Steam Systems in Industry:
Energy Use and Energy Efficiency Improvement Potentials

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ABSTRACT

Steam systems are a part of almost every major industrial process today. Thirty-seven percent of the fossil fuel burned in US industry is burned to produce steam. In this paper we will establish baseline energy consumption for steam systems. Based on a detailed analysis of boiler energy use we estimate current energy use in boilers in U.S. industry at 6.1 Quads (6.4 EJ), emitting almost 66 MtC in CO_2 emissions. We will discuss fuels used and boiler size distribution. We also describe potential savings measures, and estimate the economic energy savings potential in U.S. industry (i.e. having payback period of 3 years or less). We estimate the nationwide economic potential, based on the evaluation of 16 individual measures in steam generation and distribution. The analysis excludes the efficient use of steam and increased heat recovery. Based on the analysis we estimate the economic potential at 18-20% of total boiler energy use, resulting in energy savings approximately 1120-1190 TBtu (1180-1260 PJ). This results in a reduction of CO_2 emissions equivalent to 12-13 MtC.

Introduction

Steam systems are a part of almost every major industrial process today. Thirty-seven percent of the fossil fuel burned in US industry is burned to produce steam. This steam, in turn, is used to heat processes, to concentrate and distill liquids, or is used directly as a feedstock. All of the major industrial energy users devote significant proportions of their fossil fuel consumption to steam production: food processing (57%), pulp and paper (81%), chemicals (42%), petroleum refining (23%), and primary metals (10%). Since industrial systems are very diverse, but often have major steam systems in common, it makes a useful target for energy efficiency measures. In this paper we will establish baseline energy consumption for steam systems, describe potential savings measures, and estimate a cost effective energy savings potential for the industry. These energy savings are also presented as CO_2 emissions reductions to show the potential for energy efficiency measures to reduce the industrial contribution to GHG emissions.

Methodology

To establish a cost effective energy efficiency potential, we first must derive a baseline steam energy consumption for all industry and for the energy intensive industries[1]. This energy consumption estimate is based on the Manufacturing Energy Consumption Survey (MECS) produced by the Energy Information Administration. MECS gives the percentage of

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[1] The energy intensive industries are considered to be: food processing, pulp and paper, chemicals, petroleum refining, and primary metals.

fossil fuels that are used in boilers, but does not give this percentage for waste and biomass fuels. As a result we had to combine the MECS boiler fuel use data with our own estimates of how much waste and biomass fuel was used for steam production in each industry. Since we only had information on biomass and waste fuel use in the major energy intensive industries, an estimated 2% of all industrial fuel use is still unallocated.

Next, several technologies are analyzed for their savings potential. We only included only measures that were commonly available and easily applicable to a wide variety of industries. This was done ensure that our savings estimate was robust, but also means that our estimate is very conservative. If we had taken more costly, newer, and more industry specific technologies, there would likely have been some additional savings not described in our paper.

The savings potential is based on technical estimates of energy savings and experiential estimates. The energy savings estimates come from many case studies, where the technology was implemented. The information we used comes primarily from industry journals, but also includes data from organizations that promote energy efficiency. We take the savings and apply it to the industrial steam systems where it is still possible to implement. The implementation potential is based on the extent to which the measure is already implemented, and the possibility that there are barriers to implementation. For example, we have estimated that boiler maintenance could be improved in 20% of plants, based on our discussions with industry (CIBO, 1998; OIT, 1998).

With the baseline and the series of energy efficiency measures, we are able to produce an overall savings estimate. We calculate a total cost effective efficiency potential by summing the potential of all measures where implementation cost is lower than fuel cost savings. We determine the cost of implementation by calculating the Cost of Conserved Energy (CCE) which summarizes the annual costs associated with saving a GJ (approximately 0.95 MBtu) of energy with a particular measure. The CCE is calculated as follows:

$$\text{CCE} = \frac{\text{Annualized Investment(\$)} + \text{Annual Change in O \& M Costs (\$)}}{\text{Annual Energy Savings (GJ)}}$$

The annualized investment, in turn, is calculated as follows:

$$\text{Annualized Investment} = \text{Capital Cost} \times \frac{d}{\left(1-(1+d)^{-n}\right)}$$

where d is the discount rate (set to 30%[2]), and n is the expected lifetime of the measure.

