Improved Efficiency of Energy-Intensive Processes through Control of Build-Up on Critical Heat-Transfer Surfaces

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ABSTRACT

The energy intensive Kraft recovery boiler process is a production bottleneck in the modern pulp mill. As such, there exists a need to accurately monitor and remove by-product build-up on critical heat-transfer surfaces to maintain high throughput, as well as energy efficiency. Current monitoring methods utilize heuristic data and observable boiler trends to indirectly measure build-up. These methods lack the ability to provide instant and accurate fouling-level feedback, resulting in sub-optimal cleaning strategies. To enable more optimized cleaning, a system has been developed that generates real-time fouling-level data and uses statistical learning methods to enable automatic closed-loop feedback control. This technology utilizes state-of-the-art image processing methods to produce a build-up index and establish a cleaning strategy that balances heat-transfer efficiency and cleaning sub-system energy usage, maximizing overall boiler efficiency. Conservative calculations predict that the statistical learning system significantly improves on existing methods, resulting in annual per boiler energy and cost savings in upwards of $200,000, and increased efficiency for pulps mill in general.

Problem Overview

Rising energy prices, as well as the latest economic recession, have stimulated innovative efforts to optimize many industrial processes. This trend has evolved into an industrial necessity to encourage the development of technologies that precisely and efficiently control energy-intensive operations, such as the Kraft chemical recovery boiler. The Kraft boiler (where useful white liquor is recovered from pulping by-product black liquor) is a key component of the pulping process, both chemically and as a source of energy, producing a large portion of the operating mill's steam. While the Kraft boiler is in service, large amounts of solid combustion by-products (slag) unavoidably deposit onto heat-transfer surfaces, consequently causing undesirable energy losses and reduced boiler efficiency. To bypass shutting down the boiler regularly for scheduled cleaning, which would result in the ceased operation of the entire pulp mill, large sootblowing systems, often automated by some means, are incorporated as a boiler sub-system. Sootblowing requires high-temperature, high-pressure steam, typically diverted from the header of the boiler it cleans, making it a highly energy intensive industrial sub-system, as well as parasitic to facility steam demand. Due to the need for a system that effectively cleans boilers without wasting unnecessary steam, there is demand for a reliable and precise control method for sootblowing.

The effectiveness of a typical sootblower depends on the following parameters: 1) the overall steam jet power, 2) the thickness and coverage of the slag, and 3) the blowing control strategy. Most current control systems are operated on a timed sequence based on heuristic data; therefore, over blowing is a common trend for the operation of many Kraft boilers. Consequently, the optimization of sootblowing requires an intelligent system that can provide real-time data and on-demand sootblowing control. Nevertheless, diverse research groups have focused on overall fouling reduction by improving both the blower steam delivery and the combustion process, rather than furthering sootblowing optimization through developing new means of system control. This disproportion, as well as the potential for untapped optimization strategies in obtaining significant energy savings, forced us to rectify existing monitoring tools to provide feedback for sootblowing systems. Significant energy savings can result from even a small abatement of Kraft boiler energy consumption provided by an intelligent sootblowing system through reduced sub-system steam demand. In time, such energy savings will lead to significant energy cost reductions, with Kraft recovery boiler processes usually encompassing 14% of total mill operating costs (

Figure 6).

Observed methods for the automatic control and remote supervision of sootblowing (which have been developed since the early years of the 20th century [1]) were found to be unresponsive to the industry's needs and require serious modifications. Therefore, the personnel managing Kraft boilers do not currently have adequate instruments and measurement tools to estimate and visualize slag build-up on internal element surfaces. The existing design of most Kraft boilers feature multiple access ports periodically scattered along the perimeter wall, so that personnel may observe or enter the interior of the boiler. However, visibility through these ports during operation is dramatically limited due to flame brightness and sparking. Low visibility inhibits the acquisition of accurate data pertaining to current build-up levels in the boiler. Consequently, operating personnel are forced to use archaic cleaning methods that generally activate high-energy sootblowers in timed sequences and often consume approximately 10% of the boiler's output energy. Furthermore, such methods need manual supervision, requiring substantial expertise and a significant subjectivity factor. In eliminating these disadvantages, automatic supervision and control systems based on visual monitoring are desired.

