Techno-economic impact assessments of energy efficiency improvements in the industrial combustion systems

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ABSTRACT

Industrial energy efficiency assessments not only provide benefits to manufacturers, but also generate significant economic and environmental benefits to localities, states, and the nation through indirect and induced benefits. Quantifying these benefits requires a systematic economic framework for capturing these interactions. This article employs methodologies for improving the energy efficiency of small and medium-size industry through their combustion systems. Combustion systems offer large opportunities to enhance energy efficiency through adopting advanced technologies and better-informed operations. The case studies presented illuminate the potential savings and impacts from implementing energy-efficient combustion recommendations and the importance of energy audits and energy efficiency in the fight against climate change. This study describes and quantifies the cascading economic and environmental impacts of implementing the industrial energy efficiency recommendations offered by an energy auditing program by participating facilities over a ten-year period. Results showed that it is expected that a total of $185M would be saved in energy costs and 2.3 million metric tons of carbon dioxide emissions would be avoided annually, and about 972 jobs could be created in the studied region if all the combustion recommendations would be implemented. The broader view afforded by the proposed study can be used to support better energy efficient practices in manufacturing facilities, communities, and states.

Keywords: Combustion systems, Energy efficiency, Energy audits, Techno-economic analysis

1. Introduction

The energy crisis of the 1970s led to the creation of energy efficiency programs and changes in energy policy in the United States and other countries around the world [1]. These programs, policies, and government regulations have made industrial facilities more aware of their practices. Industry production accounts for 22% of total greenhouse gas emissions created by human activity in the United States [2], primarily from burning fossil fuels for energy and certain chemical reactions involved in producing goods. Adding the greenhouse emissions from the electricity employed by industry would further increase the industry's share of such emissions. Industrial facilities must implement energy efficiency practices in order to minimize pollution and use of natural resources while continuing production and employing many people. These practices will also benefit industry in many other ways, from saving money and resources to improving the company's culture [3, 4].

Yet various issues and barriers can discourage manufacturers from implementing energy-efficient practices. Some barriers include the cost, risk, and inconvenience of possible production issues and a lack of knowledge and information on these energy-efficient practices [5, 6]. Energy audits can help alleviate some of these concerns, address potential issues, and identify ways for industrial facilities to save money and resources through energy-efficient practices[7, 8]. Such audits target specific industrial systems, such as combustion systems, to help facilities identify energy-efficient practices that could be implemented. Out of many existing audit programs all around the world [9, 10], Industrial Assessment Centers (IACs) are funded by the U.S. Department of Energy and organized through universities across the country to provide energy audits for small to medium sized industrial facilities at no cost [11].

Even as energy audits benefit individual facilities, they can also benefit their greater communities by saving money, contributing to the local economy by creating jobs or purchasing materials, and improving the health of residents in the region by reducing greenhouse gas emissions [12]. These impacts can be quantified through energy audits and economic input-output models [13, 14]. The following description of this process opens with background information on energy-efficient combustion systems in section 2, followed with an explanation of the research steps and methodologies of the study in section 3. Section 4 then provides examples of the energy-efficient recommendations regarding combustion systems and analyzes their economic and environmental impacts on a facilities level. Section 5 analyzes the economy-wide impact of these energy-efficiency investments in combustion systems, and section 6 discusses the results and presents conclusions.

2. Energy efficient combustion systems

Combustion systems constitute a large part of industrial manufacturers' operations. Combustion processes release energy from burning a mixture of fuel and air and are used within manufacturing plants to produce heat or generate electricity. The traditional fuel and air used in combustion processes present opportunities to be updated for great cost and emission savings. A widely adopted energy-efficient oxy-fuel combustion practice replaces air with pure oxygen in combustion processes [15, 16], which minimizes the amount of nitrogen in the flue gas. In a coal combustion experiment, the oxy-fuel process provided a much higher carbon dioxide concentration than atmospheric combustion, raising that concentration from about 16% to 95% [17]. The resulting flue gas is made of carbon dioxide and water, which allows the carbon dioxide to be easily captured and recovered [18]. The oxy-fuel combustion process thus provides both a reduction in nitrous oxide emissions and greater combustion efficiency, as without the nitrogen in atmospheric combustion, the flame has a higher temperature and greater stability [19, 20].

Coal and natural gas boilers are frequently used for combustion in industrial settings with boilers accounting for nearly 40% of energy consumption in the industrial sector in the United States [21]. Coal combustion has a carbon emission factor of over half that of natural gas [22]. Switching a fuel to one that has a low carbon to hydrogen ratio can decrease emissions in the atmosphere [23]. In some instances, the addition of methanol to natural gas combustion has resulted in a faster burning rate and a decrease in hydrocarbon emissions [24, 25]. Several studies have reviewed alternative fuels that have the potential to decrease harmful emissions while retaining or improving the energy efficiency of combustion systems [26-28]. Aside from a few instances at varying energy levels, biodiesel fuels generally emitted fewer pollutants and were about as efficient as diesel operations at lower energy levels [29, 30].

According to a study performed on industrial boilers, the factors that contributed to lower boiler efficiencies included heat loss due to flue gas and unburnt carbon, which could account for up to 10% of lost heat [31]. A theoretical air to fuel ratio is calculated, but excess air, needs to be added to ensure enough oxygen for the complete combustion of the fuel, or else it can lead to the unburnt carbon and an increase in emissions [32]. According to the U.S. Environmental Protection Agency, the optimal excess air in a natural gas heating system for energy efficiency and pollution prevention is about 10% [33]. Higher levels of excess air decreases efficiency because they absorb heat and decrease the quantity of useful heat available to the process [34].

