Waste Heat Recovery:
Technology and Opportunities in U.S. Industry

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Waste Heat Recovery: -
Technology and Opportunities in U.S. Industry -

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Abstract -

The U.S. industrial sector accounts for about one-third of the total energy consumed in the United States and is responsible for about one-third of fossil-fuel-related greenhouse gas emissions. It is estimated that somewhere between 20 to 50% of industrial energy input is lost as waste heat in the form of hot exhaust gases, cooling water, and heat lost from hot equipment surfaces and heated products. As the industrial sector continues efforts to improve its energy efficiency, recovering waste heat losses provides an attractive opportunity for an emission-free and less-costly energy resource. Numerous technologies and variations/combinations of technologies are commercially available for waste heat recovery. Many industrial facilities have upgraded or are improving their energy productivity by installing these technologies. However, heat recovery is not economical or even possible in many cases. This study was initiated in order to evaluate RD&D needs for improving waste heat recovery technologies. A bottom-up approach is used to evaluate waste heat quantity, quality, recovery practices, and technology barriers in some of the largest energy-consuming units in U.S. manufacturing. The results from this investigation serve as a basis for understanding the state of waste heat recovery and providing recommendations for RD&D to advance waste heat recovery technologies. Technology needs are identified in two broad areas: 1) extending the range of existing technologies to enhance their economic feasibility and recovery efficiency, and 2) exploring new methods for waste heat recovery, especially for unconventional waste heat sources.

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Executive Summary

The United States industrial sector accounts for approximately one third of all energy used in the United States, consuming approximately 32 quadrillion Btu (10^{15} Btu) of energy annually and emitting about 1,680 million metric tons of carbon dioxide associated with this energy use.[†] Efforts to improve industrial energy efficiency focus on reducing the energy consumed by the equipment used in manufacturing (e.g., boilers, furnaces, dryers, reactors, separators, motors, and pumps) or changing the processes or techniques to manufacture products. A valuable alternative approach to improving overall energy efficiency is to capture and reuse the lost or "waste heat" that is intrinsic to all industrial manufacturing. During these manufacturing processes, as much as 20 to 50% of the energy consumed is ultimately lost via waste heat contained in streams of hot exhaust gases and liquids, as well as through heat conduction, convection, and radiation from hot equipment surfaces and from heated product streams.[‡] In some cases, such as industrial furnaces, efficiency improvements resulting from waste heat recovery can improve energy efficiency by 10% to as much as 50%.[*]

Captured and reused waste heat is an emission-free substitute for costly purchased fuels or electricity. Numerous technologies are available for transferring waste heat to a productive end-use. Nonetheless, anywhere from 5-13 quadrillion Btu/yr of waste heat energy remains unrecovered as a consequence of industrial manufacturing. This report investigates industrial waste heat recovery practices, opportunities, and barriers in order to identify technology research, development, and demonstration (RD&D) needed to enable further recovery of industrial waste heat losses.

Three essential components (Figure A) are required for waste heat recovery: 1) an accessible source of waste heat, 2) a recovery technology, and 3) a use for the recovered energy. This study specifically examines large energy-consuming processes (totaling 8,400 trillion Btu/yr, or TBtu/yr) and identifies unrecovered waste heat losses in exhaust gases totaling ~1,500 TBtu/yr. Topics investigated for each waste heat source include waste heat quantity and quality, available recovery technologies, and barriers to implementing heat recovery. The results of this analysis are used as the basis for identifying RD&D needs that can increase industrial energy efficiency by improving and developing waste heat recovery technologies.

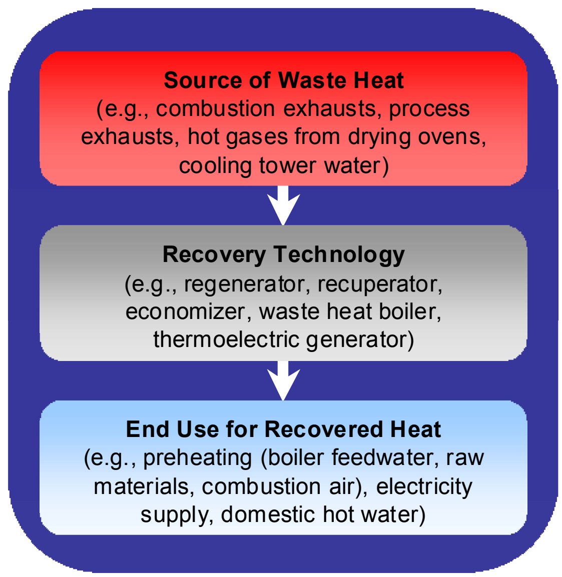


Figure A – Three Essential Components Are Required for Waste Heat Recovery

RD&D opportunities include optimizing existing recovery technologies as well as developing new heat recovery technologies. Existing technologies can be further improved to maximize recovery, expand application constraints, and improve economic feasibility. Emerging and novel technologies may hold promise for replacing existing technologies in some cases, enabling heat recovery from "new" heat

[†] Includes energy and emissions associated with electric power generation. (US DOE EIA. *Annual Energy Review 2006).*

[‡] Energetics, *Energy Use, Loss, and Opportunities Analysis: U.S Manufacturing & Mining*, p. 17. 2004

[*] EPA, *Climate Wise. Wise Rules for Energy Efficiency: A Toolkit for Estimating Energy Savings and Greenhouse Gas Reductions, p. 18.* 1998

sources not typically considered for recovery, and increasing "end-use" options for heat recovery. Moreover, despite the significant environmental and energy savings benefits of waste heat recovery, its implementation depends primarily on the economics and perceived technical risks. Industrial manufacturing facilities will invest in waste heat recovery only when it results in savings that yield a "reasonable" payback period (<< 3 years) and the perceived risks are negligible. A key consideration in any RD&D effort, therefore, should be minimizing economic costs of waste heat recovery technologies.

