Not Just Hot Air: Low-Cost Decarbonization through Heat Recovery

Joel Zahlan, Cadmus
Evan Talan, Cadmus

ABSTRACT

Industrial facilities are responsible for approximately 23% of total greenhouse gas emissions in the United States (EPA 2020a), totaling over 1,500 million metric tons of CO_2 equivalent. Emissions primarily come from burning fossil fuels for energy and from chemical reactions necessary to produce goods from raw materials. The DOE estimates that between 20% to 50% of industrial energy input is wasted as heat in the form of waste streams of air, exhaust gases, hot equipment surfaces, heated products, and liquids (U.S. Department of Energy 2017). An estimated 1.4 quadrillion BTUs of waste heat could economically be recovered, which would translate to 9% to 10% of the total industrial energy use in the U.S (Energetics, Inc. and E3M).

Over the past year, Cadmus evaluated waste heat recovery projects across several energy efficiency programs in the U.S. These projects generally resulted in high energy savings with relatively low capital costs, resulting in short paybacks and significant reductions in energy use and greenhouse gas emissions. This paper provides an overview of 12 of the largest waste heat recovery projects, which saved more than 10 million therms per year, offsetting over 52,000 metric tons of CO_2 per year. We discuss the sources of waste heat, detail the recovery methods used, calculate the cost per MMBtu of savings associated with waste heat recovery projects, and compare these costs with those of other large electric and gas savings opportunities in energy efficiency programs. Finally, we discuss barriers and opportunities to implementing waste heat recovery based on interviews with program managers, energy advisors, and customers.

Introduction

Greenhouse Gas Emissions and Energy Use in the U.S Industrial Sector

In 2019, U.S greenhouse gas emissions (GHG) totaled 6,558 million metric tons of carbon dioxide equivalents. The industrial sector represented the third largest emitter of GHG emissions at over 1,500 million metric tons of carbon dioxide equivalents or 23% of total GHG emissions in the U.S. The transportation and electricity sectors are the only two larger emitters at 29% and 25% respectively (EPA 2020a). Figure 1 from the Environmental Protection Agency (EPA 2020b) shows historical GHG emissions by economic sector from 1990 to 2019.

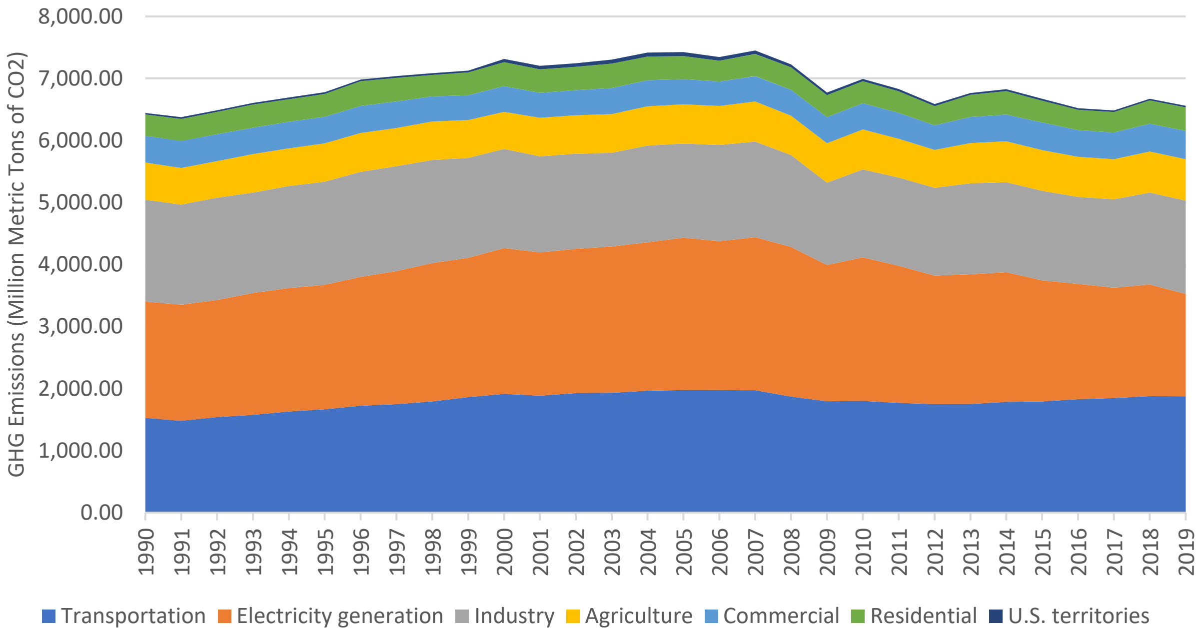

Figure 1. U.S Greenhouse Gas Emissions by Economic Sector, 1990-2019 (EPA 2021b)

The EPA further breaks down the industrial sector GHG emissions in Figure 2 below. As it shows, the largest contributor to GHG in industry is through fossil fuel combustion, which contributes close to half of total GHG in industry.