Heat loss due to flue gases and other practices can be improved by updating technology and operations [35]. Operating boilers in a modulation mode is better than in an on/off mode because it reduces the amount of heat lost from flue purging and drafts [36]. Stack dampers, which help manage the air flow through the exhaust stacks to save heat and energy, can prevent large amounts of heat loss by prohibiting natural air drafts from cycling through the flue chambers while a boiler is off [37]. Energy audits performed in lime manufacturers found that the vertical kilns used had about a 55% efficiency because they would lose large amounts of heat from flue gases exiting at high temperatures; with technology updates, that efficiency could increase up to 80-90% [38]. A portion of the high temperature heat could be recovered using a heat recovery system like a heat exchanger and be used elsewhere in the process, such as pre-heating the feedwater or combustion air for the boiler [39, 40]. In similar situations, heat for pre-heating the feedwater could be captured from the boiler blowdown [41], although optimizing boiler blowdown requires minimizing the amount of scale deposit in the boiler tubes, which can waste 2-5% of fuel [42].

By enforcing energy-efficient practices such as those discussed in this paper, it is estimated, greenhouse gas emissions in the United States could decrease by 50% in the next thirty years, with carbon dioxide emissions decreasing by up to 57% [43]. This article describes just a few of these energy-efficient practices, their savings, and cascading economic effects.

3. Methodology

To examine the direct benefits to the facility and broader benefits to the economy of implementing energy-efficient practices, the following steps were taken to determine the economic and environmental impacts of implementing energy-efficient combustion systems recommended by energy audits.

First, data was collected on 41 energy-efficiency recommendations regarding combustion systems that were implemented between 2008 and 2018 by facilities after an energy audit. During that period, a total of 223 participating manufacturing plants received such audits, which included 124 recommendations offered regarding the facilities' combustion systems. The combustion systems addressed by these recommendations can be divided into three major categories: furnaces, boilers, and fuel switching as shown in Table 1.

Table 1. Types of recommendations for making combustion systems more energy efficient

Category	Energy Efficiency Recommendations	Example of Specific EE recommendation
Furnaces, Ovens, & Directly Fired Operations	Improve combustion control capability	Convert two smelters' gas burners from atmospheric combustion to oxy-fuel combustion Replace pneumatic with motorized dampers and turn off the catalytic incinerator system during unoccupied period Run boiler in modulation mode while turning off the secondary boiler control stack fan based on burner operation Adjust operating pressure control to increase boiler cycling period
	Install automatic stack dampers	Install actuated damper in hot water boiler exhaust stack Partially close exhaust damper of continuous oven to reduce infiltration Install barometric damper in boiler flue Install actuated damper in boiler flue stack
Boilers	Analyze flue gas for proper air to fuel ratio	Trim boiler excess air to 10% Reduce excess combustion air in boilers Tune steam generators to maintain 10% excess air Reduce excess air by installing O_2 trim controls on thermal fluid heaters Tune oil heaters to reduce excess air to 10% Reduce excess combustion air to 20% on steam boiler
	Keep boiler tubes clean	Descale boilers
	Operate boilers on high-fire setting	Install a steam accumulator to minimize steam generator cycling Adjust boiler controls to operate all boilers in parallel
	Replace boiler	Utilize a larger hot oil boiler to reduce purge losses Replace old boiler controlled in on/off mode with new high efficiency boiler controlled in modulation mode
	Reduce excessive boiler blowdown	Install automatic blowdown controls on all process steam boilers Eliminate deaerator condensate overflow
	Replace obsolete burners with more efficient ones	Install VFD burner on boilers Use high efficiency water heater instead of steam boiler to produce hot water
	Use heat from boiler blowdown to preheat boiler feed water	Utilize boiler economizers
	Establish burner maintenance schedule	Shut-off boilers during non-production hours
Fuel Switching	Burn a less expensive grade of fuel	Utilize natural gas boiler as primary boiler and coal boiler as secondary Operate coal boiler in limited circumstances and use the natural gas boiler to meet steam demand

In the second step, the actual or estimated losses and gains were calculated in the combustion processes, necessary investments, and savings during the period under study. The implementation costs of the proposed recommendations include both labor and material costs. Maintenance and technology recommendations also require recurring labor or material costs. The annual savings calculated for this study include dollar and resource amounts that were saved by implementing these recommendations and thus could be reinvested into the facility and stimulate the local economy. In the third step, to further investigate the impact of implementing the energy-efficient recommendations upon the local economy, the Economic Input-Output Analysis method was adopted and applied [44]. In short, the economic impacts of such implementations can be direct, indirect, or induced. Direct impacts are due to increases in production sectors from implementing the energy-efficiency equipment. Indirect effects happen when these direct sectors are connected to other sectors by business interactions, which can lead to greater job creation and compensation for supplier. Induced effects include the additional spending due to the increased income of the personnel in the supply chain of the direct and indirect sectors. In the fourth step, the total environmental impacts of implementing the combustion system recommendations in the given period were calculated. Lastly, the energy audit data was used to extrapolate data for the region's entire manufacturing sector to put the impacts into perspective.