Previously developed auto-monitoring technologies exist that utilize infrared imaging cameras and image processing algorithms. While both of these components have been substantially ameliorated in recent years, several serious concerns regarding slag detection accuracy still exist. For instance, existing systems incorporate cameras that detect the high frequency end of the infrared spectrum, which have limited vision in environments with high particulate levels. Furthermore, the image quality of these cameras greatly depends on air turbulence, which frequently appears in boilers with air-injected systems. While implementation of such viewing systems provides satisfactory observation in the lower sections of Kraft boilers, where particulates in the air are at low levels, these cameras have been demonstrated to be significantly less useful in the upper chambers of the boiler where particulate levels are high and the most critical heat transfer surfaces exist. Therefore, camera systems currently perform a limited role in typical blowing control systems, and additional sensors and methods must be utilized for slag detection in the most problem build-up areas.

Sensor data from existing boiler systems is often used to detect possible slag build-up through inference. Signals and data often considered in the formulation of a given Kraft boiler's “optimized” cleaning strategy include measurements from superheater loop thermocouples, draft losses across boiler sections, and heat transfer coefficient calculations. Although systems incorporating these means of control can easily be automated on a large scale, the lack of visual information pertaining to slag distribution prevents resulting cleaning methods from being optimized in a reasonable time [2].

In comparing the discussed advantages and drawbacks of both IR-camera and non-visual sensor optimization methods, we concluded that the former provided the most promising technologic-base for the development of an intelligent sootblowing system. Accordingly, we began examining possible camera technologies and image processing algorithms that could be used to collect accurate, real-time fouling-level information in the hostile environment of the Kraft boiler’s upper chambers. While this paper presents a system developed for use in a specific boiler, we believe a similar system, with minimal alterations from the discussed, incorporating the same basic camera and image processing principles, can be implemented in other types of industrial boilers, which also have fouling issues and significant blowing systems.

Technological Requirements and Constraints

A Kraft boiler’s sootblowing system is a necessary evil in the modern pulp mill. While it consumes large amounts of high energy steam (often of the highest pressures in the facility), it assures the reliable operation of the Kraft boiler, which due to large energy throughput and cost, serves as the production bottleneck of the entire mill. Therefore, a major objective in developing a more intelligent sootblowing control system is to be able to strike a balance between blowing steam use and overall boiler efficiency and reliability. We believe obtaining this mark can be accomplished with a control system that meets the following requirements:

1) **Accuracy:** In order to support the ability to precisely measure input signals, all sensors installed in the boiler have to be resistant to stochastic noise.
2) **Reliability:** High temperature oscillating in a wide range, soot particulates, such as ash and clinker, and humidity should not distort sensor operation, nor should supporting wires installed in this harsh environment induce physical disruption, experience frequent breakages, or require frequent servicing, in order to avoid boiler shut down.
3) **Ergonomics:** Implementation of the slag evaluation system needs to be a compact built-in device in order to preclude serious reconstruction of the existing boiler, decrease installation expenses, and minimize the influence of geometrical parameter modifications on the boiler’s overall properties.
4) **Decision validation:** A decision making algorithm, which will analyze input signal quality and detected slag levels, must be established to generate executive commands and alarm alerts, preventing improper sootblowing initiations.
5) **Communication:** Input and output compatibility with pre-existing facility control-systems and installed devices; ability to transmit information for remote control and monitoring.

Build-Up Recognition and Slag Index Calculation

This section will outline the main components of the system developed as a solution to the problematic inadequacies of current blowing control systems, as well as to meet the technological specifications enumerated in the previous section. The proposed system includes a single PyrOptix IR-camera (Figure 1) provided by Enertechnix, LLC, which will be installed at a boiler port (Figure 2) to monitor zones that are known to have the most problematic issues with slag build-up. The PyrOptix IR-camera kit includes double-wall protection and air-cooling to prevent heat damage, an auto-retract mechanism and port wiper to keep the lens free from air-dispersed ash particles, and armored wiring to connect to the image-processing and control systems.