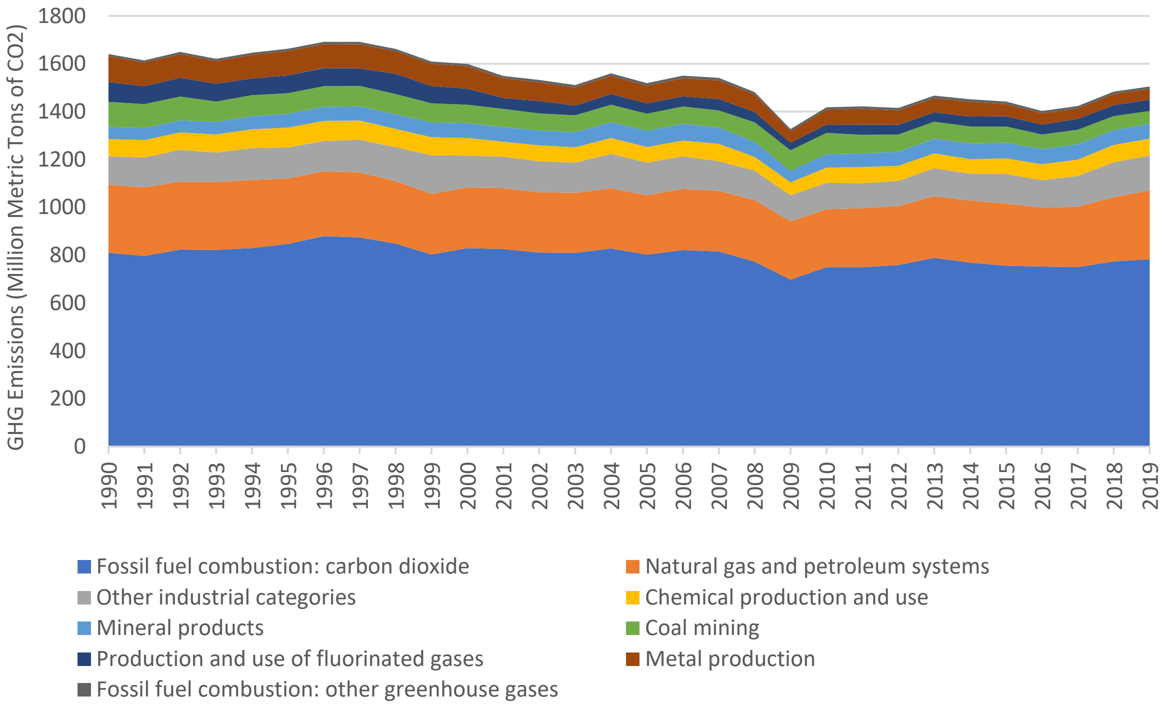

Figure 2. U.S Greenhouse Gas Emissions by Industrial Sector, 1990-2019 (EPA 2021b)

One of the primary methods of reducing GHG emissions in industrial facilities is through energy efficiency. The DOE estimates that between 20 to 50% of industrial energy input is wasted as heat in the form of waste streams of air, exhaust gases, hot equipment surfaces, heated products, and liquids (U.S. Department of Energy 2017). An estimated 1.4 quadrillion BTUs of waste heat could economically be recovered, which would translate to 9% to 10% of the total industrial energy use in the U.S (Energetics, Inc. and E3M) and a significant reduction in fossil fuel (in this case natural gas) combustion.

Definition of Waste Heat Recovery for this Paper

Waste heat is the energy generated by industrial processes that is lost into the environment in the form of waste streams of air, exhaust gases, or liquids. The loss of waste heat energy is often considered thermal pollution. Recovering waste heat can be accomplished using various waste heat recovery technologies to provide valuable energy and reduce overall energy consumption and greenhouse gas emissions. For the purpose of this paper, waste heat recovery projects will also include projects that involve process improvements to reduce heat loss and projects that involve repairs to improve performance of a piece of equipment or a technology.

Types of Heat Recovery

There is a wide variety of waste heat recovery systems available in industry. Most larger systems are designed specifically for manufacturer needs, and suppliers tend to provide application-specific designs that meet the manufacturer or process needs. Table 1 below offers a summary of commonly available waste heat recovery systems by temperature range.