4. Case Studies of Energy-Efficient Combustion Systems

This section comprises seven selected technical examples that illustrate various energy-efficient combustion practices that were recommended by the audits and implemented by manufacturing facilities. A full list of the energy-efficient combustion recommendations can be found in Table 1. A total of 223 participating manufacturing plants received audits in the region between 2008 and 2018, which included 124 recommendations offered regarding the facilities' combustion systems.

4.1. Convert gas burners from atmospheric combustion to oxy-fuel combustion

One manufacturing plant had two smelter gas burners used for atmospheric combustion. Improving the combustion capability of the gas burners could be improved by converting the atmospheric combustion to oxy-fuel combustion. The oxy-fuel combustion process then provides a more energy-efficient process with a decrease in emissions. The efficiency levels of the atmospheric combustion and the oxy-fuel combustion processes were calculated using data gathered from the manufacturing plant. Using an energy balance on the combustion process, the combustion efficiency, η, can be written as in Eq. 1. This equation assumes an adiabatic process at constant pressure with no cooling where the chemical energy released during combustion is converted into sensible energy gain of the gasses.

$$\eta = \frac{[1+AF_s\times(1+EA)]\times c_p \times(T_c-T_{ex})}{HR} \tag{1}$$

Where:

Excess Air (EA) – 0.05

Specific Heat of Exhaust Products (c_p) – 1.089 kJ/kg-K

Exhaust Temperature (T_{ex}) – 1,672 K

Combustion Temperature (T_c) – 2,705 K

Heat of Reaction (HR) – 50,009 kJ/kg

The combustion for natural gas and atmospheric air is shown in Eq. 2.

$$CH_4 + 2(O_2 + 3.76\, N_2) \rightarrow CO_2 + 2\, H_2O + 7.52\, N_2 \tag{2}$$

The stoichiometric oxidizer to fuel ratio, AF_s, for Eq. 2 is 17.12. Replacing the atmospheric air with pure oxygen can decrease the oxidizer to fuel ratio. The combustion equation using pure oxygen can be written as Eq. 3.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{3}$$

Thus, the stoichiometric oxidizer to fuel ratio can be calculated as 4.00. Using pure oxygen would allow the combustion temperature to increase to 9,129 K. The efficiency of the combustion process was calculated as 42.8% for using natural gas and 84.4% by using pure oxygen. This is a significant increase from the efficiency of the atmospheric air combustion process. The natural gas savings from increased efficiency can be seen in Table 2.

Table 2. Recommendation savings calculations

	Value	**Units**
Current Natural Gas Usage	15,978	GJ/year
Proposed Natural Gas Usage	8,103	GJ/year
Natural Gas Savings	7,875	GJ/year

Though the process is significantly more efficient when using pure oxygen, the annual cost of pure oxygen would be about $65,600 for this facility. Implementing the oxy-fuel combustion process would require retrofitting the gas burners from the atmospheric combustion process. Plant management estimated this would cost about $150,000, of which $50,000 would be labor costs.

Taking this cost into account, the annual savings would be \$9,890. The carbon dioxide emission savings would be about 391 metric tons annually, and the payback for this implementation would be 182 months.

4.2. Install actuated damper in hot water boiler exhaust

In this case, a manufacturing plant had an atmospheric hot water boiler, which used natural gas and ambient air in the combustion process. In such a boiler, the exhaust fan in the flue draws air up from the bottom of the unit and the combustion products exit through the flue at the top of the hot water stack. When the boiler is not firing, the ambient air continues to be drawn through the boiler and exhausted to the outside. As the ambient air passes through the boiler, it cools the water inside the boiler. When the boiler is fired again, it must replace the heat lost when it was not firing. Heat losses to the ambient air can be significant. To minimize these losses, the exhaust fan can be turned off when the boiler is not firing and a damper can be placed in the flue to close it when the boiler is not firing. According to plant personnel, this boiler was firing 65% of the time. The heat lost when the boiler was not firing could be calculated using Eq. 4:

$$Q_{loss} = AAV \times PCP \times (T_{out} - T_{in}) \tag{4}$$

Where:

Actual Air Volume (AAV) – 3.52 m^3/s

Volumetric Heat Capacity (PCP) – 1210 J/m^3-K

Ambient Air Temperature (T_{in}) – 299 K

Nonfiring Stack Temperature (T_{out}) – 353 K

AAV can be calculated from the stoichiometric air volume of the natural gas as seen in Eq. 5.

$$AAV = \frac{EA \times RI \times \rho_{NG} \times AF_S}{\rho_A \times CF} \tag{5}$$

Where:

Excess Air (EA) – 5

Rated Input (RI) – 2,052 kJ/s

Density of Natural Gas (ρ_{NG}) – 0.8 kg/m^3

Stoichiometric Oxidizer to Fuel Ratio (AF_S) – 17.12

Density of Air (ρ_A) – 1.293 kg/m^3

Conversion Factor (CF) – 31,736 kJ/m^3

It is worth noting that the excess air in the boiler was measured using a combustion analyzer and outputted to be 500%. In this case, the energy loss was calculated to be 223,753 J/s. Using the calculated energy loss, the total energy savings can be calculated by Eq. 6:

$$E_s = \frac{Q_{loss} \times HPY}{\eta} \tag{6}$$

Where:

Heat Lost (Q_{loss}) – 223,753 J/s
Non-Firing Time (TPY) – 7,668,000 seconds/year
Boiler Efficiency (η) – 0.60

The total energy savings from implementing this recommendation were calculated as 2,860 GJ/yr and the total annual cost savings as $20,941. The total cost of implementing this recommendation was estimated to be $600, $400 of which was for labor. The estimated decrease in annual carbon dioxide emissions was 159 metric tons. With these costs and savings, the simple payback period would be about 1 month.