Figure 1. CAD Software Generated Model of PyrOptix IR-Camera

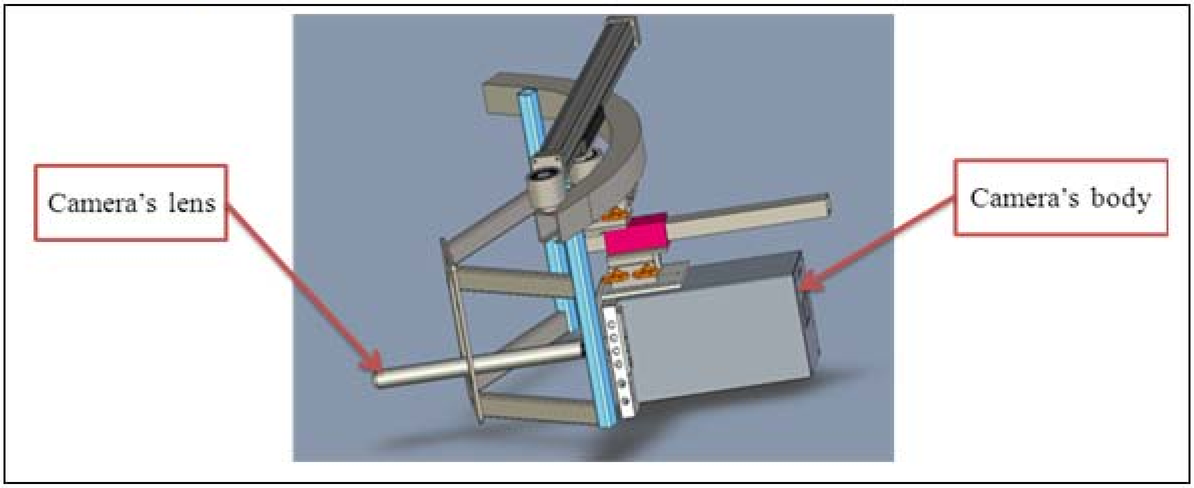
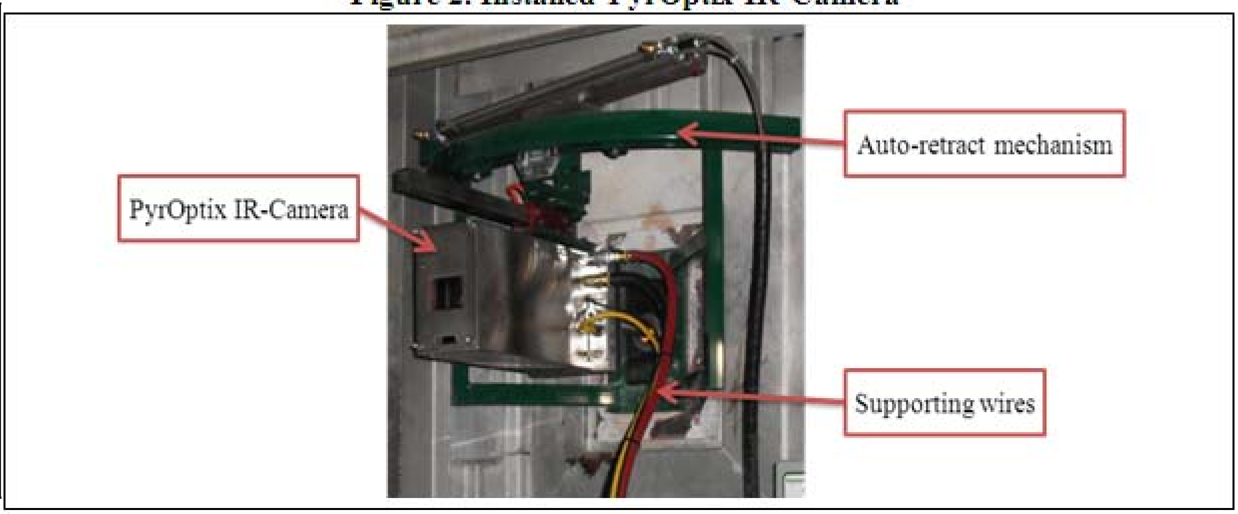