Study Approach

This study uses a bottom-up approach to identify technology needs in industrial waste heat recovery by characterizing specific, large industrial waste heat streams, describing current recovery practices and barriers, and using these results to identify RD&D needs. The report evaluates unrecovered waste heat from some of the most energy-intensive processes in U.S. manufacturing, such as coke ovens and aluminum melting furnaces. The investigation focuses primarily on exhaust streams from high-temperature processes since these applications are some of the most significant sources of high-quality waste heat. However, during the course of this study, it also became apparent that non-conventional sources of waste heat (e.g., aluminum furnace sidewall losses, losses from heated products, and lower-quality waste heat) should also be targeted for research in heat recovery technologies.

Each waste heat stream is investigated in terms of its waste heat quantity (the approximate energy contained in the waste heat stream), quality (typical exhaust temperatures), current recovery technologies and practices, and barriers to heat recovery. Energy content of waste heat streams is a function of mass flow rate, composition, and temperature, and was evaluated based on process energy consumption, typical temperatures, and mass balances. The enthalpy of waste heat streams was estimated from two reference (*Ref*) temperatures: 77°F [25°C] and 300°F [150°C]. Ambient conditions are represented at 77°F [25°C], while 300°F [150°C] represents a common design point used to avoid condensation with many waste gas streams. Since waste heat temperature is an important quality in the feasibility of waste heat recovery, this study reports typical exhaust temperatures of all waste heat sources investigated. Additionally, the work potential or efficiency of converting waste heat to another form of energy (i.e., mechanical or electrical) was estimated. The work potential (based on Carnot efficiency) is a measure of the maximum energy that could be recovered by using the waste heat to drive a heat engine. Quantifying work potential allows a better comparison of waste heat sources with different exhaust temperatures.

The potential for heat recovery is further scoped out by discussing current waste heat recovery practices and barriers to heat recovery for each unit assessed. Finally, the results from the bottom-up analysis of waste heat sources were used to identify technology development needs for wider implementation of industrial waste heat recovery. Technology needs are discussed in the context of existing technologies, which can be further optimized, as well as developing technologies that may provide new opportunities for heat recovery.

Waste Heat Profile

This study analyzed selected industrial processes that consume about 8,600 TBtu, or one third of the energy delivered to U.S. industrial facilities.[†] Investigation of current waste heat recovery practices shows that waste heat is generally recovered from clean, high-temperature waste heat sources in large capacity systems. Key opportunities are available in optimizing existing systems, developing technologies for

[†] Based on 25 quadrillion Btu of energy consumption, which excludes losses associated with electricity generation. US DOE EIA *Annual Energy Review 2006.*

chemically corrosive systems, recovering heat from non-fluid heat sources, and recovering low-temperature waste heat. Observed trends are described below.

- Waste heat recovery systems are frequently implemented, but constrained by factors such as temperature limits and costs of recovery equipment.
  There are a number of cases where heat recovery equipment is installed, but the quantity of heat recovered does not match the full recovery potential. Key barriers include heat exchanger material limits and costs for extending recovery to lower-temperature and higher-temperature regimes.

- Most unrecovered waste heat is at low temperatures.
  The waste heat streams analyzed in this study showed that roughly 60% of unrecovered waste heat is low quality (i.e., at temperatures below 450°F [232°C]). While low-temperature waste heat has less thermal and economic value than high-temperature heat, it is ubiquitous and available in large quantities. Comparison of total work potential from different waste heat sources showed that the magnitude of low-temperature waste heat is sufficiently large that it should not be neglected in pursuing RD&D opportunities for waste heat recovery. New technologies are developing that may provide significant opportunities for low-temperature heat recovery.

- There are certain industrial subsectors where heat recovery is less common, due to factors such as heat source's chemical composition and the economies-of-scale required for recovery.
  High-temperature, high-quality heat is wasted in some subsectors due to corrosive/fouling chemicals contained in the waste heat stream, or due to economies-of-scale that limit recovery (e.g., small metal casting and glass operations).

- Losses from nontraditional waste heat sources are difficult to recover, but significant.
  This study focused on exhaust gas waste heat losses; however, it was found that alternate sources of waste heat are also significant. These include heat lost from hot product streams (e.g., hot cast steel) and hot equipment surfaces (e.g., aluminum sidewalls). Heat losses from heated solid streams in the iron and steel industry total 600 TBtu/yr, and losses from primary aluminum cell walls total 45 TBtu/yr. These heat losses alone are about one-third the size of off-gas losses from all the processes analyzed in this report.

Research, Development, and Demonstration Opportunities: Conventional and Novel Technologies

Waste heat recovery technologies, although currently employed to varying degrees at many industrial facilities, face technical and economic barriers that impede their wider application. In order to promote waste heat recovery and process integration, efforts must be undertaken to extend the economic feasibility of conventional recovery technologies, as well as promote new technologies that can be applied to waste heat sources not typically exploited for waste heat recovery.