The method to calculate efficiency potential is necessarily limited, since we did not include measures to improve the transfer of heat from the steam to the final process. Our financial analysis was limited to capital, maintenance, and energy costs, while additional factors, such as: productivity increases, changing environmental compliance costs, work safety and health compliance costs, as well as opportunity costs were not considered for this analysis.

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[2] This rate is higher than the average market return, but is deliberately set high to account for hurdle rates commonly used in industry.

Process Overview

The use of steam as a heat source has a long and diverse history, first applied to home heating as early as Roman times and common today in large industrial settings. While the exact size and use of a modern system varies greatly, there is an overall pattern that steam systems follow, as shown in Figure 1.

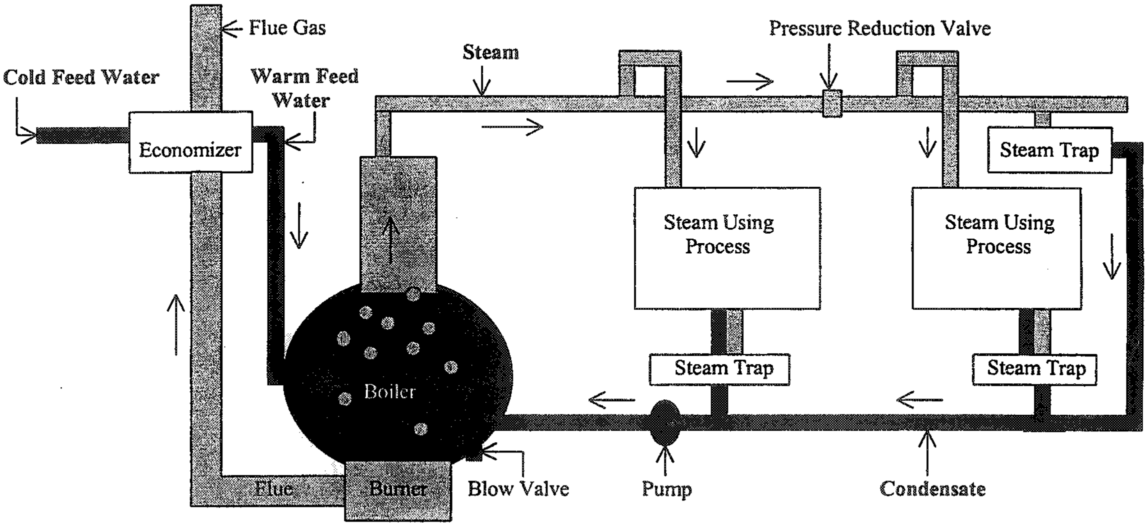

Figure 1. Schematic Presentation of a Steam Production and Distribution System.

Treated cold feed water is fed to the boiler, where it is heated to form steam. Chemical treatment of the feed water is required to remove impurities. The impurities would otherwise collect on the boiler walls. Even though the feed water has been treated, some impurities still remain and can build up in the boiler water. As a result, water is periodically drained from the bottom of the boiler in a process known as blowdown. The generated steam travels along the pipes of the distribution system to get to the process where its heat will be used. Sometimes the steam is passed through a pressure reduction valve if the process requires lower pressure steam. As the steam is used to heat processes, and even as it travels through the distribution system to get there, the steam cools and some of it condenses. This condensate is removed by a steam trap, which allows condensate to pass through, but blocks the passage of steam. The condensate can be recirculated to the boiler, thus recovering some heat and reducing the need for fresh treated feed water.