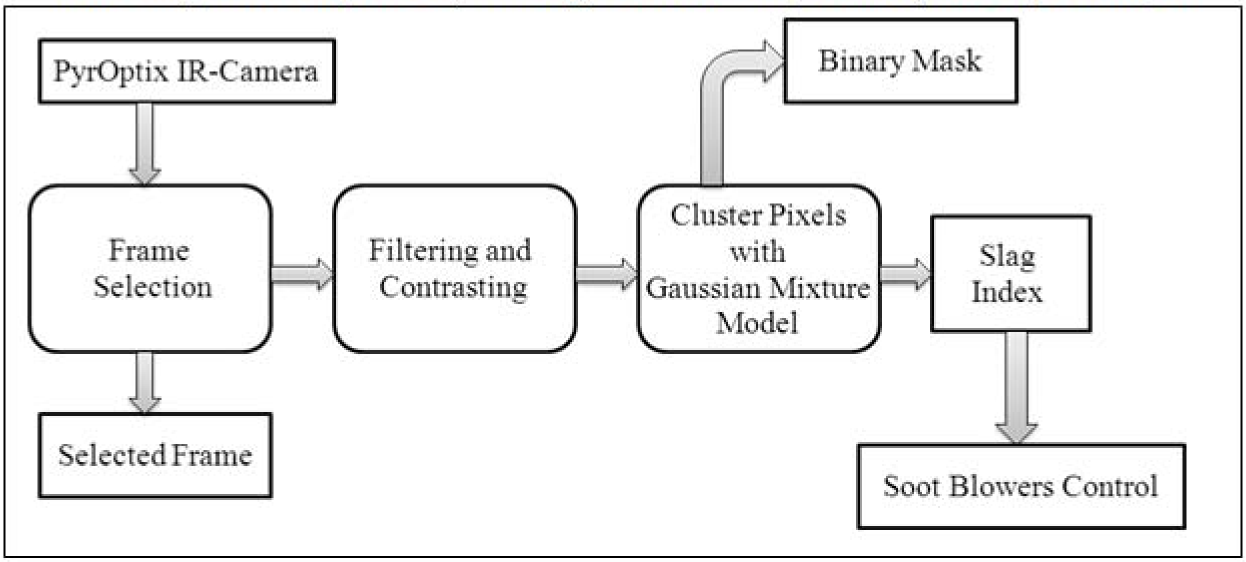
Figure 2. Installed PyrOptix IR-Camera



The PyrOptix IR-camera improves on the standard IR-camera by utilizing a patented, extensively researched wavelength in the infrared spectrum that both maximizes viewable distance and image quality, while minimizing light absorption by particulate matter. Due to the patent, it is the only camera utilizing this infrared range and the only known camera capable of imaging in the turbulent upper boiler sections. In the lower boiler sections, the PyrOptix camera has approximately twice the viewing range of any comparable device. In the upper-boiler regions, this technology provides 10 times greater light propagation than competing systems, making the PyrOptix IR-camera the most suitable imaging component for the designed system.

The bases of the developed slag detection algorithm is the Gaussian mixture model, being among the most statistically mature methods for image processing and a proven instrument in separating any digital image into various parts based on a target parameter. In terms of this project, the target is slag; the Gaussian identifies the build-up coverage and separates it from non-problem surfaces through the stark contrast of blackened and whitened zones. While based on this well-known model, the slag-detection algorithm is unique and state-of-the-art; Figure 3 illustrates the flow of said algorithm.