4.3. Trim boiler excess air

In another case study, a manufacturing plant had six boilers that provided steam to heat the curing and hydraulic press processes. The boilers used mechanical linkages that connected the natural gas supply valves with combustion air inlet dampers. In this configuration, combustion air intake is controlled based on natural gas input to the boiler. Excess air varies over the firing range, increasing as firing rate decreases. The savings in this case study were calculated using simulation software called HeatSim [45]. In this combustion simulation, the values in Table 3 were inputted to obtain the fuel savings for boiler 1 if the excess air was changed from more than 33% to just 10%. The other five boilers had differing inputs that affected their outputs.

Table 3. Input for combustion system simulation

Inputs	**Boiler 1**	**Units**
Rated burner input	2,726	kJ/s
Fraction rated burner input	95	%
Feedwater inlet temperature	361	K
Steam outlet temperature	459	K
Combustion air inlet temperature	300	K
Exhaust gas outlet temperature	515	K

Current fraction excess air	0.334	-
Target fraction excess air	0.10	-
Annual operation hours	8,760	Hours/year

The savings from changing the excess air to 0.10 in boiler 1 are shown in Table 4.

Table 4. Boiler 1 savings calculations

	Value	**Units**
Current Heat Input	2,589	kJ/s
Proposed Heat Input	2,537	kJ/s
Annual Natural Gas Savings	1,654	GJ/year

Applying the same calculations to the other boilers, they would have significant fuel savings ranging from 5,861 J/s to 62,546 J/s. By reducing the excess air for all six boilers, the manufacturing plant would save about $26,548 annually and decrease carbon dioxide emissions by 262 metric tons per year. Implementing these changes to all boilers would cost about $2,400 in labor costs. Taking the savings and costs into consideration, the simple payback of implementing this recommendation would be about 2 months.

4.4. Install VFD burners

A manufacturing plant was interested in replacing obsolete burners with variable frequency drive (VFD) burners, which were more advanced and efficient than the plant's existing burners. By controlling the amount of air used in combustion, VFD improves the efficiency of the process. It was recommended that new VFD burners be installed in two boilers in the plant. HeatSim can calculate the combustion efficiency when given the fuel type, inlet air temperature, exhaust temperature, and excess air of the process [45]. The results showed that combustion efficiency would increase from 80.1% to 82.0% and from 79.1% to 80.9% for boilers 1 and 2, respectively. Boilers 1 and 2 were rated at 1,318,844 and 1,494,689 J/s, respectively, and operate a total of 6,240 hours per year. Plant personnel estimated the boilers were 60% loaded, on average. Using the current and proposed efficiency values, the natural gas requirement can be calculated with Eq.7, and the heat delivered from the boiler can be calculated with Eq.8:

$$NG = RI \times L \tag{7}$$

$$\beta = NG \times \eta \tag{8}$$

Where:

Boiler 1 Rated Input (RI) –1,319 kJ/s

Boiler 1 Percent Loaded (L) – 0.60

Boiler 1 efficiency (η) – 0.801

By utilizing Eq.6 and Eq.7, the natural gas savings for both boilers were calculated as shown in Table 5.

Table 5. Boiler savings calculations

	Boiler 1	**Boiler 2**	**Units**
Current Natural Gas Requirement	711	897	kJ/s
Current Heat Delivered	634	709	kJ/s
Proposed Natural Gas Requirement	520	574	kJ/s
Natural Gas Savings	191	323	kJ/s

The annual savings would be $74,000. According to plant management, the implementation cost would be $124,534. The annual carbon dioxide emission savings would be 668 metric tons. The simple payback would be around 21 months.

4.5. Shutting off boilers during non-production hours

The manufacturing plant in another case had boilers that operated during production and non-production hours year-round. The boilers operated at about 827 kpa during production hours and 345 kpa during non-production hours. Although reducing the boiler pressure during non-production hours did reduce boiler natural gas consumption, the boilers still used about 60% as much gas during non-production hours as during production hours. Shutting off the boilers during non-production hours for eight months per year could offer significant savings at the plant. It was anticipated that during the four coldest months of the year, at least one boiler might need to remain running during off-production hours to prevent the plant from becoming too cold. To estimate the boilers' natural gas consumption during production and non-production hours, the boiler and steam system was modeled as shown in Fig. 1. In this simplified model, all process heat used and non-production heat losses were assumed to occur in the presses, which were the largest steam users in the plant. During production hours, the throttling valve reduced steam pressure to the presses from 827 kpa to 414 kpa. During non-production hours, this valve would reduce steam pressure from 345 kpa to 172 kpa.