- Extending The Economic Operating Range Of Conventional Technologies
  Numerous technologies are already well developed for waste heat recovery (e.g., recuperators, regenerators, etc.). However, the challenge is that technologies are not always economical for a given application (e.g., applications with dirty exhaust streams). This report includes an overview of existing technologies and practices and includes summary tables showing the status of technologies in diverse applications. Meanwhile, there are cases where recovery systems are installed, but they operate under constraints which prevent more efficient heat recovery. RD&D

efforts could further optimize existing technologies to better meet various challenges presented by industry.

- Conducting RD&D In Emerging And Novel Technologies
  New and developing technologies offer promise in recovering waste heat more efficiently and from non-traditional sources. For example, recently developed recovery technology such as the Kalina cycle has proven successful for recovering low- to medium-temperature waste heat. Efforts are also underway to demonstrate compact membrane condensers, which could enhance recovery of latent heat in exhaust gases. Meanwhile RD&D efforts are exploring direct conversion technologies such as thermoelectric generation. Finally, there may be opportunities for new technologies that could recover heat from sources not typically considered for heat recovery (e.g., losses from heated product streams and sidewall losses in aluminum cells).

Barriers and Research, Development, and Demonstration Needs Identified for Promoting Waste Heat Recovery Practices

Numerous barriers impact the economy and effectiveness of heat recovery equipment and impede their wider installation. Many of these barriers, described below, are interrelated, but can generally be categorized as related to cost, temperature restrictions, chemical composition, application specifics, and inaccessibility/transportability of heat sources.

1.) Costs

a. Long Payback Periods - Costs of heat recovery equipment, auxiliary systems, and design services lead to long payback periods in certain applications. Additionally, several industry subsectors with high-quality waste heat sources (e.g., metal casting) are renowned for small profit margins and intense internal competition for limited capital resources.

b. Material Constraints and Costs - Certain applications require advanced and more costly materials. These materials are required for high-temperature streams, streams with high chemical activity, and exhaust streams cooled below condensation temperatures. Overall material costs per energy unit recovered increase as larger surface areas are required for more efficient, lower-temperature heat recovery systems.

c. Economies-of-Scale - Equipment costs favor large-scale heat recovery systems and create challenges for small-scale operations.

d. Operation and Maintenance Costs - Corrosion, scaling, and fouling of heat exchange materials lead to higher maintenance costs and lost productivity.

2.) Temperature Restrictions

a. Lack of a Viable End-Use - Many industrial facilities do not have an on-site use for low-temperature heat. Meanwhile, technologies that create end-use options (e.g., low-temperature power generation) are currently less developed and more costly.

b. Material Constraints and Costs-

i. High temperature - Materials that retain mechanical and chemical properties at high temperatures are costly. Therefore, waste heat is often quickly diluted with outside air to reduce temperatures. This reduces the quality of energy available for recovery.

ii. Low temperature - Liquid and solid components can condense as hot streams cool in recovery equipment. This leads to corrosive and fouling conditions. The additional cost of materials that can withstand corrosive environments often prevents low-temperature recovery.

iii. Thermal cycling - The heat flow in some industrial processes can vary dramatically and create mechanical and chemical stress in equipment.

c. Heat Transfer Rates - Small temperature differences between the heat source and heat sink lead to reduced heat transfer rates and require larger surface areas.

3.) Chemical Composition

a. Temperature Restrictions - Waste heat stream chemical compatibility with recovery equipment materials will be limited both at high and low temperatures.

b. Heat Transfer Rates - Deposition of substances on the recovery equipment surface will reduce heat transfer rates and efficiency.

c. Material Constraints and Costs - Streams with high chemical activity require more advanced recovery equipment materials to withstand corrosive environments.

d. Operation and Maintenance Costs - Streams with high chemical activity that damage equipment surfaces will lead to increased maintenance costs.

e. Environmental Concerns - Waste heat recovery from exhaust streams may complicate or alter the performance of environmental control and abatement equipment.

f. Product/Process Control - Chemically active exhaust streams may require additional efforts to prevent cross-contamination between streams.

4.) Application-specific Constraints

a. Process-specific Constrains - Equipment designs are process specific and must be adapted to the needs of a given process. For example, feed preheat systems vary significantly between glass furnaces, blast furnaces, and cement kilns.

b. Product/ Process Control - Heat recovery can complicate and compromise process/quality control systems.

5.) Inaccessibility/Transportability

a. Limited Space - Many facilities have limited physical space in which to access waste heat streams (e.g., limited floor or overhead space)

b. Transportability - Many gaseous waste heat streams are discharged at near-atmospheric pressure (limiting the ability to transport them to and through equipment without additional energy input).

c. Inaccessibility - It is difficult to access and recover heat from unconventional sources such as hot solid product streams (e.g., ingots) and hot equipment surfaces (e.g., sidewalls of primary aluminum cells).

RD&D needs to address these barriers are summarized in Table A.