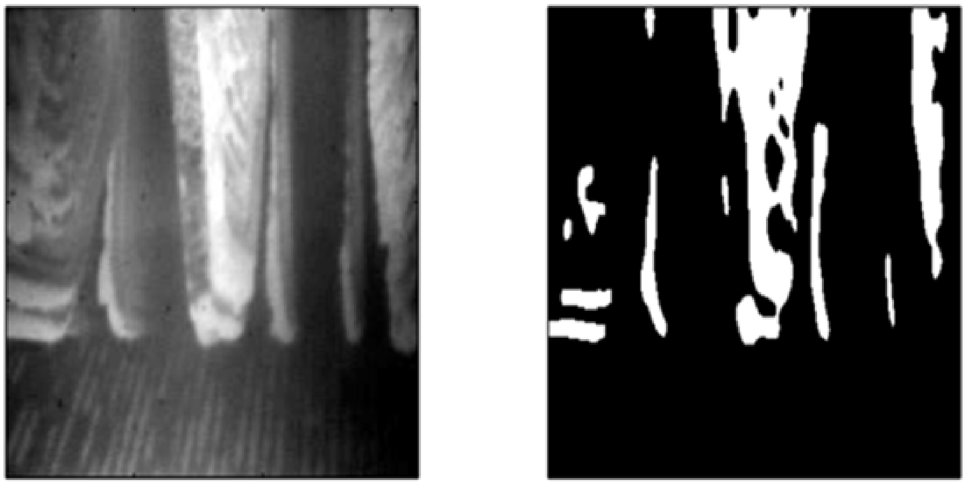
Figure 3. Systematic Flow Chart of Slag Evaluation Algorithm: Oval Blocks Represent Processing Related Opeations, Rectangular Blocks Repersent System Input/Output



A. **Frame selection.** The installed PyrOptix IR-camera transmits real-time video to the image-processing unit. Due to input sensitivity at later stages of the algorithm, the system automatically evaluates each frame as an empiric function of its clearness and brightness to select the most useful frames for processing.

B. **Filtering and image contrasting.** The collective imperfection of the system's data-acquisition and electrical transmission equipment, which can be attributed to the natural phenomenon of "electrical noise", as well as actual physical damage due to the harsh industrial setting, frequently proved detrimental to the accuracy of the final slag calculation. To compensate for these irremovable defects, the developed system uses median filtering to smooth noise appearance in a selected frame [2]. Median filtering replaces the value of each pixel with the median value of neighboring pixels. In terms of this project, the median filter is additionally advantageous due to its ability to save image sharpness, a critical element for the next operation: contrast-limited adaptive histogram equalization (CLAHE). This signal processing method partitions frames of many pixels into smaller zones, and separately implements histogram equalization to each zone, which enhances contrast by remapping the gray level of the image with respect to the probability distribution function of the inputting gray levels. While CLAHE is sensitive enough to gain high contrast in the output image, it produces some 'graphical' noise and contrasts frames indiscriminately, i.e., it may increase the contrast of background noise, while decreasing the useful signal [3]. To clean up the resulting gray scale contrasted image, the discussed median filter is again used. Figure 4 illustrates the post-median filter, gray scale contrasted image, along with its completely processed counterpart.

Figure 4. On the Left – The Gray Scale Contrasted Frame, On the Right – The Binary-Contrasted output Image



C. **Clustering.** Cluster analysis is a well-known image processing technique to organize a given set of data into subsets with respect to a certain parameter. In terms of slag recognition, the algorithm evaluates the portion of the contrasted image associated with detected build-up, pixel-by-pixel, with a certain probability factor. To support pixel clustering, the expectation-maximization (EM) algorithm is used to accurately compute a probability factor. The EM algorithm is an iterative, maximization technique that can be described as two steps:

- *Expectation*: calculation of the expected value of the input argument that maximizes the system defining probability function; this is done with respect to unknown variables and considers the previous estimation of the input argument as well as observed data.
- *Maximization:* revaluation of the probability function, which is determined using the expected value chosen in the previous step.

Like many algorithms, EM has its disadvantages. This is an iterative technique, with which finite iterations will only produce an approximation of the input argument that maximize the probability density function; complete convergence would require infinite iterations. Additionally, the probability density function is not guaranteed to have only one peak; therefore, approximated arguments may be associated with local maxima instead of absolute. However, these deficiencies rarely manifest as large sources of error and the EM method has been proven to be a dependable and powerful tool in application [4]. Such has been confirmed by the resulting contrasted images, which have been observed to regularly depict slag covered areas as white clusters of pixels, as shown in Figure 4.

D. **Slag index calculation.** System calculates a “slag index” as a ratio of pixels associated with slag to the total number of pixels in the processed image.