Industry uses steam for a wide variety of purposes, the most important being process heating, drying or concentrating, steam cracking, and distillation. Drying or concentration uses steam to evaporate water to concentrate solids in a solution, or to dry out a solid product. Cracking is used to produce lighter fuels, and simply consists of heating steam and fuel together in a high-pressure chamber. Distillation is used to separate out specific chemicals or fuels out of a complex feedstock. Table 1 summarizes steam use in various sectors of US industry.

Table 1. Steam Use by Industry Sector. Estimates include MECS boiler fuel use and fuel that we assumed was used in boiler (see also Table 2).

Industry Sector	Total (PJ)	% of Total
All Industry Groups	6,383	100.0%
All Energy Intensive Industry Groups	5,442	85.3%
Food and Kindred Products	706	11.1%
Tobacco Products	3	0.0%
Textile Mill Products	138	2.2%
Apparel and Other Textile Products	9	0.1%
Lumber and Wood Products	310	4.9%
Paper and Allied Products	2,256	35.3%
Printing and Publishing	13	0.2%
Chemicals and Allied Products	1,463	22.9%
Petroleum and Coal Products	777	12.2%
Petroleum Refining	758	11.9%
Rubber and Misc. Plastics Products	76	1.2%
Leather and Leather Products	4	0.1%
Stone, Clay and Glass Products	34	0.5%
Cement, Hydraulic	2	0.0%
Primary Metal Industries	260	4.1%
Blast Furnace and Basic Steel Products	220	3.5%
Primary Aluminum	0	0.0%
Fabricated Metal Products	45	0.7%
Industrial Machinery and Equipment	36	0.6%
Electronic and Other Electric Equipment	35	0.5%
Transportation Equipment	97	1.5%
Instruments and Related Products	42	0.7%
Misc. Manufacturing Industries	7	0.1%

Source: EIA, 1997

Baseline Energy Consumption for Steam Production

We had to establish a 'new' baseline for energy use by boilers because, firstly, the statistics for fuel input and steam output come from different databases. These databases set slightly different parameters for which boilers they count, making it impossible to compare the two and produce an overall boiler efficiency measurement. Secondly, there are no statistics for heat demand at the process end, so direct calculation of steam system efficiency is impossible.

Table 2 shows the fuel used by steam systems in industry. The values shown represent final energy use[3] and higher heating values of fuels[4]. Table 3 shows that the main fuels used in steam generation are natural gas and coal.

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[3] Final energy simply represents all the energy consumed at an industrial facility. Purchased electricity and steam are accounted by simple energy content as they enter the facility. This is in contrast to primary energy which includes the energy used to make that steam and electricity. For the United States in 1994, the electric generation efficiency was 32.1%.

[4] Higher heating values represent the heat content of fuels, including the latent heat contained in the water vapor produced when the fuel is burned. Although this somewhat overestimates the useful energy contained in fuel (since flue gasses usually exit the plant hotter than the boiling point of water) it is the standard used in US statistics.

Different fuels have different efficiencies because of the hydrogen content of the fuel. When a fuel is burned, the hydrogen becomes water. Energy must be expended to boil this water, and the water escapes as part of the flue gas. Thus, the higher the hydrogen content of the fuel, the more energy is lost to the flue gas. The efficiency of coal boilers varies between 81 and 85%, for oil between 78 and 81% and for gas between 76% and 81% (HHV) (OIT, 1998). Boilers are sometimes poorly maintained, and can lose up to 30% of their original efficiency as a result (OIT, 1998). Table 4 shows the size distribution of boilers in industry. Note that the chemical industry has by far the largest capacity of small boilers, while paper has the largest capacity of large boilers.

Table 2. US Final Energy[a] Baseline for Steam Production in U.S. Industry (1994).