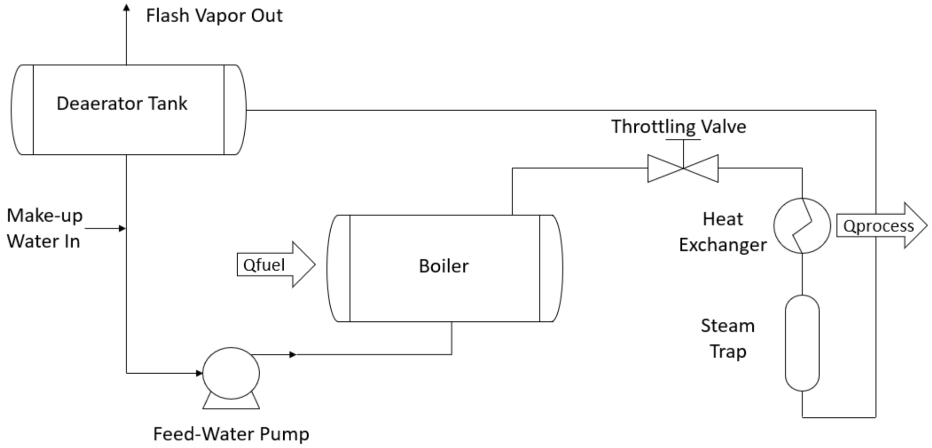

Fig. 1. Boiler system setup

Energy and mass balances were used to model the boiler and steam system. The results indicate that, during production hours, the boiler required 2,391 kJ/kg-steam of heat to deliver 2,129 kJ/kg-steam to the process. During non-production hours, the presses were left open, resulting in unrestrained heat loss. As a result, the boiler required 1,664 kJ/kg-steam of heat to deliver 1,558 kJ/kg-steam. Thus, the fraction of heat supplied by the boiler to the steam during non-production hours is about 70% of that during production hours. According to plant data, the average natural gas use per day during the 8 summer months was about 160 GJ. The plant produces parts for about 10 hours per day. The heat added by the boiler during production hours can be calculated with Eq. 9.

$$Q_{add} = \frac{NG}{TPD \times (1-.70) + 86{,}400\frac{seconds}{day} \times 0.70} \tag{9}$$

Where:

Daily Natural Gas Usage (NG) – 160 GJ
Production Time per Day (TPD) – 36,000 seconds

From the eq. 8, the heat added by the boiler is 2,244,669 GJ/s.

According to maintenance personnel, it takes 3 hours to warm up the boilers and presses, meaning that the presses would have to run for 13 hours a day if they were shut down at night. The annual natural gas savings for shutting off the boilers on nights and weekends for 8 months of the year would be 18,597 GJ. By shutting the boilers off during non-production hours, the plant would save about $180,324 annually. The cost to implement this recommendation would be about

$20,000 for labor and material. The annual carbon dioxide savings would be about 935 metric tons. The simple payback for this recommendation would be about 1 month.

4.6. Install automatic blowdown controls on all three process steam boilers

The manufacturing facility in another case study had two 149 kW boilers and one 56 kW boiler, which together provided 793 kpa of steam to the plant. Boilers must discharge some steam as blowdown to maintain acceptable levels of contaminants and avoid scaling in the boiler. Depending on the quality of the makeup water, the boiler blowdown rate typically ranges from 4% to 10% of the boiler feedwater rate. For these boilers, the blowdown was continuous at about a 10% blowdown rate. Continuous blowdown methods always result in excessive contaminant blowdown. The best way to minimize blowdown while minimizing scale and buildup is to install an automatic system that measures the concentration of a key indicator of contamination and discharges the exact amount of necessary blowdown, reducing the blowdown rate and saving natural gas, water consumption, and costs. SteamSim software is an application used to simulate boiler and steam systems [46]. All known information can be inputted into the software to get the heat consumption or losses and efficiency at various stages throughout the process. In this simulation, the blowdown input was changed from 0.1 to 0.04. Fig. 2 illustrates the facility's current steam system with a continuous 10% blowdown. According to management, the boilers operate a total of 8,760 hours per year. By running simulations of the current and the proposed steam systems, the potential natural gas, water, and sewer savings were calculated as shown in Table 6. In Fig. 2, the Q_{fuel} is the boiler's natural gas consumption, which was the only major change as a result of changing the blowdown.

Table 6. Boiler and Steam savings calculations

	Value	**Units**
Current Natural Gas Usage	2,316	kJ/s
Proposed Natural Gas Usage	2,173	kJ/s
Natural Gas Savings	143	kJ/s
Water Flow Rate Savings	0.00025	m^3/s
Current Steam System Efficiency	58.3%	-
Proposed Steam System Efficiency	62.1%	-

The fuel, water, and sewer savings would amount to a total cost savings of $35,463 annually. The implementation cost would be about $15,000. The annual carbon dioxide savings from a reduction in the natural gas consumption would be about 226 metric tons. The simple payback of implementing this recommendation would be about six months.