Table A – Research, Development, and Demonstration Needs for Addressing - Waste Heat Recovery Barriers -

RD&D Opportunity	Barriers Addressed									
	Long Payback Periods	Material Constraints and Costs	Maintenance Costs	Economies of Scale	Lack of End-use	Heat Transfer Rates	Environmental Concerns	Process Control and Product Quality	Process-specific Constraints	Inaccessibility
Develop low-cost, novel materials for resistance to corrosive contaminants and to high temperatures		x	x							
Economically scale-down heat recovery equipment (value-engineer)	x	x		x						
Develop economic heat recovery systems that can be easily cleaned after exposure to chemically active gases			x	x		x				
Develop novel manufacturing processes that avoid introducing contaminants into off-gases in energy-intensive manufacturing processes		x	x				x	x	x	
Develop low-cost dry gas cleaning systems		x	x			x	x	x		
Develop and demonstrate low-temperature heat recovery technologies, including heat pumps and low-temperature electricity generation.		x			x					
Develop alternative end-uses for waste heat					x					
Develop novel heat exchanger designs with increased heat transfer coefficients	x	x				x				
Develop process-specific heat recovery technologies				x		x	x	x	x	x
Reduce the technical challenges and costs of process-specific feed preheating systems	x			x		x		x	x	
Evaluate and develop opportunities for recovery from unconventional waste heat sources (e.g., sidewall losses)									x	x
Promote new heat recovery technologies such as solid-state generation					x					x
Promote low-cost manufacturing techniques for the technologies described above	x	x	x	x	x	x	x	x	x	x

1.0 Introduction

Industrial waste heat refers to energy that is generated in industrial processes without being put to practical use. Sources of waste heat include hot combustion gases discharged to the atmosphere, heated products exiting industrial processes, and heat transfer from hot equipment surfaces. The exact quantity of industrial waste heat is poorly quantified, but various studies have estimated that as much as 20 to 50% of industrial energy consumption is ultimately discharged as waste heat. While some waste heat losses from industrial processes are inevitable, facilities can reduce these losses by improving equipment efficiency or installing waste heat recovery technologies. Waste heat recovery entails capturing and reusing the waste heat in industrial processes for heating or for generating mechanical or electrical work. Example uses for waste heat include generating electricity, preheating combustion air, preheating furnace loads, absorption cooling, and space heating.

Heat recovery technologies frequently reduce the operating costs for facilities by increasing their energy productivity. Many recovery technologies are already well developed and technically proven; however, there are numerous applications where heat is not recovered due to a combination of market and technical barriers. As discussed below, various sources indicate that there may be significant opportunities for improving industrial energy efficiency through waste heat recovery. A comprehensive investigation of waste heat losses, recovery practices, and barriers is required in order to better identify heat recovery opportunities and technology needs. Such an analysis can aid decision makers in identifying research priorities for promoting industrial energy efficiency.

The objectives of this report are as follows:

- provide an overview of conventional and developing heat recovery technologies in the United States and abroad,
- evaluate the quantity and quality (temperature) of key industrial waste heat sources,
- describe current waste heat recovery practices in different applications,
- identify barriers to waste heat recovery, and
- suggest Research, Development, and Demonstration (RD&D) efforts that can further promote heat recovery practices.

1.1 What is Waste Heat Recovery?

Waste heat losses arise both from equipment inefficiencies and from thermodynamic limitations on equipment and processes. For example, consider reverberatory furnaces frequently used in aluminum melting operations. Exhaust gases immediately leaving the furnace can have temperatures as high as 2,200-2,400°F [1,200-1,300°C]. Consequently, these gases have high-heat content, carrying away as much as 60% of furnace energy inputs. Efforts can be made to design more energy-efficient reverberatory furnaces with better heat transfer and lower exhaust temperatures; however, the laws of thermodynamics place a lower limit on the temperature of exhaust gases. Since heat exchange involves energy transfer from a high-temperature source to a lower-temperature sink, the combustion gas temperature must always exceed the molten aluminum temperature in order to facilitate aluminum melting. The gas temperature in the furnace will never decrease below the temperature of the molten aluminum, since this would violate the second law of thermodynamics. Therefore, the minimum possible temperature of combustion gases immediately exiting an aluminum reverberatory furnace corresponds to the aluminum pouring point temperature 1,200-1,380°F [650-750°C]. In this scenario, at least 40% of the energy input to the furnace is still lost as waste heat (Appendix A: Documentation of Waste Heat Estimates).

Recovering industrial waste heat can be achieved via numerous methods. The heat can either be "reused" within the same process or transferred to another process. Ways of reusing heat locally include using combustion exhaust gases to preheat combustion air or feedwater in industrial boilers. By preheating the feedwater before it enters the boiler, the amount of energy required to heat the water to its final temperature is reduced. Alternately, the heat can be transferred to another process; for example, a heat exchanger could be used to transfer heat from combustion exhaust gases to hot air needed for a drying oven. In this manner, the recovered heat can replace fossil energy that would have otherwise been used in the oven. Such methods for recovering waste heat can help facilities significantly reduce their fossil fuel consumption, as well as reduce associated operating costs and pollutant emissions. Typical sources of waste heat and recovery options are listed in Table 1.