	Energy Intensive Industry			Total Industry		
	Steam System Consumption	**Total Consumption**	**Steam System Consumption**	**Steam System Consumption**	**Total Consumption**	**Steam System Consumption**
Fuel	(PJ)	(PJ)	(% of Energy Intensive Industry)	(PJ)	(PJ)	(% of Total Industry)
Electricity	18	1,633	1%	30	2,802	1%
Oil	306	458	67%	375	626	60%
Natural Gas	2,148	4,912	44%	2,528	6,479	39%
LPG	14	17	81%	16	104	15%
Coal	781	824	95%	923	1,264	73%
Other[b]	2,176[c]	5,066	43%	2,512[c]	6,149	41%
Total	5,442	13,516	40%	6,383	17,423	37%

Source: EIA, 1997; Worrell et al. 1999

a. Excludes feedstocks

b. Mostly biomass and waste used as fuel.

c. This number assumes the following: All biomass fuel and waste oil is used in boilers; The proportion of waste gas used in boilers is the same as the proportion of natural gas used for this purpose, and 81 PJ of coke oven gas and blast furnace gas is used to power boilers (Worrell et al. 1999)

Table 3. Carbon Emissions from the Production of Steam in US Industry (1994)

	Energy Intensive Industry			Total Industry		
	Steam System Emissions	**Total Emissions**	**Steam System Emissions**	**Steam System Emissions**	**Total Emissions**	**Steam System Emissions**
Fuel	(MtC)	(MtC)	(% of Energy Intensive Industry)	(MtC)	(MtC)	(% of Total Industry)
Electricity[a]	0.9	79.2	1%	1.4	135.9	1%
Oil	6.1	9.1	67%	7.5	12.4	60%
Natural Gas	29.6	67.6	44%	34.8	89.2	39%
LPG	0.2	0.3	81%	0.3	1.7	15%
Coal	18.7	19.8	95%	22.1	30.3	73%
Other[b]	0.0	0.0	N/A	0.0	0.0	N/A
Total	55.5	176.0	32%	66.1	269.5	25%

Source: EIA, 1997

a. Carbon Emissions from electricity are calculated based on electric utility carbon emissions. 3% of purchased electricity comes from non-utility sources (4% for energy intensive industries alone) (EIA, 1997).

b. Mostly biomass and waste used as fuel.

Table 4. Distribution of Boilers by Size and Major Industrial sector in U.S. Industry

	11-53 GJ/hr		54-106 GJ/hr		107-264 GJ/hr		>264 GJ/hr		Total
	GJ/hr	%	GJ/hr	%	GJ/hr	%	GJ/hr	%	GJ/hr
Chemicals	135,051	25.7%	82,523	15.7%	151,097	28.8%	156,373	29.8%	525,044
Food	98,573	35.9%	68,869	25.1%	69,982	25.5%	36,984	13.5%	274,409
Paper	39,282	10.1%	42,630	10.9%	96,895	24.9%	210,809	54.1%	389,617
Refining	34,744	15.7%	29,934	13.5%	50,607	22.9%	106,106	47.9%	221,391
Primary Metals	56,341	28.2%	24,583	12.3%	43,694	21.9%	75,216	37.6%	199,834

Source: GRI, 1996. Note: The size ranges are uneven numbers because the original data was in Btu

Energy Efficiency Measures for Boilers

1. Improved process control. Flue gas monitors are used to maintain optimum flame temperature, and monitor CO, oxygen and smoke. The oxygen content of the exhaust gas is a combination of excess air (which is deliberately introduced to improve safety or reduce emissions) and air infiltration (air leaking into the boiler). By combining an oxygen monitor with an intake airflow monitor, it is possible to detect (small) leaks. Using a combination of CO and oxygen readings, it is possible to optimize the fuel/air mixture for high flame temperature (and thus the best energy efficiency) and low emissions. We assume that this measure can be applied to all large boilers (62% of total boiler capacity) because of its 0.6 year payback (IAC, 1999), saving about 3% (Zeitz, 1995). This measure may be too expensive for small boilers.

2. Reduce flue gas quantities. Often, excessive flue gas results from leaks in the boiler and the flue, reducing the heat transferred to the steam, and increasing pumping requirements. These leaks are often easily repaired. Savings amount to 2-5% (OIT, 1998). This measure consists of a periodic repair based on visual inspection. The savings from this measure and from flue gas monitoring are not cumulative, as they both address the same losses, hence we exclude it in our savings estimate.