Table 1: WHR systems by temperature range (U.S. Department of Energy 2015)

Ultra-Low Temperature (<250°F)	Low Temperature (250°F to 600°F)	Medium Temperature (600°F to 1200°F)	High Temperature (1200°F to 1600°F)	Ultra-High Temperature (>1600°F)
Shell and tube type heat exchangers Plate type heat exchangers Air heaters for waste heat from liquids Heat pumps HVAC applications (i.e., recirculation water heating or glycol-water recirculation) Direct contact water heaters Non-metallic heat exchanger	Convection recuperator (metallic) of many different designs Finned tube heat exchanger (economizers) Shell and tube heat exchangers for water and liquid heating Heat pumps Direct contact water heaters Condensing water heaters or heat exchangers Metallic heat wheel Heat pipe exchanger	Convection recuperator (metallic) Finned tube heat exchanger (economizers) Shell and tube heat exchangers for water and liquid heating Self-recuperative burners Waste heat boilers for steam or hot water condensate Load-charge preheating Metallic heat wheel Heat pipe exchanger	Convection recuperator (metallic) – mostly tubular Radiation recuperator Regenerative burners Heat recovery boilers Waste heat boilers including steam turbine generator–based power generation Load or charge preheating Metallic heat wheels (regenerative system)	Refractory (ceramic) regenerators Heat recovery boilers Regenerative burners Radiation recuperator Waste heat boilers including steam turbine generator–based power generation Load or charge preheating

Common Waste Heat Recovery Technologies

Heat Exchangers. Most commonly, heat exchangers are used to recover heat from exhaust fumes and heat inlet combustion air. In general, heat exchangers are used to recover heat from waste streams and redirect it to processes that required additional thermal energy. One such system that we discuss in this paper involves thermal oxidizers, which are used in facilities that produce a harmful level of volatile organic compounds (VOCs) as a byproduct. Thermal oxidizers use natural gas to burn process emissions thereby destroying VOCs and reducing impacts on the environment. There are two main types of thermal oxidizer systems: direct fired (DFTO) and regenerative (RTO). RTOs utilize their exhaust stream to preheat process air before combustion, thus reducing fuel use.

Load Preheating. Load preheating happens when waste heat is used to preheat a load entering the system, thus reducing the energy needed to raise the temperature of the load. For example, boiler economizers that use exhaust fumes to preheat feedwater reduce the fuel necessary to bring the water up to the required temperature. Load preheating in direct fired systems is not widely used because of risks from product quality, environmental emissions, and system complexity.

Low Temperature Heat Recovery. Low temperature waste heat recovery methods, often overlooked because they have not been cost-effective, are becoming more interesting as facilities aim to continuously improve. Many of the challenges of recovering low temperature heat include corrosion, size constraints, and limited use for lower temperature heat. Systems that recover low temperature heat for process use include deep economizers, indirect contact condensation recovery, direct contact condensation recovery, and transport membrane condensers. Systems that have no end use for low temperature heat, such as heat pumps or low-temperature power generation, can be used for recovery.

Power Generation. Power generation from waste heat most commonly employs excess boiler steam to drive an electric generator. These power cycles are very common in facilities that use low pressure steam. However, newer technologies have been able to generate electricity directly from heat. Power generating systems are available at a wide range of temperatures and vary significantly in cost as shown below in Table 2.

Table 2. Options for heat recovery via power generation (Johnson, I, W. Choate, and A. Davidson 2008)

Thermal conversion technology	Temperature range	Typical sources of waste heat	Capital cost
Traditional steam cycle	Medium, High	Exhaust from gas turbines, reciprocating engines, incinerators, and furnaces	\$1,100–\$1,400/kW
Kalina cycle	Low, Medium	Gas turbine exhaust, boiler exhaust, heated water, and cement kilns	\$1,100–\$1,500/kW

Organic Rankine cycle	Low, Medium	Gas turbine exhaust, boiler exhaust, heated water, and cement kilns	\$1,500–\$3,500/kW
Thermoelectric generation	Medium, High	Not yet demonstrated in industrial applications	\$20,000–\$30,000/kW
Piezoelectric generation	Low	Not yet demonstrated in industrial applications	\$10,000,000/kW
Thermalphotovoltaic	Medium, High	Not yet demonstrated in industrial applications	N/A

Heat-Recovery Potential in the U.S. Manufacturing Industry

As discussed above there is tremendous opportunity for heat recovery at industrial facilities in the United States with the potential to offset 9%-10% of energy use in industrial facilities. Table 3 illustrates the typical energy system losses in manufacturing facilities. Per the Energy Use, Loss, and Opportunities Analysis report[3], using the Manufacturing Energy Consumption Survey (MECS) data published by the U.S. Energy Information Administration (EIA) there are significant losses to major energy systems across manufacturing plants. Table 3 below displays some of these losses and highlights the importance of improving efficiency through waste heat recovery. As can be seen in the table most energy systems experience significant losses with overall energy loss ranging from a few hundred TBtu to a few thousand TBtu.

Table 3. Typical energy losses for major energy systems in a manufacturing plant (1998) (U.S. Department of Energy 2015)

Energy systems	Percentage of energy lost	Estimated annual energy loss
Steam systems (generation + distribution)	30%–35%	2,220 TBtu
Power generation	24%–45%	270 TBtu
Energy distribution (except steam)	~3%	340 TBtu
Energy conversion	10%–50%	2,860 TBtu
Motor systems	30%–80%	1,120 TBtu

Furthermore, per Johnson et al, the table below highlights four reports over the last 40 years that have pointed to significant opportunity in waste heat recovery and significant potential for savings.