Field tests have demonstrated that both the PyrOptix IR-camera and developed slag recognition algorithm meet the design requirements needed to develop an effective statistical learning system. The detected “slag index”, along with addition sensory measurements, should also prove sufficient in developing a decision making algorithm which will enable automatic, on-demand sootblower control; we are confident that the realization of said algorithm will be finalized through future longer-term field tests and the continued cooperation of our Kraft boiler operating industrial partners. Furthermore, we have developed a user-friendly interface for future use in facility control rooms; the simultaneous display of real-time video, processed images, and slag index provided by this interface, along with expert analysis, should increase understanding of slag depositing mechanisms, some of which may be currently unknown.

Energy Savings and the Economic Impact in the US

In developing this technology, we analyzed market observation data gathered on 74 already installed monitoring systems, in 25 states, to predict industrial penetration of the proposed system, as well as to estimate the monetary, ecological, and social benefits associated with large-scale implementation. In accordance with our preliminary expectations, deployment gains will be observed in energy savings from decreased steam-demand, operational cost savings from decreased production costs, air-pollution abatement, and job retention in energy-intensive industries.

In order to conservatively calculate direct production cost savings, we interpolated the effectiveness of already installed IR-cameras, as judged by boiler operating personnel, in deriving savings achieved with the automatic intelligent supervising system, which would provide at least the same benefits. While this is a fairly contingent assessment of system related savings, it does provide a lower boundary of the expected impact, at which modest levels of savings would suggest favorable circumstances for the support of system implementation. For example, in accordance with estimations based on DOE BCSTools, in Washington State, where presently 45,000 forest product jobs are at stake, companies would save approximately $1 million per year in cleaning steam costs, reduce energy use by roughly 200 billion BTU per year, and eliminate emissions of about 30,000 tons of CO_2 per year. In addition to the direct financial benefits, we expect energy savings of 200 billion BTU per year, based on costs of $33.41 per million BTUs [5]. These energy savings would free up $6.7 million of capital annually for additional investments. These impressive figures associated with system implementation confined to Washington State would only be amplified upon nationwide market penetration.

Figure 5 shows that there are 168 Kraft recovery boilers in the United States with a collective capacity of 4,134 MW. These boilers are used in the U.S. pulp and paper industry, which grosses annual sales of $115 billion, employs nearly 400,000 people, and pays approximately $30 billion in annual compensation. Pulp and paper is also one of the most heavily burdened industries in terms of energy cost dependency, as shown in

Figure 6. Implementation of the proposed technology in only 25% of the U.S. recovery boilers would result in savings of $11 million per year in avoided blowing steam cost, reduce energy use by roughly 2.9 trillion BTU per year, and significantly eliminate greenhouse emissions: 400 thousand tons of CO_2, 1,250 tons of SO_2, and 400 tons of NO_x per year. Undoubtedly, the most significant immediate effect will be raw cost savings, such should help support U.S. pulp mills, which have to operate on an ever-increasingly tight bottom-line due to foreign competition.

In addition to the pulp and paper market, we considered 1310 facilities in the U.S. using coal, oil, and chemical-fired boilers with an approximate collective capacity of 175 GW, which can potentially use the proposed system. These boilers represent sources of energy for a range of national industries, including power generation, steel manufacturing, and waste disposal. Every state in the U.S. contains at least one or more utilities that operate a non-recovery boiler requiring a large, automated sootblowing system; coal dependent states like Florida, Illinois, and Pennsylvania alone run 51, 85, and 95 of such utilities, respectively. Installing this technology nationwide at these non-recovery industrial boilers would save an estimated $160 million annually through a collective reduction in steam demand of 100,000 tons of steam per day, corresponding to annual per-boiler savings of $120,000. Additionally, non-recovery boiler blowing optimization will lead to annual energy savings of approximately 35 trillion Btu, eliminating 3.3 million tons of CO_2, 1,270 tons of SO_2 and 1,134 tons of NO_x emissions per year.