3. Reduce excess air. The more air is used to burn the fuel, the more heat is wasted in heating air. Air slightly in excess of the ideal stochiometric fuel/air ratio is required for safety, and to reduce NO_x emissions, but approximately 15% is adequate (OIT, 1998; Ganapathy, 1994). Poorly maintained boilers can have up to 140% excess air. Reducing this back down to 15% even without continuous automatic monitoring would save 8%. The vast majority of boilers already operate at 15% excess air or lower, and the measure is not considered to result in significant savings.

4. Improve insulation. New materials insulate better, and have a lower heat capacity. Savings of 6-26% can be achieved if this improved insulation is combined with improved heater circuit controls. This improved control is required to maintain the output temperature range of the old firebrick system. As a result of the ceramic fiber's lower heat capacity the output temperature is more vulnerable to temperature fluctuations in the heating elements. (Caffal, 1995). We do not have sufficient information to determine energy savings in US industries.

5. Maintain boilers. In the absence of a good maintenance system, the burners and condensate return systems can wear or get out of adjustment. These factors can end up costing a steam system up to 20-30% of initial efficiency over 2-3 years (OIT, 1998). We estimate a 10% possible energy savings (OIT, 1998) for 20% of all boilers, based on energy audits across US industries (IAC, 1999).

6. Recover heat from flue gas. Heat from flue gasses can be used to preheat boiler feed water in an economizer. While this measure is fairly common in large boilers, there is often still potential for more heat recovery. The limiting factor for flue gas heat recovery is the economizer wall temperature that should not drop below the dew point of acids in the flue gas. Traditionally this is done by keeping the flue gasses at a temperature significantly above the acid dew point. However, the economizer wall temperature is more dependent on the feed water temperature than flue gas temperature because of the high heat transfer coefficient of water. As a result, it makes more sense to preheat the feed water to close to the acid dew point before it enters the economizer. This allows the economizer to be designed so that the flue gas exiting the economizer is just barely above the acid dew point. 1% of fuel use is saved for every 25°C reduction in exhaust gas temperature. (Ganapathy, 1994). Since exhaust gas temperatures are already quite low, we assume a 1% savings across all boilers, with a payback of 2 years (IAC, 1999).

7. Recover steam from blowdown. When the water is blown from the high pressure boiler tank, the pressure reduction often produces substantial amounts of steam. This steam is low grade, but can be used for space heating and feed water preheating. We assume that this measure can save 1.3% of boiler fuel use[5] for all small boilers (38% of total boiler capacity)[6] with a payback of 2.7 years (IAC, 1999).

Table 5. Summary of Energy Efficiency Measures in Industrial Boilers

Measure	**Fuel Saved**	**Payback Period (years)**	**Implementation Potential**	**Other Benefits**
Improved Process Control	3%	0.6	59%	Reduced Emissions
Reduced Flue Gas Quantity	2-5%	-	-	Cheaper emission controls
Reduced Excess Air	1% improvement for each 15% less excess air	-	0%	
Improved Insulation	6-26%	?	-	Faster warm-up
Boiler Maintenance	10%	0	20%	Reduced emissions
Flue Gas Heat Recovery	1%	2	100%	
Blowdown Steam Heat Recovery	1.3%	2.7	41%	Reduced damage to structures (less moist air is less corrosive).
Alternative Fuels	Variable	-	-	Reduces solid waste stream at the cost of increased air emissions

Energy Efficiency Measures for Heat Distribution

1. Improve insulation. This measure can be to use more insulating material, or to make a careful analysis of the proper insulation material. Crucial factors in choosing insulating

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[5] Based on the following assumptions: 10% of boiler water is blown down (OIT, 1998) and 13% of the energy can be recovered from this (Johnston, 1995).

[6] All heavy industry boilers less than 100MMBtu/hr (GRI, 1996).

material include: low thermal conductivity, dimensional stability under temperature change, resistance to water absorption, and resistance to combustion. Other characteristics of insulating material may also be important depending on the application, e.g. tolerance of large temperature variation and system vibration, and compressive strength where insulation is load bearing (Baen and Barth, 1994). Improving the insulation on the existing stock of heat distribution systems would save an average of 3-13% in all systems (OIT, 1998) with an average payback period of 1.1 years[7] (IAC, 1999).