Table 4. Estimates of waste heat loss and recovery potential (Johnson, I, W. Choate, and A. Davidson 2008)

Study	Estimated waste heat loss and/or recovery potential
Cooke, 1974	Waste heat losses in the United States total 50% of energy inputs
EPA, 1986	Losses from exhaust gases from industrial processes and power generation sites total 14.1 quadrillion Btu/yr. About 1.5 quadrillion Btu/yr could be recovered at temperatures above 300°F. This would correspond to about 31% and 3% of industrial energy inputs, respectively
Energetics, 2004	Waste heat could range from 20%–50% of industrial inputs. Selected energy saving opportunities from waste heat recovery could total 1.6 quadrillion Btu/yr
PNNL, 2006	The chemical energy contained in exhaust gas streams totals about 1.7 quadrillion Btu/yr.

Benefits of Waste Heat Recovery

Waste heat recovery provides numerous benefits to industry by reducing the following.

- Utility costs: Recovered waste heat directly reduces utility consumption and costs.
- Reduction in equipment sizes: Waste heat recovery can directly result in the reduction of equipment sizes through improvement of efficiency requiring smaller equipment to perform the same task or a reduction in fuel consumption and flue gas produced which results in a reduction of gas handling equipment like fans, stacks ducts, etc.
- Operating costs: Since waste heat recovery reduces energy costs and often also reduces capital costs, it reduces operating costs.
- Reduction in pollution: Waste-heat recovery in industry reduces GHG emissions associated with industrial processes through the replacement of additional combustion for heating processes.

Economics and Cost-Effective Waste-Heat Recovery

The cost-effectiveness of waste heat recovery systems depends mainly on the temperature and quality of heat waste streams but also on the cost of various fuels, such as natural gas and coal. Table 4 below highlights typical temperature ranges and cleanliness for sources of waste heat. Generally, as mentioned above, higher temperature and cleaner sources provide greater opportunities for recovery.

Table 4. Typical temperature range and characteristics for industrial waste heat sources (U.S. Department of Energy 2015)

Waste heat source	Temperature range (°F)	Quality of heat
Furnace or heating system exhaust gases	600–2000	Varies
Gas turbine exhaust gases	900–1,100	Clean
Jacket cooling water	190–200	Clean
Exhaust gases (for gas fuels)	900–1,100	Mostly clean
Hot surfaces	Post-intercooler water	Clean

Compressor post – intercooler water	100–180	Clean
Hot products	200–2,000	Mostly clean
Steam vents or leaks	250–600	Mostly clean
Condensate	150–500	Clean
Emission control devices – thermal oxidizers, etc.	150–1,500	Mostly clean

U.S. manufacturing relies heavily on fossil-fuel process heating equipment and boilers. Natural gas accounts for about 70% of total energy used by process heating equipment in industry, followed by coal (10%) (EIA 2002). Natural gas also accounts for 70% of total energy used by industrial boilers, followed by coal (25%) (EIA 2002). In general, to recover heat cost effectively, there are several factors to consider:

- Identification of waste heat sources of sufficient quality
- Quantity of heat available to recover
- Temperature of heat loss
- Ability to reuse recovered waste heat

Through our experience evaluating numerous waste heat projects across programs all over the U.S., we have determined that there is ample opportunity to recover waste heat in most industrial facilities even at lower temperatures, and there are numerous opportunities to reuse this heat within the facility. Findings from the paper suggest reasonable pay-back periods and a significant reduction in greenhouse gas emissions are achievable across different kinds of heat recovery applications and manufacturing facilities and from various waste streams.

Background and Selected Projects

Over the past year, we evaluated a substantial number of large waste heat recovery projects across several energy efficiency programs in the U.S. These projects generally resulted in high energy savings at relatively low capital cost resulting in short payback periods and significant reductions in energy use and greenhouse gas emissions. The 12 selected projects represent some of the largest projects across several energy efficiency program evaluations. For each of these projects, Cadmus conducted in-depth measurement and verification activity to confirm energy savings. Information collected included metered data, trend data, and spot measurements. The team used various methodologies such as weather and production dependent regression analysis to determine savings and extrapolate across the full year. The team met with respective site contacts to discuss the projects in detail and understand the operational characteristics of the systems.

The projects were implemented across several industries, including forest products, chemicals, metals, and sewage treatment and involved various waste heat streams and waste heat recovery technologies. The following section covers the sources of waste heat, the recovery methods used, and the costs associated with implementing these projects. We also calculate the cost per therm savings associated with each of these waste heat recovery projects. Overall, the projects saved more than 10 million therms per year, offsetting over 52,000 metric tons of CO_2 per year.