Table 1 – Examples of Waste Heat Sources and End-Uses

Waste Heat Sources	Uses for Waste Heat
• Combustion Exhausts: Glass melting furnace Cement kiln Fume incinerator Aluminum reverberatory furnace Boiler • Process off-gases: Steel electric arc furnace Aluminum reverberatory furnace • Cooling water from: Furnaces Air compressors Internal combustion engines • Conductive, convective, and radiative losses from equipment: Hall-Hèroult cells [a] • Conductive, convective, and radiative losses from heated products: Hot cokes Blast furnace slags [a]	• Combustion air preheating • Boiler feedwater preheating • Load preheating • Power generation • Steam generation for use in: power generation mechanical power process steam • Space heating • Water preheating • Transfer to liquid or gaseous process streams

a. Not currently recoverable with existing technology

Combustion air preheat can increase furnace efficiency by as much as 50%, as shown in Table 2. Another advantage of waste heat recovery is that it can reduce capacity requirements for facilities' thermal conversion devices, leading to reductions in capital costs. For example, consider the case of combustion exhaust gases used to heat building air for space heat. In addition to replacing purchased fuels, the recovered waste heat can potentially eliminate the need for additional space heating equipment, thereby reducing capital and overhead costs.[1]

In addition to the economic benefits of waste heat recovery for the facility, waste heat recovery is a greenhouse-gas-free source of energy. The U.S. industrial sector consumes about 32 x 10^{15} Btu/yr, or one-third of the energy consumed in the United States. It is likewise responsible for about one third of energy-related greenhouse gas emissions.[2] Reducing the Nation's fossil fuel demand will result in accompanying reductions in greenhouse gas emissions.

Table 2 - Furnace Efficiency Increases with Combustion Air Preheat -

Furnace Outlet Temperature	Combustion Air Preheat Temperature				
	400°F [204°C]	600°F [316°C]	800°F [427°C]	1,000°F [538°C]	1,200°F [649°C]
2,600°F [1,427°C]	22%	30%	37%	43%	48%
2,400°F [1,316°C]	18%	26%	33%	38%	43%
2,200°F [1,204°C]	16%	23%	29%	34%	39%
2,000°F [1,093°C]	14%	20%	26%	31%	36%
1,800°F [982°C]	13%	19%	24%	29%	33%
1,600°F [871°C]	11%	17%	22%	26%	30%
1,400°F [760°C]	10%	16%	20%	25%	28%

Source: EPA 2003, Wise Rules for Energy Efficiency. Based on a natural gas furnace with 10% excess air.

1.2 Need for This Study

The purpose of this report is to identify RD&D efforts required to expand waste heat recovery practices across the U.S. industrial sector. Numerous sources indicate a significant percentage (20-50%) of industrial energy inputs is lost as waste heat, totaling anywhere from 5 to 13 quadrillion Btu/yr.[†] However, there is a dire lack of information on the source of the largest waste heat losses in different sectors and processes and the nature of different waste heat sources (e.g., the waste heat quality and chemical composition) — knowledge of these factors is critical in determining the feasibility and extent of opportunity for waste heat recovery. This study identifies RD&D needs built on a thorough investigation of waste heat losses and barriers across various energy-intensive processes/equipment.

Previous analysis of nationwide waste heat losses includes studies by Energetics,[3] PNNL,[4] EPA,[5] and Cooke[6] (Table 3). The Energetics study conducted in 2004 evaluates energy losses at multiple stages of manufacturing. It does not quantify waste heat losses, but acknowledges that these losses may total 20-50% of energy delivered to plants. The study also uses rough approximations of efficiency improvement opportunities to estimate that 1.6 quadrillion Btu/yr could be saved through various heat recovery efforts.[‡] PNNL also conducted a study in 2006 that included estimates of chemical energy in waste heat streams (e.g., the chemical energy of uncombusted CO, CH_4, etc.). Another study by EPA in 1984 used stack temperature databases to estimate waste heat losses; limitations of that study include that final exhaust temperatures were lower than furnace exit temperatures, and that the study was conducted over 20 years ago.

This study further expands on previous studies by a) evaluating application-specific waste heat losses and recovery practices, and b) evaluating the quality/work potential of waste heat.

† Based on 25 quadrillion Btu of energy consumption, which excludes losses associated with electricity generation. US DOE EIA *Annual Energy Review 2006.*

‡ Energetics 2004, p. 72 Energy saving potential includes chemicals, petroleum, and forest product industries (851 TBtu), drying processes (377 TBtu), metals and non-metallic minerals manufacture (235 TBtu), calcining (74 TBtu), and metal quenching/cooling (57 TBtu).

Table 3 - Estimates of Waste Heat Loss and Recovery Potential -

Study	Estimated Waste Heat Loss and/or Recovery Potential
Cooke[6], 1974	Waste heat losses in the United states total 50% of energy inputs
EPA[5], 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.[7]
Energetics[3], 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[4], 2006	The chemical energy contained in exhaust gas streams totals about 1.7 quadrillion Btu/yr.

1.3 Structure of This Report

Part A provides the reader with a background in waste heat recovery concepts and technologies. Section 2 describes factors influencing waste heat recovery feasibility, including waste heat quantity, temperature, chemical composition, and thermodynamic restrictions. Section 3 provides a description of waste heat recovery technologies, including conventional technologies (e.g., recuperators and regenerators), and developing technologies such as solid-state generation devices.

Part B (Section 4) evaluates current waste heat losses and recovery practices in some of the most energy-intensive processes in the largest energy-consuming industries in the United States. The processes analyzed consume about 8,600 TBtu of energy per year, which make up about 40% of the annual energy delivered to the industrial sector. The focus of the discussion is on flue gases from high-temperature processes, but some losses such as convective and radiative losses from equipment and cooling water losses from certain applications are also mentioned. Items addressed include waste heat loss estimates, exhaust temperatures, chemical constraints, existing recovery practices, and barriers to further waste heat recovery.