2. Maintain insulation. It is often found that after repairs, the insulation is not replaced. In addition, some types of insulation can become brittle, or rot. As a result, energy can be saved by a regular inspection and maintenance system (CIBO, 1998). Exact energy savings and payback periods are, however, unknown.

3. Improve steam traps. Using modern thermostatic element steam traps can reduce energy use while improving reliability. The main advantages offered by these traps are that they open when the temperature is very close to that of the saturated steam (within 2°C), purge noncondensible gases after each opening, and are open on startup to allow a fast steam system warm-up. These traps are also very reliable, and useable for a wide variety of steam pressures (Alesson, 1995). We could not estimate the exact savings.

4. Maintain steam traps. A simple program of checking steam traps to ensure they operate properly can save significant amounts of energy. If the steam traps are not regularly monitored, 15-20% of the traps can be malfunctioning. Energy savings for a regular system of steam trap checks and follow-up maintenance is estimated at 10% (OIT, 1998; Jones 1997; Bloss, 1997) with a payback period of 0.5 years (IAC, 1999). This measure offers a quick payback but is often not implemented because maintenance and energy costs are separately budgeted. Some systems already use this practice, so we estimate that this can be applied to 50% of steam systems.[8]

5. Monitor steam traps automatically. Attaching automated monitors to steam traps in conjunction with a maintenance program can save even more energy, without significant added cost. This system is an improvement over steam trap maintenance alone, because it gives quicker notice of steam trap malfunctioning or failure. Using automatic monitoring is estimated to save an additional 5% over steam trap maintenance, with a payback of 1 year[9] (Johnston, 1995; Jones, 1997). Systems which are able to implement steam trap maintenance are also likely to be able to implement automatic monitoring, so we estimate that 50% of systems can still implement this measure.

6. Repair leaks. As with steam traps, the distribution pipes themselves often have leaks that go unnoticed without a program of regular inspection and maintenance. In addition to saving 3% of energy costs having such a program can reduce the likelihood of having to repair

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[7] The IAC database shows a series of case studies where a particular technology was used. It gives a wide variety of information, including the payback period for each case. We calculated an overall payback for a technology by averaging all the individual cases.

[8] This assumption is based on the fact that this measure has a short payback, but will not be applied to all systems because maintenance and energy budgets are often separate (CIBO, 1998).

[9] Calculated based on a UK payback of 0.75 years. The US payback is longer because energy prices in the US are lower, while capital costs are similar.

major leaks. (OIT, 1998). We estimate that this is applicable to 12% of industry[10] with a payback of 0.4 years (IAC, 1999).

7. Recover flash steam. When a steam trap purges condensate from a pressurized steam distribution system to ambient pressure, flash steam is produced. This steam can be used for space heating or feed water preheating (Johnston, 1995). The potential for this measure is extremely site dependent, as it is unlikely that a producer will want to build an entirely new system of pipes to transport this low grade steam to places where it can be used, unless it can be used close to the steam traps. Hence, the savings are site dependent and not included in our analysis.

8. Return condensate. Reusing the hot condensate in the boiler saves energy and reduces the need for treated boiler feed water. The substantial savings in energy costs and purchased chemicals costs makes building a return piping system attractive. This measure has, however, already been implemented in most places where it is easy to accomplish. We assume a 10% energy savings (OIT, 1998) with a payback of 1.1 years for 2% of the boiler population (IAC, 1999).