Project Selection Criteria

We selected projects for this study considering a broad variety of waste heat projects within the industrial sector. These included installation of new equipment and repair of existing equipment. Our sample included heat exchangers, regenerative thermal oxidizers, water recirculation systems, and other systems designed to utilize waste heat. A large variety of facility types are also represented including paper mills, roofing products, sugar production, and grain mills. The primary fuel for all projects in the sample was natural gas. The waste streams themselves include exhaust air, steam, and hot water. All projects are listed and characterized in Table 5 below.

Table 5. Waste Heat Project Characteristics

Recovery Methods	Stream Source	Facility type	Savings (Therms)	CO2 savings (0.0053 metric tons CO2/therm)	$/ton CO2 saved	Lifetime $/therm[2]	Gas Price $/MMBtu	Payback Period (Years)
Heat exchanger	Exhaust air	Paper mill	250,000 to 500,000	39,467	$5.69	$0.030	$5.66	0.80
New grain dryer	Exhaust air	Grain mill	250,000 to 500,000	32,019	$51.77	$0.274	$5.66	7.28
RTO	Exhaust air	Wood Products	750,000 to 1,000,000	69,355	$4.87	$0.026	$5.66	0.69
RTO	Exhaust air	Building Materials	above 1,000,000	103,350	$0.87	$0.005	$5.66	0.12
Heat exchanger	Hot water	Paper mill	750,000 to 1,000,000	74,123	$2.02	$0.011	$5.66	0.28
Heat exchanger plate and frame	Hot water	Paper mill	above 1,000,000	114,047	$0.41	$0.002	$5.66	0.06
Recirculation and chemical treatment of used water	Hot water	Paper mill	500,000 to 750,000	57,057	$1.32	$0.007	$5.66	0.19
Valve repair improved system	Hot water	Paper mill	500,000 to 750,000	45,164	$0.28	$0.001	$5.66	0.04
Direct contact stillage evaporator	Steam	Ethanol production	750,000 to 1,000,000	77,548	$17.43	$0.092	$5.66	2.45
Increased condenser efficiency	Steam	Packaging products	above 1,000,000	109,752	$5.70	$0.030	$5.66	0.80
Plate and frame heat exchanger	Steam	Food Products	Less than 250,000	15,942	$3.64	$0.019	$5.66	0.68
Reduced excess heating	Steam	Paper mill	500,000 to 750,000	51,009	$16.66	$0.088	$5.66	2.34

[1] Average Gas Price ($/MMBtu) across the United States

[2] To calculate Lifetime $/therm, estimated Useful Life (EUL) of recovery methods fall within 10-20 years which is reflected in program Technical Reference Manuals.

Representative Project Description

The projects analyzed for this study were broken down into three groups by waste streams: exhaust air, hot water, and steam. Each of these groups contained four projects and we provide a description of a representative project from each group.

Exhaust air typically requires a heat exchanger from the exhaust pipe of a combustion system for preheating inlet combustion air or process load. Of the four exhaust air projects analyzed, one evaluated the energy savings of an RTO versus a DFTO at a large building materials manufacturer. This facility operated 24/7 constantly producing VOCs as a result of the manufacturing process. When facility managers decide between the two system types, they usually are concerned with meeting environmental regulations and cost. Typically, RTO systems are slightly less effective at destroying harmful VOCs than DFTOs but use significantly less energy. Both systems were evaluated to determine estimated energy consumption. We evaluated the DFTO as the baseline using manufacturer specifications and on-site facility measurements. We evaluated the RTO in the pre-install case using similar assumptions as the DFTO and the post-install case using on-site trend data. The resulting energy savings was over 1,250,000 therms. This project cost $0.005/therm over the effective useful life of the RTO. This highlights the benefits of installing systems that are purpose built to recover waste heat.

Steam as a waste stream is highly valuable as it carries much more energy than hot air. Steam can be utilized in a variety of ways described in the technologies section of this study. One project analyzed evaluated the energy savings of eliminating direct steam injection to heat product by installing heat exchangers at a food processing facility. This saved steam by utilizing the heat without condensing water into the liquid product. This project saved over 150,000 therms and costs around $50,000 to implement, giving a cost of $0.02/therm saved over the effective useful life of the equipment. This project was initially identified by facility engineers looking to increase production efficiency. The facility processes large quantities of product each day so major projects are under extreme scrutiny for a quick payback period. With such a low cost per savings, waste heat projects are easy to justify to management and can often be implemented with minimal downtime.

Hot water, like steam, carries much more energy than air and in certain industries is abundant. Three paper mills implemented projects that utilized waste heat from hot water. One of them recycled water with minimal heat loss resulting in large savings and minimal cost. This project cost $0.01/therm saved and had a 0.19-year payback.

Assumptions and Uncertainties

In this section we cover some assumptions and uncertainties used to derive some of the conclusions in this paper.

Handpicked projects. We handpicked the projects that we reviewed for this paper. These generally represented the largest energy savings projects within industrial programs. Cost was not one of the considerations for project selection, however considering the size of these projects, the cost per therm results may be skewed and may not be representative of some smaller waste heat projects.

