "drawn" sample for this "fixed priority" case are shown in Table 6 below.

Year	1	2	3	4	5	6	7	8	9	10	10 Year Totals
Fixed Priority Fuel Svgs ($/yr)	$1,014,979	$885,791	$883,877	$943,083	$951,508	$915,406	$1,098,951	$1,140,066	$1,046,790	$1,293,773	$10,174,226
Fixed Priority NOx Svgs ($/yr)	$1,070,452	$1,139,427	$1,484,085	$1,630,341	$1,676,937	$1,486,767	$1,377,334	$2,098,899	$2,202,952	$1,968,097	$16,135,290
Total Fixed-Priority Svgs ($/yr)	$2,085,431	$2,025,218	$2,367,962	$2,573,424	$2,628,446	$2,402,172	$2,476,286	$3,238,965	$3,249,742	$3,261,870	$26,309,516

Table 6. Annual and Ten-Year Total Boiler Optimization Savings for "Fixed Priority" Case

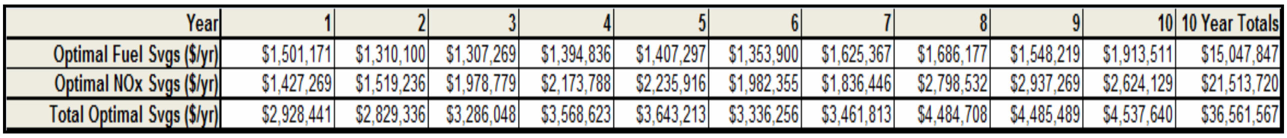
Annual Fuel Savings and NOx Allowance Benefits: Optimal Monetized Tradeoffs

In contrast with the Fixed Priority optimization case described above, the "Optimal Monetized Tradeoffs" case allowed the percentage delta heat rate and NOx reduction to co-vary with the costs for each for any given year, based on the probabilistically determined scenario pertaining to fuel prices or NOx allowances for that year.

For example, if the simulated fuel price for a given year reflects the Base scenario, the heat rate reduction applied for that year would be 0.68 percent. If the simulated fuel price reflected the Low or High scenarios, the assigned heat rate reduction would be either 0.35 percent or 1.00 percent respectively. Similarly, if the simulated NOx allowance value for a given year reflects the Base scenario, the NOx reduction applied for that year would be 15 percent. If the simulated fuel price reflected the Low or High scenarios, the assigned heat rate reduction would be either 7.5 or 20 percent respectively.

Note that the actual fuel cost and NOx allowance values are stochastically simulated, and allowed to vary around the expected value for the probabilistically determined scenario randomly, in a manner reflecting the 25 and 50 percent “volatility factors” assigned to reflect expected variation for each input cost for fuel and NOx respectively.

This simulation reflects the ability of an integrated boiler optimization system to manage tradeoffs between heat rate improvement and NOx reduction based on the monetized value of each input cost. The resulting annual and ten-year total savings for a single “drawn” sample are shown in Table 7 below.



Year	1	2	3	4	5	6	7	8	9	10	10 Year Totals
Optimal Fuel Svgs ($/yr)	$1,501,171	$1,310,100	$1,307,269	$1,394,836	$1,407,297	$1,353,900	$1,625,367	$1,686,177	$1,548,219	$1,913,511	$15,047,847
Optimal NOx Svgs ($/yr)	$1,427,269	$1,519,236	$1,978,779	$2,173,788	$2,235,916	$1,982,355	$1,836,446	$2,798,532	$2,937,269	$2,624,129	$21,513,720
Total Optimal Svgs ($/yr)	$2,928,441	$2,829,336	$3,286,048	$3,568,623	$3,643,213	$3,336,256	$3,461,813	$4,484,708	$4,485,489	$4,537,640	$36,561,567

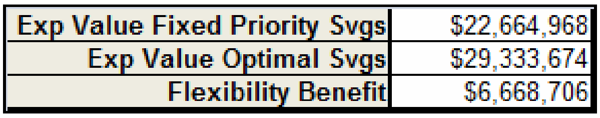
Table 7. Annual and Ten-Year Total Boiler Optimization Savings with Optimal Tradeoff Management

Thus for the “single sample draw” values shown in Tables 6 and 7, the Optimal Tradeoff cases provides for $10.2 million of additional benefits relative to the “Fixed Priority” case over the ten year analysis timeframe.

Determination of Expected Value Benefits for “Fixed Priority” and “Optimal Tradeoff” Cases

These annual values and the differences between the “Optimal Tradeoff” and “Fixed Priority” cases represent just one point in the probability distributions that reflect the assumed form and variability underlying the uncertainty in fuel and NOx allowance markets. To capture the expected value savings associated with both cases, a Monte Carlo simulation was performed to compare the difference between the cases, which employed 50 samples or “draws” to determine and compare the expected values associated with the “Optimal Tradeoff” and “Fixed Priority” cases.

The expected value benefits for both cases and the difference between the two based on the average of 50 samples is shown in Table 8 below.



Exp Value Fixed Priority Svgs	$22,664,968
Exp Value Optimal Svgs	$29,333,674
Flexibility Benefit	$6,668,706

Figure 8. Expected Value of “Fixed Priority” vs. “Optimal Tradeoff” Cases

While the ten-year total fuel and NOx-related savings of $22.7 million for a single 350 MW coal-fired unit is substantial, an additional $6.7 million dollars in total benefits would be obtained using boiler optimization technology where the tradeoffs between heat rate improvement and NOx reduction can be optimally managed in response to uncertain and volatile markets determining the value of each.

Conclusion

This $6.7 million dollar "flexibility benefit" for the illustrative 350 MW coal-fired unit employed for this analysis represents nearly a 30 percent increase in total 10-year benefits, suggesting that the ability for optimization technology to account for market behavior and associated monetized benefits is an important attribute to consider when investing in optimization technology. Assuming that all US generators will likely be operating under a mandatory federal cap and trade market for CO_2 allowances and the magnitude of the anticipated required reductions, both the "base case" benefits and those derived from the flexibility to manage tradeoffs in yet another uncertain and volatile market will be even greater.