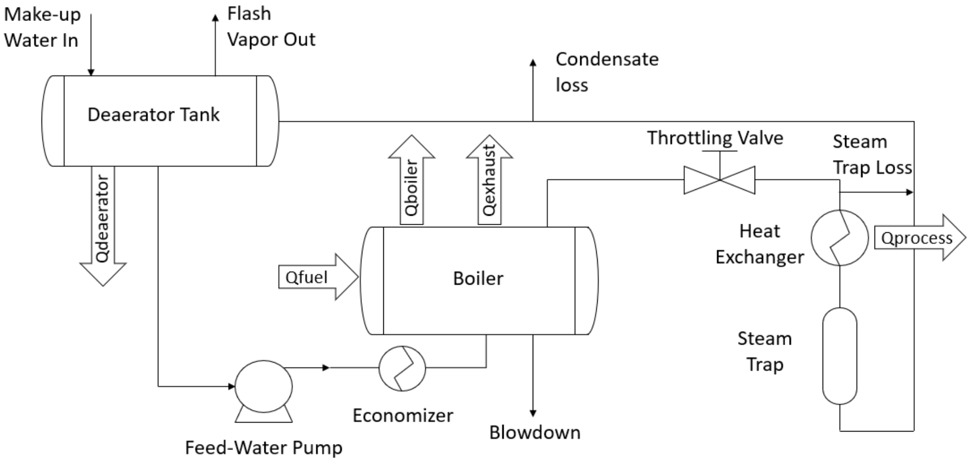

Fig. 2. Boiler system setup

4.7. Switch fuels to a less expensive grade

In the final case study, a manufacturing plant used two boilers for the space conditioning and heating of two buildings. Together, the primary boiler, which runs on coal, and the secondary boiler, which runs on natural gas, provided 689-827 kpa of steam. The plant's boiler operator indicated that the natural gas boiler could be operated as the primary boiler and the coal boiler as the secondary boiler without any system modifications, which would result in fuel and cost savings due to the gas boiler's higher generation efficiency and lower fuel unit cost. Using the information from the plant, the efficiency of the coal steam system was calculated to be 55.3%. The cost of coal at this plant was $6.03/GJ, resulting in a unit cost of $10.89/ GJ steam delivered from coal. For the natural gas boiler, the efficiency was 64.9% and the cost of natural gas was $4.32/GJ, leading to a unit cost of $6.65/GJ for steam delivered from natural gas. According to plant personnel, the natural gas boiler could be consistently operated at 6.93 kg-steam/s if it were the primary boiler. The steam demand at the facility would only be greater than 6.93 kg-steam/s for 20 days per year, during which the coal boiler would need to be operated. Given that peak facility steam demand is 10.08 kg-steam/s, the need for the coal boiler should not exceed 3.15 kg-steam/s on a high-demand day, or an annual steam generation of about 5,443,108 kg steam. Applying the energy efficiency of the coal boiler, the annual coal use would be 19,994 GJ.

By utilizing the natural gas boiler as the primary boiler, the plant would save about $544,478 annually. Furthermore, there would be no cost for implementing this recommendation because it would not require any system modifications. The annual carbon dioxide emission savings would be 9,517 metric tons. The simple payback would be immediate.

5. Regional economic and environmental impacts

The cost, savings, and simple payback for the 41 energy efficient combustion system recommendations in 2008-2018 are provided in Table 7.

Table 7. Implementation costs and expected savings from the EE combustion systems (2008-2018)

Category	Labor Cost	Material Cost	Savings	Avg. Payback (yrs)
Furnaces, Ovens, Directly-Fired	\$52,000	\$108,460	\$57,058	2
Boilers	\$39,743	\$261,754	\$713,084	0.5
Fuel Switching	\$0	\$0	\$968,902	0
Total	**\$91,943**	**\$370,214**	**\$1,739,044**	**1**

Beyond the energy cost savings to the industry illustrated by the above case studies, the broader impact of these changes were determined. These included the direct economic impact of purchasing energy-efficiency equipment from other manufacturers; the indirect economic impact of obtaining goods and services associated with the manufacturing and installation of energy efficiency measures; the induced economic impact of the increased disposable income of the workforce; and the job creation made possible by direct, indirect, and induced economic activities. The North American Industry Classification System (NAICS) consists of 546 economic sectors [47]. Six industry sectors were identified that would be directly impacted by the implementation of combustion systems and allocated the identified labor and material implementation costs to those sectors as shown in Table 8. Using IMPLAN software, the impact on each was analyzed for the entire region between 2008 and 2018, expressed in 2020 dollars.

Table 8 Economic sectors where direct cash investments were made by implementations

NAICS	Economic sector description	Allocated investment
221330	Water, sewage, and other systems	\$23,620
332410	Power boiler and heat exchanger manufacturing	\$4,700
333414	Heating equipment (except warm air furnaces) manufacturing	\$283,634
334512	Automatic environmental control manufacturing	\$21,360
334513	Industrial process variable instruments manufacturing	\$26,630
238220	Commercial and industrial machinery repair and maintenance	\$80,643

This analysis identified which areas would be most impacted by implementing energy efficient combustion practices. Fig. 3 shows a percentile breakdown of the impacts for the top 15 affected economic sectors. Five of those sectors reflect direct investments made to improve the energy efficiency of combustion systems through purchases of technology or engineering consulting services to install the measures. The sectors that are indirectly impacted by these direct investments are typically sectors that supply parts for the direct economic sectors. This analysis also identified some sectors that unexpectedly benefited from the investment of the energy-efficient combustion systems by manufacturers, such as the hospitals and real estate sectors, which profited from increased spending made possible by higher compensation or job increases among residents related to the energy-efficient combustion systems.