Maintenance and upkeep of systems. We did not consider maintenance and upkeep in the overall costs. The expectation is that yearly maintenance and upkeep costs will factor into an increased cost of the system over its lifetime.

Estimated Useful Life (EUL). We estimated EULs from program data and technical reference manuals. These are determined through research studies on attribution and technical specifications from manufacturers. EULs factor into the lifetime savings of the projects.

Electrical Penalties. For the purpose of this paper, we did not include any positive or negative impacts on electricity consumption. We assumed that these would cancel each other out across a larger sample. In general, some changes in electrical energy use included different pump sizing, additional pumping capacity to handle waste liquid streams, etc. Changes in electrical energy use were negligible compared with the therms savings resulting from heat recovery savings.

Analysis and Benchmarking

In total we analyzed twelve projects from three different waste streams for their reduction in natural gas consumption. Reducing natural gas consumption results in a direct reduction in the amount of carbon dioxide released into the atmosphere. We analyzed the tons of CO_2 saved on average in each stream by converting therms saved into CO_2 saved using the Environmental Protection Agency's (EPA) Greenhouse Gases Equivalencies Calculator conversion factor:

$$0.1\,\frac{\text{mmbtu}}{1}\,\text{therm} \times 14.43\,\text{kg}\,\frac{\text{C}}{\text{mmbtu}} \times 44\,\text{kg}\,\frac{\text{CO2}}{12}\,\text{kg C} \times 1\,\text{metric}\,\frac{\text{ton}}{1{,}000}\,\text{kg}$$
$$= \mathbf{0.0053\ metric\ tons}\,\frac{\mathbf{CO2}}{\mathbf{therm}}$$

We multiplied annual savings by the effective useful life (EUL) of each project to get lifetime therm savings. This is representative of the total gas saved as a result of the project.

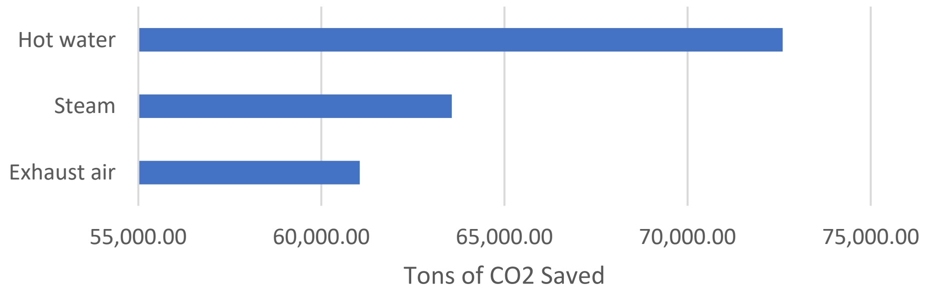

Figure 3. Tons of CO2 Saved by Waste Stream in Metric Tons

Figure 3 shows the scale at which these projects are reducing emissions. Of the 12 projects selected, the hot water projects on average reduced the highest emissions of the three waste streams saving around 73,000 tons of CO_2. All three waste streams are viable for saving large amounts of energy and thus CO_2.

Payback was calculated by multiplying first year gas savings and the average price of gas to get cost savings, then dividing project cost by that result to express the payback in units of years.

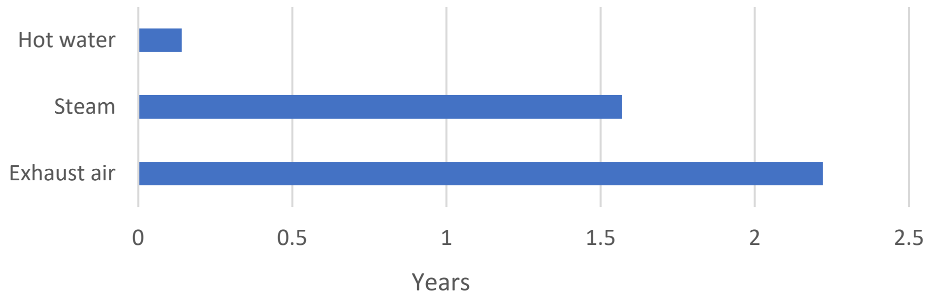

Figure 4. Average payback period by waste stream in years

Figure 4 shows hot water projects had the shortest payback period with an average of 0.14 years. Payback period goals at industrial facilities vary by facility size and type. From program managers interviewed and Cadmus experience we have found that payback periods less than two to three years are generally accepted. As can be seen from Figure four above, all 12 projects came in below the three-year mark.

Dollars per ton CO_2 saved is calculated by dividing the total project cost by the lifetime CO_2 saved.