Part C consolidates the findings from our assessment of waste heat losses and recovery practices. Section 5 describes observed trends in unrecovered waste heat and identifies opportunity areas, and Section 6 identifies key barriers and RD&D needed to further promote waste heat recovery.

Part A: -
Background -

2.0 Factors Affecting Waste Heat Recovery Feasibility

Evaluating the feasibility of waste heat recovery requires characterizing the waste heat source and the stream to which the heat will be transferred. Important waste stream parameters that must be determined include:

- heat quantity,
- heat temperature/quality,
- composition,
- minimum allowed temperature, and -
- operating schedules, availability, and other logistics. -

These parameters allow for analysis of the quality and quantity of the stream and also provide insight into possible materials/design limitations. For example, corrosion of heat transfer media is of considerable concern in waste heat recovery, even when the quality and quantity of the stream is acceptable.

The following provide an overview of important concepts that determine waste heat recovery feasibility.

2.1 Heat Quantity

The quantity, or heat content, is a measure of how much energy is contained in a waste heat stream, while quality is a measure of the usefulness of the waste heat. The quantity of waste heat contained in a waste stream is a function of both the temperature and the mass flow rate of the stream:

$$\dot{E} = \dot{m}\, h(t) \qquad \text{Equation (1)}$$

Where Ė is the waste heat loss (Btu/hr); m is the waste stream mass flow rate (lb/hr); and h(t) is the waste stream specific enthalpy (Btu/lb) as a function of temperature.

Enthalpy is not an absolute term, but must be measured against a reference state (for example, the enthalpy of a substance at room temperature and atmospheric pressure). In this report, the enthalpy of waste heat streams is calculated at atmospheric pressure and two reference temperatures: 77°F [25°C] and 300°F [150°C]. A reference of 77°F [25ºC] was used to provide a basis for estimating the maximum heat attainable if a gas is cooled to ambient temperature. The second reference temperature of 300°F [150ºC] is more representative of current industrial practices since the majority of industrial heat recovery systems do not cool gases below this value (see - Section 2.4 Minimum Allowable Temperature).

Although the quantity of waste heat available is an important parameter, it is not alone an effective measure of waste heat recovery opportunity. It is also important to specify the waste heat quality, as determined by its temperature.

2.2 Waste Heat Temperature/Quality

The waste heat temperature is a key factor determining waste heat recovery feasibility. Waste heat temperatures can vary significantly, with cooling water returns having low temperatures around 100 - 200°F [40 - 90°C] and glass melting furnaces having flue temperatures above 2,400°F [1,320°C]. In order to enable heat transfer and recovery, it is necessary that the waste heat source temperature is higher than the heat sink temperature. Moreover, the magnitude of the temperature difference between the heat source and sink is an important determinant of waste heat's utility or "quality". The source and sink temperature difference influences a) the rate at which heat is transferred per unit surface area of heat exchanger, and b) the maximum theoretical efficiency of converting thermal from the heat source to another form of energy (i.e., mechanical or electrical). Finally, the temperature range has important ramifications for the selection of materials in heat exchanger designs

Waste heat recovery opportunities are categorized in this report by dividing temperature ranges into low-, medium-, and high-quality of waste heat[8] sources as follows:

High:	1,200ºF [649ºC]	and higher
Medium:	450ºF [232ºC]	to 1,200ºF [650ºC]
Low:	450ºF [232ºC]	and lower[9]

Typical sources of low-, medium-, and high-temperature waste heat are listed in Table 4, along with related recovery advantages, barriers, and applicable technologies.

2.2.1 Heat Exchanger Area Requirements

The temperature of waste heat influences the rate of heat transfer between a heat source and heat sink, which significantly influences recovery feasibility. The expression for heat transfer can be generalized by the following equation:

$$\dot{Q} = UA\Delta T \text{ (W or Btu/s)} \qquad \text{Equation (2)}$$

Where Q is the heat transfer rate; U is the heat transfer coefficient; A is the surface area for heat exchange; and ΔT is the temperature difference between two streams.

Since heat transfer is a function of U, area, and ΔT, a small ΔT will require a larger heat transfer. Figure 1