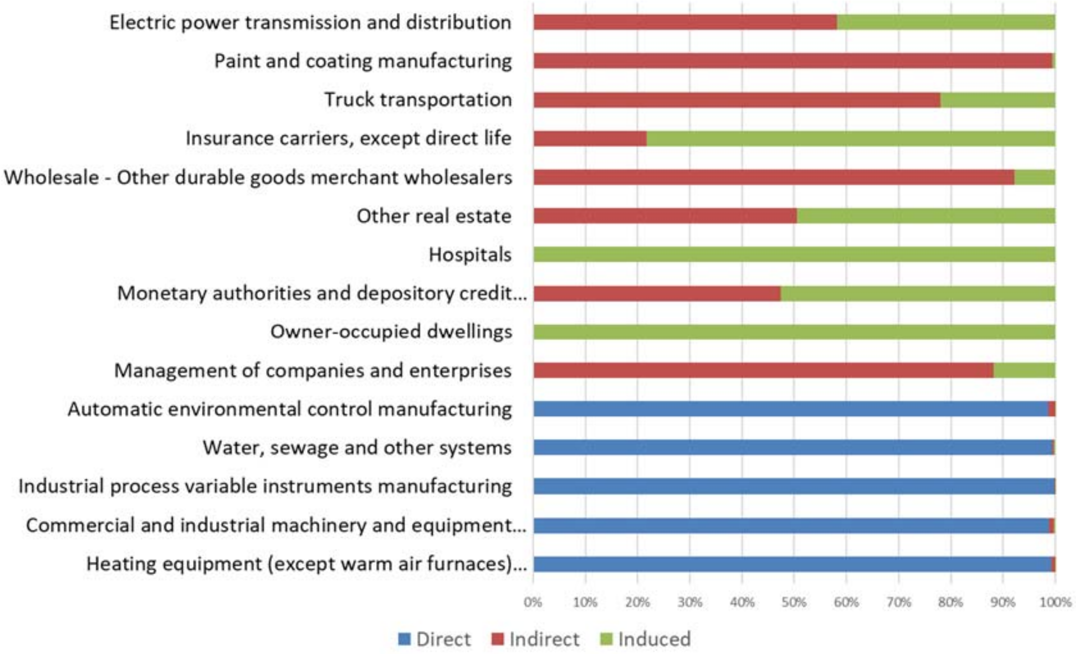

Fig. 3. Percentage breakdown of economic impact on 15 selected sectors

Fig.4 shows the economic and environmental impacts of implementing the recommended energy efficient combustion systems. The first scenario includes the estimated savings and impacts from the 41 combustion recommendations that were implemented during the studied time and region. The second scenario includes the estimated savings and impacts of the 82 non-implemented combustion recommendations made in that time period and region. The third scenario considers the likely results if all 123 recommendations had been implemented. Scenario 1 indicates that the audited SMEs implemented recommendations that provided a quicker simple back period, which averaged 3.2 months. The annual savings of the 41 implemented recommendations were about $1.74 million, for which SMEs invested about $462k in implementation costs. Scenario 2 shows that the expected simple payback for the non-implemented assessment recommendations would be 10.4 months, which is still a good payback. Because the energy intensity of combustion systems is typically higher than that of other industrial energy systems, these energy savings are significant when implemented. Nonetheless, the high initial investment costs of these non-implemented recommendations are often a significant burden for SMEs. In terms of emissions, similar amounts of carbon dioxide could expect to be avoided by implementing scenarios 1 and 2. If all 123 combustion recommendations were implemented, as in scenario 3, the average simple payback period would be 6.7 months, and 43,000 metric tons of carbon dioxide would be avoided annually.

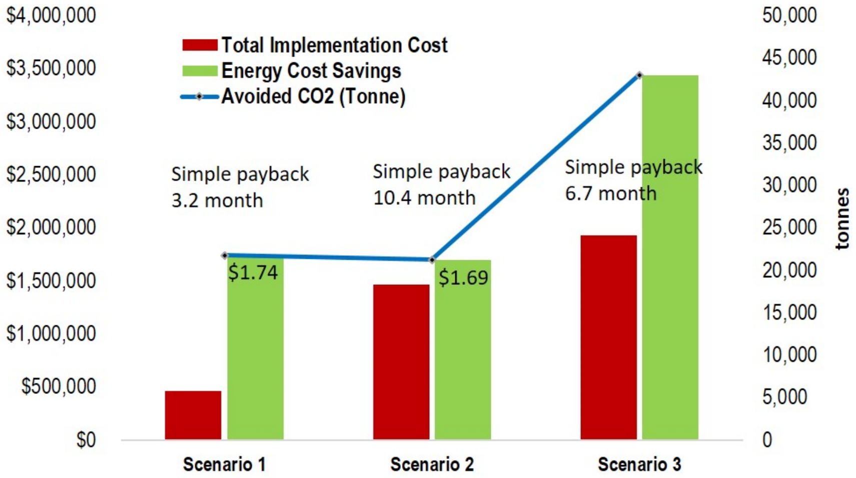

Fig. 4 Comparison of economic and environmental impacts of three scenarios

To put these savings and impacts from the recommendations into perspective, estimations for the entire region were extrapolated from the same data. Between 2008 and 2018, the implementation rate for the studied energy efficiency recommendations for combustion systems was 33%. The studied region has an annual manufacturing output of over $112 billion from over 12,000 manufacturing firms [48]. In terms of emissions, the region's industrial sector produces about 35.5 million metric tons annually, about 17.3% of the entire region's total carbon dioxide emissions [49]. If all the combustion recommendations were implemented among all manufacturers in the region, it is expected that a total of $185M would be saved in energy costs and 2.3 million metric tons of carbon dioxide emissions would be avoided annually.