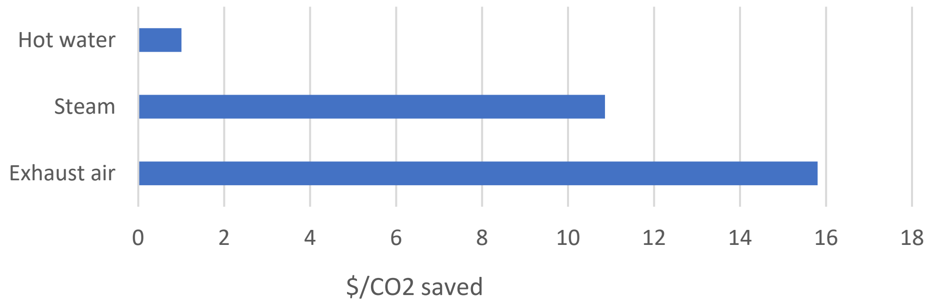

Figure 5. Average dollar per ton of CO2 saved

Figure 5 shows hot water outperformed both steam and exhaust air for the twelve projects selected, with savings of $1.01 dollars per ton of CO_2.

The hot water waste stream source outperforming the other categories could lead to multiple conclusions. All four of the projects were from the paper production industry which relies heavily on hot water. Since hot water is used directly in process heat, it can be transferred much more efficiently by adding it directly into the process instead of incurring losses through heat exchangers. Also, many of the hot water projects in this sample were system repairs, thus reducing project cost significantly. We expected that steam would be closer to hot water in all three categories, however high project costs resulted in longer payback and higher cost per ton of

CO_2 saved. It should be noted that many of the steam projects analyzed were system replacements or upgrades. Further research could be performed to analyze a larger sample of more-representative industrial waste heat measures across the relevant metrics.

Cost per therm is the result of dividing total project cost by lifetime therms saved.

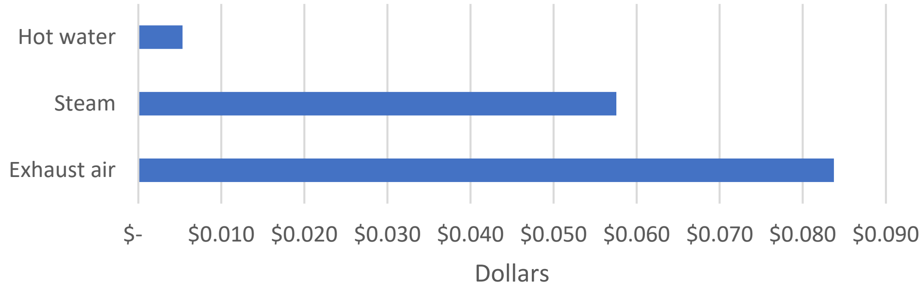

Figure 6. Average cost per lifetime therms saved

That exhaust air had the highest cost per lifetime therms saved ($0.084/therm) is not surprising given most of the projects were also replacement or installation of entire systems (RTOs and grain dryers). Exhaust air also is the most difficult of the three streams from which to recover heat. Steam was second most expensive with a cost per therm saved of $0.058/therm. Hot water again outperformed both other streams substantially with a cost per therm of $0.005/therm. All of the energy savings from the analyzed streams are significantly less expensive than average natural gas prices.

We performed benchmarking through the population datasets of multiple industrial energy efficiency programs. We removed any projects with electrical savings, and used the total lifetime therms saved and cost data to get a benchmark dollar per lifetime therm. The average $/lifetime therm saved of the programs we reviewed was $0.154. Other studies have found higher costs per therm saved, but for comparison we used the program data which suggests that the average cost to save one therm for gas projects in the energy efficiency programs is significantly higher than the twelve projects reviewed in this paper.

It should also be noted that many of the projects reviewed had multiple drivers for recovering waste heat. In some cases, energy efficiency and cost savings were not the main driver: improved production, improved product quality, and reduced maintenance and operating costs all played a role in the upgrade.

Barriers to Waste Heat Recovery

This section of the paper discusses the barriers and challenges to waste heat recovery. The information in this section was collected through discussions with subject matter experts, program implementers, industrial customers, and primary research. It is important to note that for the most part, there is wide agreement that opportunities exist in all industrial facilities to recover waste heat. The barriers noted below are general to our findings and may not apply directly to all opportunities at a facility.

Cost

- **Long payback periods.** The costs associated with of purchasing and installing heat recovery equipment can have long payback periods in certain applications.
- **Materials and costs.** Certain industry applications require more costly materials. These materials are required for high temperature streams, streams with high chemical activity, and exhaust streams cooled below condensation temperatures.
- **Economies of scale.** Equipment costs are generally lower for large scale heat recovery systems and more costly for small scale operations.
- **Operation and Maintenance (O&M).** Yearly O&M is required to maintain systems. Corrosion, scaling, and fouling of heat exchange materials lead to higher maintenance costs and lost productivity.