Table 6. Energy Efficiency Measures in Industrial Steam Distribution Systems

Measure	**Fuel Saved**	**Payback Period (years)**	**Implementation Potential[11]**	**Other Benefits**
Improved Insulation	3-13%	1.1	100%	
Improved Steam Traps	Unknown	Unknown	-	Greater reliability
Steam Trap Maintenance	10-15%	0.5	50%	
Automatic Steam Trap Monitoring[12]	5%	1	50%	
Leak Repair	3-5%	0.4	12%	Reduced requirement for major repairs
Flash Steam Recovery/ Condensate Return	83%[13]	Unknown	-	Reduced water treatment costs
Condensate Return Alone	10%	1.1	2%	Reduced water treatment costs

Cost Effective Energy Savings

In order to calculate the cost-effective energy savings potential, we present the measures in a supply curve. With the measures plotted in this way, it is easy to see which measures are economical for given investment criteria, i.e. a discount rate of 30%. We have generated two supply curves, one for industry as a whole, and one for the energy intensive industries alone. We also used a range of fuel prices for each curve. The high-end fuel price is the average price for fuel used in industrial boilers according to MECS. The low-end fuel price assumes that waste fuels are free. The question of what waste fuels cost is largely an accounting

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[10] This estimate is based on the percentage of IAC heat system projects where leak repairs were implemented.

[11] This refers to the percentage of boilers that could implement this measure cost effectively

[12] In addition to a regular maintenance program

[13] Includes flash steam recovery from the boiler. Although this represents actual savings achieved in a case study, it seems much to high to be a generally applicable savings number. As a result, it is not included in our total savings estimate.

question since the industry has to purchase the precursor to the waste fuel anyway. Since determining the cost of processing waste fuel could be subject of a separate study, we have chosen to use the high and low range of possible average fuel prices to evaluate the potential for energy-efficiency improvement. Figure 2 and Table 7 demonstrate that a substantial economic potential for energy efficiency improvement exists in US industry, equivalent to 1181-1258 PJ. The savings represent a 19-20% savings in steam system final energy consumption, equivalent to approximately 7% of total industry final energy consumption. The measures would result in carbon dioxide emission reductions of 12.2-13.0 Mtonnes C. In the energy intensive industries alone the savings would result in 10-11 Mtonnes C.