Figure 5. State-by-State Distribution of Kraft Recovery and Non-Recovery Industrial Boilers

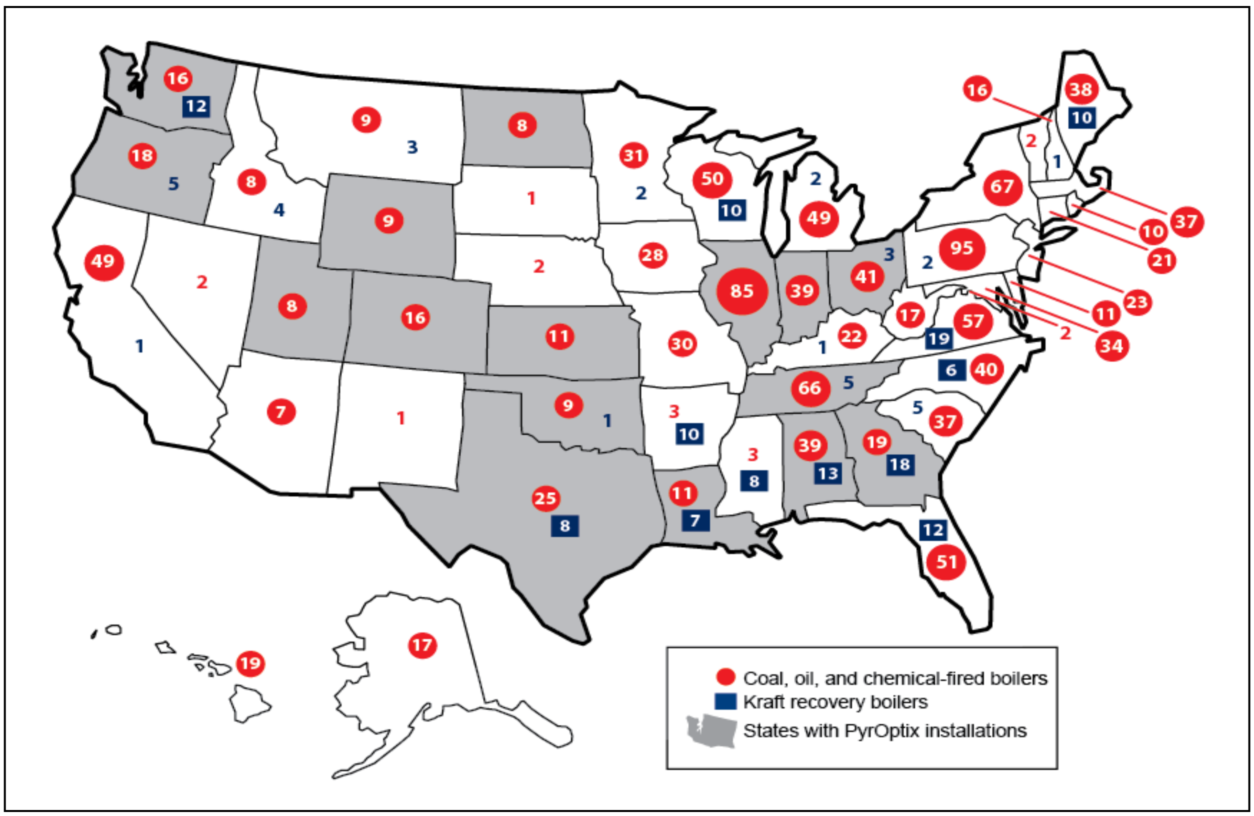
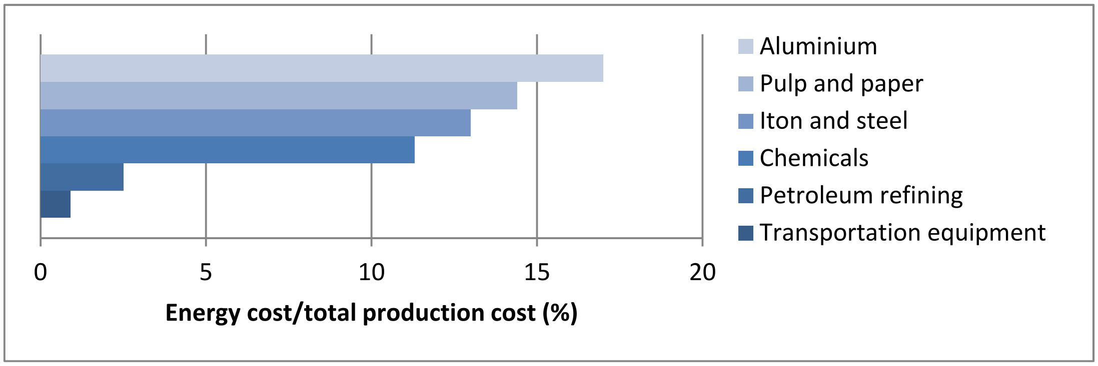