Time/Risk/Status Quo

- **Lack of time.** Facility staff are generally focused on running the production equipment and ensuring that there are no breakdowns and machinery is operating as needed. Without a formal energy efficiency program, facility staff will generally not invest a lot of time on energy efficiency measures.
- **Risk.** There is inherent risk in changing a process that is already operating well. Recovering waste heat and reusing it in process lines could affect the quality of the product and the performance of the equipment.
- **Status quo.** There is little incentive at the facility level to save energy. Management may not support changing processes that are currently performing well.
- **Lack of a viable end use.** Some industrial facilities do not have use for low temperature heat. This dissuades industrial facilities from taking advantage of low temperature heat recovery.
- **Process-specific constraints.** Equipment designs are process specific and must be adapted to the needs of a given process. Most of the heat recovery systems covered in the 12 projects outlined were custom and specific to the facility which generally costs more and requires more expertise.
- **Management Buy-in.** The approval process for changes and expenditures can be cumbersome at some facilities which dissuades staff from looking for opportunities to recover waste heat. Management buy in can also factor into barriers for implementing waste heat measures at facilities. If management is unwilling to make changes and invest in facility improvements, it will be difficult for facility staff to get measures approved.

Materials and Chemical Composition

- **Corrosive Materials.** Low temperature liquid and solid streams condense as hot streams which leads to corrosive and fouling conditions. Materials that can withstand corrosive environments are costly and not feasible for low temperature recovery.
- **Stress on Equipment.** The heat flow in some industrial processes can vary dramatically and create mechanical and chemical stress in equipment.
- **Heat Transfer Rates.** Small temperature differences between the heat source and heat sink lead to reduced heat transfer rates and require larger surface areas.

Inaccessibility/Transportability

- **Limited Space.** Facilities and equipment may have limited physical space in which to access waste heat streams.
- **Transportability.** Gaseous and liquid streams of heat may require additional cost to transport across different parts of the site. This could include additional pumps or fans.
- **Inaccessibility.** It is difficult to access and recover heat from unconventional sources such as hot solid products and hot equipment surfaces.

Opportunities and insights:

In addition to the barriers highlighted above the interviewees provided insights into overcoming barriers and opportunities for implementing waste heat recovery projects at industrial facilities:

- Overarching agreement that there is a lot opportunities for waste heat recovery.
- The main driver for heat recovery can be a mix of cost savings, process improvements, product quality improvements, safety, regulatory requirements, social responsibility, GHG reductions, and reduction in maintenance.
- Utility ad program incentives continue to play an important role and encouraging waste heat recovery projects.
- Knowledgeable on-site employee, energy advisors and external consultants are the main drivers for waste heat projects. In general, the larger projects are driven by external consultants and subject matter experts.
- Awareness of importance for GHG reduction and social responsibility is playing a more important role in decision making and helping ease management approvals.
- Education resources through energy efficiency programs and energy advocates, help increase awareness of opportunities for energy efficiency at industrial facilities.
- Awareness of energy efficiency among plant personnel and maintenance staff is raising, allowing for identification of opportunities.
- Energy Efficiency programs and offerings play a key role by not only providing incentives, but also by providing experienced staff that can help facilities navigate through complex projects, identify potential opportunities, and estimate energy savings. These programs also offer educational opportunities for customers and help raise awareness of energy efficiency opportunities.

Conclusions

Overall, the results imply that waste heat recovery is a cost-effective way to reduce energy consumption and therefore CO_2 emissions. A summary averaging all twelve projects can be seen in the table below.

	CO_2 savings (0.0053 metric tons CO_2/therm)	\$/ton of CO_2 saved	Lifetime \$/therm	Gas Price \$/MMBtu	Payback Period
Average	65,736	\$9.22	\$0.05	\$5.66	1.31

As discussed above there are several benefits to recovering waste heat. These benefits generally fall into two main categories: reductions in cost and environmental benefits. As this paper has shown, a review of 12 large projects highlighted a significant opportunity for energy savings with a payback period of less than two years. In most cases, the projects we reviewed had payback periods of less than one year. The average lifetime $/therm was found to be one third of the benchmarked value. These projects also succeeded in significantly reducing GHG over their lifetimes and in offsetting purchases of fuel.

The paper also highlights that there still exist challenges and barriers to implementing waste heat measures. Generally, cost is one of the largest barriers to implementation. Technology limitations, waste heat sources, temperatures, chemical compositions, and application constraints all play important roles as well. Facility personnel play a key role in implementing waste heat projects; and time constraints, risks with implementing projects, management buying into, and approval can be barriers to implementing waste heat projects.

While barriers exist, the paper also notes tremendous opportunities to recover waste heat and reduce GHG emissions. Key drivers include cost reductions, social responsibility, incentive opportunities, increase in awareness and educational opportunities, and easier access to expert and professional advice and guidance through energy efficiency programs and external consultants.

With waste heat accounting for 20-50% of industrial energy losses it is imperative and expected that heat recovery projects will play a critical role in the effort to decarbonize industry and reduce GHG emissions.

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