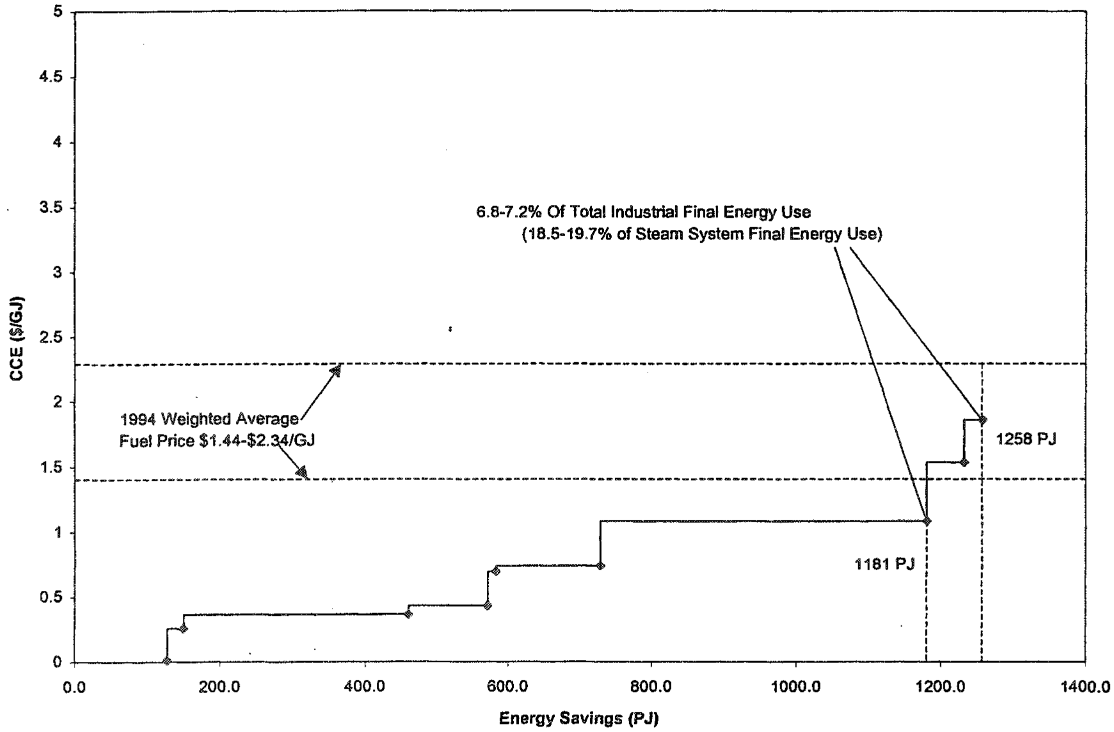

Figure 2. Supply Curve for Energy Efficiency Improvement in U.S. Industry Steam Systems

Table 7. Summary of Energy Efficiency Measures in US Industry Steam Systems

	Measure	Energy Savings (PJ)	CCE ($/GJ)	Payback Period (yr)
1	Boiler Maintenance	128	0.01	0
2	Leak Repair	150	0.26	0.4
3	Steam Trap Maintenance	462	0.36	0.5
4	Improved Process Control	572	0.43	0.6
5	Condensate Return	584	0.69	1.1
6	Automatic Steam Trap Monitoring	729	0.74	1.0
7	Improved Insulation	1181	1.08	1.1
8	Flue Gas Heat Recovery	1233	1.53	2.0
9	Blowdown Steam Recovery	1258	1.86	2.7

Discussion

Most of the work that has been done so far on industrial boilers has limited itself to recommending technological efficiency improvements for individual plants, but does not give an estimate for total potentials, which can be used in strategic planning and policy planning. Our paper focuses on the latter.

The source of energy consumption data, MECS, is a reliable source of data but has several shortcomings. It does not include fuel input, steam output, or heat demand on steam systems. This information would be very useful in calculating efficiencies for steam production and consumption. While these pieces of information are available from other sources, there is too wide a variation between sources of boiler data to make comparisons between two sources meaningful. MECS figures also include fuel use for steam generation from co-generation. While some of the measures in the boiler and all the steam distribution measures still apply, this may lead to a lower actual potential for energy efficiency improvement. On the other hand, various other measures have not been included in our analysis, which could lead to a higher potential for energy efficiency improvement in steam systems.

We had to use the efficiencies demonstrated by case studies where technologies were implemented in average plants. While we took care select typical plants for this analysis, it is true that there are variations from plant to plant which may impact the energy saved. For example, the estimates for applicability and costs were often based on the results of the IAC database. The IAC database contains thousands of energy audits of medium and small enterprises. However, large plants may be more efficient than the sites typically found in the IAC database. However, even audits of specific large facilities (e.g. as part of the US DOE Best Practices program) often find potentials comparable to those we identified.

Finally, there is still a large potential for energy savings in steam systems through the use of process integration. Pinch analysis and other methods can help to identify large savings, as evidenced by many case-studies and plant analyses. Pinch analysis carefully matches heat and cooling demand within a plant, but is necessarily very site dependent. Without detailed studies of where pinch analysis could be implemented, it is difficult to estimate the savings. Preferably, any large overhauls in a steam system should be accompanied by a process integration study to find the optimal steam system for a site.

Conclusion

There is considerable opportunity for energy efficiency improvement in industrial steam systems. We estimate that 1260 PJ of energy could be saved with a payback period of three years or less. The savings represent approximately 19% of final energy use, and 7% of total industry final energy use. These savings represent a substantial reduction in carbon dioxide emissions, i.e. 13 MtC, or 5% of industry's emissions. Our research suggests that even a proactive maintenance program can save considerable amounts of energy. The application of good heat integration, and automated computer control are also major areas where energy can be saved.

Acknowledgements. This work was supported by the Climate Protection Division, Office of Air and Radiation, U.S. Environmental Protection Agency through the U.S. Department of

Energy under Contract No. DE-AC03-76SF00098. We are thankful to many people who have been very helpful in the data collection and review of earlier versions of this report.

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