Fig. 5 illustrates the regional economy-wide impacts of the three scenarios explained above. IMPLAN software was utilized to determine the cascading impacts of implementing these energy efficiency measures for combustion systems. The direct impacts would be generated from the increased production of equipment and labor required for implementing the combustion EE measures. The indirect impacts would be accrued by the supply chain of the OEM of the combustion EE measures. The induced impacts capture the likely increased economic activities from the backward-linked regional economic sectors. If all 123 recommendations were implemented by the 223 participating manufacturing plants, about 18 jobs could be created; extrapolating this number to all manufacturers in the region, 972 jobs could be created. As the figure demonstrates, scenario 2 has larger cascading economic impacts than scenario 1 because higher direct investments would be required for implementing the energy efficiency measures.

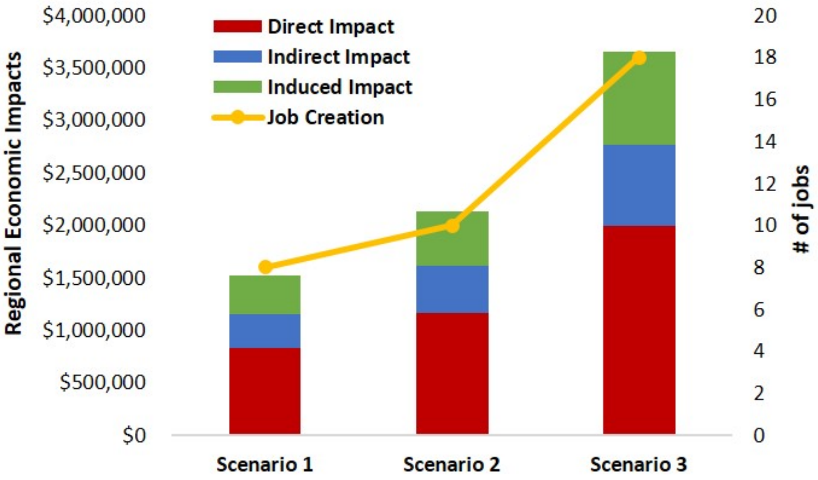

Fig. 5 Comparison of economic and environmental impacts of three scenarios

6. Conclusions

Improving energy efficiency is becoming increasingly necessary in manufacturing industries due to decreasing natural resources and increasing greenhouse gas emissions. These case studies of combustion recommendations that were implemented in industrial facilities from 2008 to 2018 provide examples of the kinds of measures that can be taken and the positive direct, indirect, and induced economic impacts they can have on industries, local communities, states, and even the country.

Though all these case studies exhibit important impacts on the facilities and their communities, the case studies with the most immediate payback and energy savings should be investigated at all facilities where applicable. First, installing an actuated damper would reduce unwanted air flow through the boiler. Though this is not a novel recommendation, it is relatively easy to implement. Next, monitoring and trimming boiler excess air when needed is important maintenance that optimizes the boiler's efficiency and prevents high pollution levels. Lastly, shutting off boilers when not in use can be an easy recommendation to adopt with immediate results. These three recommendations have low implementation costs, so the immediacy of energy savings and emission reductions is high which guarantees a quick and long-lasting effect on the facility.

As the results of this study show, energy-efficient combustion practices offer an opportunity to significantly increase savings and decrease carbon dioxide emissions while contributing to economic growth. The energy savings that result from improving or updating the operations and technologies in a manufacturing facility lead to a reduction in utility usage and carbon dioxide emissions. The implementation costs of the recommendations also spur an increase in the demand for regional economic goods and services. Though this paper focuses on one region, similar methods can be applied to other larger regions to determine the value of energy-efficient practices in combustion systems in manufacturers of all sizes.

Governmental policies can help manufacturers transition to energy efficient practices. Because some facilities are hesitant to implement recommendations because it is inconvenient, or the implementation cost is too high, state and federal subsidies or rebates might encourage energy efficient practices by manufacturers by easing the cost and inconvenience of the transition. The broader view afforded by the proposed framework can be used to support better energy policy decisions and improve the current understanding of the relationship between energy and the economy and environment while emphasizing the importance of energy efficient practices in manufacturing facilities, communities, and states.

Although the economic input-output model is a great methodology to analyze the interindustry transaction of an economy, the model includes some potential limitations. The model assumes constant returns to scale. In other words, the industrial production recipe is fixed, and the model does not treat the interindustry transaction dynamically. It is good for the stationary economy; however, it lacks on accounting for the technical changes in the economy dynamically. In the future, some other advanced economic model can be adopted to estimate more accurate broader impacts of industrial combustion system's energy savings opportunities.

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Disclaimer

Nomenclature

EA – excess air
C_p – specific heat of exhaust products
T_{ex} – exhaust temperature
T_c – combustion temperature
HR – heat of reaction
AF_S – stoichiometric oxidizer to fuel ratio
Q_{loss} – heat lost
AAV – actual air volume
PCP – volumetric heat capacity
T_{in} – ambient air temperature
T_{out} – nonfiring stack temperature
RI – rated input
ρ_{NG} – density of natural gas
ρ_A– density of air
CF – conversion factor
TPY – time per year
η – efficiency
L – percent loaded

NG – natural gas requirement

β – heat delivered

Q_{add} – heat added by boiler

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