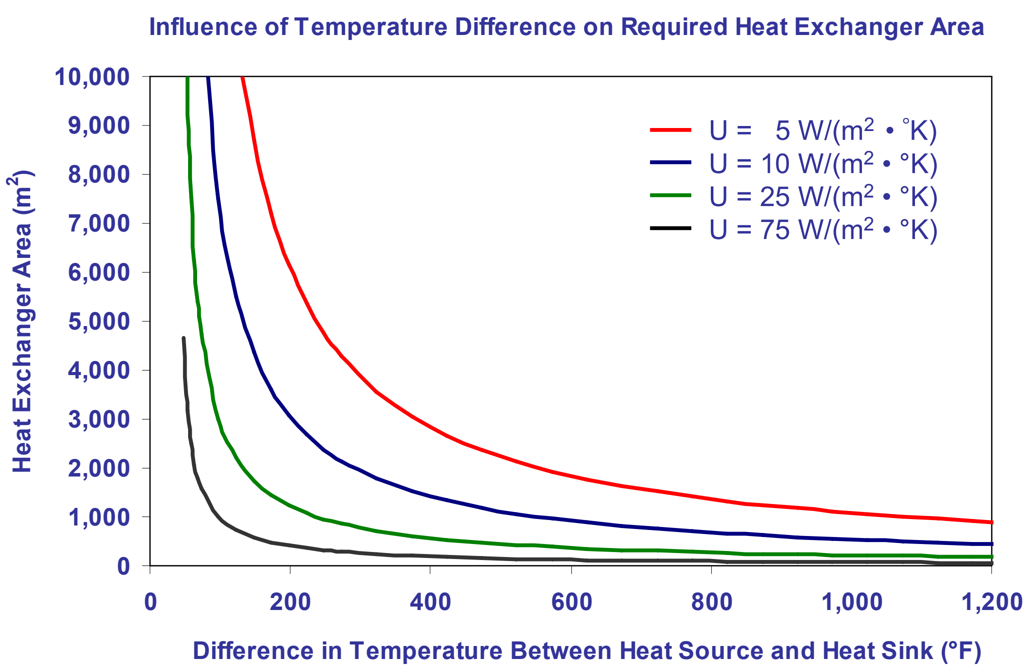


Figure 1 - The Influence of Source and Sink Temperature (ΔT) on Required Heat Exchanger Area
This figure graphs the surface area (m^2) required for recovering 10 million Btu/hr from a gaseous exhaust stream with a mass flow rate of 5 million lbs/hr by transfer to liquid water flowing at 1 ft^3/s. Calculated from Equation 2 using estimated log mean temperature difference for ΔT.

Table 4 - Temperature Classification of Waste Heat Sources and Related Recovery Opportunity

Temp Range	Example Sources	Temp (°F)	Temp (°C)	Advantages	Disadvantages/ Barriers	Typical Recovery Methods/ Technologies
High >1,200°F [> 650°C]	Nickel refining furnace	2,500-3,000	1,370-1,650	High-quality energy, available for a diverse range of end-uses with varying temperature requirements High-efficiency power generation High heat transfer rate per unit area	High temperature creates increased thermal stresses on heat exchange materials Increased chemical activity/corrosion	Combustion air preheat Steam generation for process heating or for mechanical/ electrical work Furnace load preheating Transfer to med-low temperature processes
	Steel electric arc furnace	2,500-3,000	1,370-1,650			
	Basic oxygen furnace	2,200	1,200			
	Aluminum reverberatory furnace	2,000-2,200	1,100-1,200			
	Copper refining furnace	1,400-1,500	760-820			
	Steel heating furnace	1,700-1,900	930-1,040			
	Copper reverberatory furnace	1,650-2,000	900-1,090			
	Hydrogen plants	1,200-1,800	650-980			
	Fume incinerators	1,200-2,600	650-1,430			
	Glass melting furnace	2,400-2,800	1,300-1,540			
	Coke oven	1,200-1,800	650-1,000			
	Iron cupola	1,500-1,800	820-980			
Medium 450-1,200°F [230-650°C]	Steam boiler exhaust	450-900	230-480	More compatible with heat exchanger materials Practical for power generation		Combustion air preheat Steam/ power generation Organic Rankine cycle for power generation Furnace load preheating, feedwater preheating Transfer to low-temperature processes
	Gas turbine exhaust	700-1,000	370-540			
	Reciprocating engine exhaust	600-1,100	320-590			
	Heat treating furnace	800-1,200	430-650			
	Drying & baking ovens	450-1,100	230-590			
	Cement kiln	840-1,150	450-620			
Low <450°F [<230°C]	Exhaust gases exiting recovery devices in gas-fired boilers, ethylene furnaces, etc.	150-450	70-230	Large quantities of low-temperature heat contained in numerous product streams.	Few end uses for low temperature heat Low-efficiency power generation For combustion exhausts, low-temperature heat recovery is impractical due to acidic condensation and heat exchanger corrosion	Space heating Domestic water heating Upgrading via a heat pump to increase temp for end use Organic Rankine cycle
	Process steam condensate	130-190	50-90			
	Cooling water from:					
	furnace doors	90-130	30-50			
	annealing furnaces	150-450	70-230			
	air compressors	80-120	30-50			
	internal combustion engines	150-250	70-120			
	air conditioning and refrigeration condensers	90-110	30-40			
	Drying, baking, and curing ovens	200-450	90-230			
	Hot processed liquids/solids	90-450	30-230			

demonstrates the relative heat exchanger area required to transfer heat from a hot gas at varying temperatures to liquid water. As shown, there is an inflection point at lower temperatures where the required area for heat transfer increases dramatically. The shape of the curve and the area required will vary depending on the heat transfer fluids, heat transfer coefficient, and desired heat transfer rate.

2.2.2 Maximum Efficiency for Power Generation: Carnot Efficiency

Heat sources at different temperatures have varying theoretical efficiency limits for power generation. Maximum efficiency at a given temperature is based on the Carnot efficiency, which is defined as:

$$\eta = 1 - \frac{T_L}{T_H} \qquad \text{Equation (3)}$$

Where T_H is the waste heat temperature; and T_L is the temperature of the heat sink.

The Carnot efficiency represents the maximum possible efficiency of an engine at a given temperature. The Carnot efficiency increases for higher temperatures and drops dramatically for lower temperatures (Figure 2).