Figure 6. Proportion of Energy Cost to Total Production Expenses for Various Manufacturing Industries



In addition to monetary and environmental benefits, energy efficiency programs have been observed to have a direct relationship to job creation. We are witnessing the growth of the energy efficiency market into a major industry at a blinding rate. In 2006, renewable energy and energy efficiency industries generated nearly a trillion dollars in industry sales, 8.5 million new jobs, more than $100 billion in industry profits, and more than $150 billion in increased federal, state, and local government tax revenues [6]. Also, specific energy efficiency programs have been observed to create more jobs at the regional or state level, as compared to energy supply projects [7]. In order to assess the economic impact of the proposed technology, direct on-site job creation, indirect job creation in support industries, and induced effects, such as increased consumer spending, collectively need to be considered. Studies of the effect that energy efficiency technology investments have on job creation [8] have argued that every $1 million invested in projects improving energy efficiency creates about 70 person-years of employment. Extrapolating from these estimates, the proposed $6.7 million savings from the deployment of this technology will lead to approximately 470 person-years of employment.

Conclusions

After the complete deployment of the proposed technology, we expect that overall benefits to manufactures and industry will include:

1) **Energy savings:** The discussed intelligent sootblowing system significantly reduces boiler cleaning steam demand and increases boiler efficiency, which consequently reduces facility steam demand by a considerable amount. Steam-demand savings result in reduced production costs through more efficient use of boiler fuel. Additionally, the technology's penetration nationally into applicable industries will diminish national dependence on foreign oil and increase industry competitiveness.
2) **Improved productivity:** Installation of the proposed system will lead to the elimination

of the human-error factor in making boiler-cleaning decisions. In addition, the accuracy of the cleaning strategy developed through the use of this technology will help boiler operators avoid unplanned shutdowns and harmful equipment damage. Finally, this system enables condition-based maintenance, both on a short-term time scale (daily operations, shift transitions) and on a long-term scale (substitution of the semiannual rather than quarterly maintenance by semiannual) and, as a result, proliferates equipment lifespan.

3) **Reduction of air-pollution:** Implementation of the proposed technology guarantees serious reduction in CO_2, SO_2, and NO_x emissions and will indirectly create a public attitude of higher tolerance to the pulp and paper industry, in an ever-increasing environmentally conscious society.

4) **Future technology R&D:** The discussed control system has the potential to stimulate and facilitate the development of new approaches to boiler optimization through the increased awareness of slag depositing mechanisms provided by intelligent monitoring. Many of these mechanisms may be currently unknown, due to the lack of adequate observation tools.

As energy costs continue to rise, the pulp and paper industry will need to collaborate with research groups to target wasteful processes, and develop new energy efficient technologies. The Kraft boiler, being the production bottleneck and primary energy producer of the modern pulp mill, is an ideal candidate for such optimization. Through the combined efforts of University of Washington researchers and industrial leaders in both energy efficient technologies and the pulp and paper industry, a statistical learning system has been developed that addresses the highly wasteful sootblowing control strategies often used to clean vital heat transfer surfaces in the upper chambers of industrial boilers. In providing automated slag detection and on-demand sootblowing capabilities, this technology has the potential to generate substantial energy savings through reduced facility steam demand and lower cost of operation. In addition, we believe that the visualizing component of the proposed technology could be useful in monitoring other industrial processes that perform in the same hostile, high-temperature, low-visibility environment, such as the glassblowing and metallurgy industries. However, the future development and marketability of this system will continue to depend on the industry's role as a partner in facilitating these efforts. With the unique environments that industrial optimization technologies must be tested in, the industry must act as a nurturer, creating laboratory settings where increasing efficiency and optimizing systems can be conceived, developed, and brought to market. Such collaboration can only accelerate the growth of the nation's energy efficiency industry, creating future jobs for the county's ever-growing, high-skilled workforce, and further establishing global leadership in this industry as energy usage becomes the world's foremost urgent and universal issue.

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