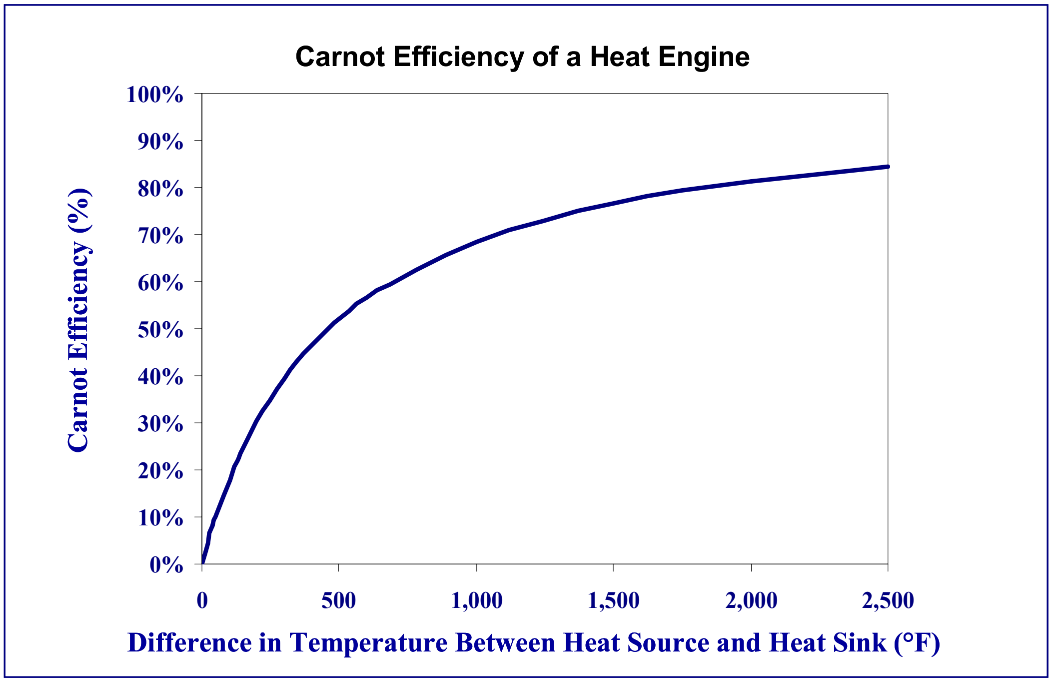


Figure 2 - Variation of Carnot Efficiency of Heat Engines as a Function of ΔT

Since the temperature of waste heat has a dramatic impact on the feasibility of heat recovery, it is important that an assessment of waste heat opportunities considers both waste heat quantity and quality. In this report, we analyze the quantity of waste heat lost from different processes, but we also analyze the work potential in order to account for variations in waste heat temperatures. The work potential represents the maximum possible work that could be extracted from a heat engine operating between the waste heat temperature and ambient temperatures. This is calculated by multiplying the waste heat by the Carnot efficiency where WP is the work potential of the heat

$$WP = \eta \dot{E} = \left(1 - \frac{T_o}{T_H}\right)\dot{E} \qquad \text{Equation (4)}$$

source; Ė is the waste heat lost to the environment; η is the Carnot efficiency; T_H is the temperature of the waste heat source; and T_O is the ambient temperature, 77°F [25°C].

2.2.3 Temperature and Material Selection

The temperature of the waste heat source also has important ramifications for material selection in heat exchangers and recovery systems. Corrosion and oxidation reactions, like all chemical reactions, are accelerated dramatically by temperature increases. If the waste heat source contains corrosive substances, the heat recovery surfaces can quickly become damaged. In addition, carbon steel at temperatures above 800°F [425ºC] and stainless steel above 1,200°F [650ºC] begins to oxidize. Therefore, advanced alloys or composite materials must be used at higher temperatures. Metallic materials are usually not used at temperatures above 1,600°F [871ºC]. Alternatives include either bleeding dilution air into the exhaust gases to lower the exhaust temperature, or using ceramic materials that can better withstand the high temperature. In the case of air bleeding, the quantity of heat contained in the exhaust stream remains constant, but the quality is reduced due to the temperature drop.

2.3 Waste Stream Composition

Although chemical compositions do not directly influence the quality or quantity of the available heat (unless it has some fuel value), the composition of the stream affects the recovery process and material selection. The composition and phase of waste heat streams will determine factors such as thermal conductivity and heat capacity, which will impact heat exchanger effectiveness. Meanwhile, the process-specific chemical makeup of off-gases will have an important impact on heat exchanger designs, material constraints, and costs.

Heat transfer rates in heat exchangers are dependent on the composition and phase of waste heat streams, as well as influenced by the deposition of any fouling substances on the heat exchanger. Denser fluids have higher heat transfer coefficients, which enables higher heat transfer rates per unit area for a given temperature difference (Table 5).

Table 5 - General Range of Heat Transfer Coefficients for Sensible - Heat Transfer in Tubular Exchangers[10 -]

Fluid Conditions	Heat Transfer Coefficient (W/(m^2 • °K)
Water, liquid	5×10^3 to 1×10^4
Light organics, liquid	1.5×10^3 to 2×10^3
Gas (P = 1,000 kPa)	2.5×10^2 to 4×10^2
Gas (P = 100-200 kPa)	8×10 to 1.2×10^2

Another key consideration is the interaction between chemicals in the exhaust stream and heat exchanger materials. Fouling is a common problem in heat exchange, and can substantially reduce heat exchanger effectiveness or cause system failure. Figure 3 displays an abandoned recuperator previously used in an aluminum-melting furnace. Deposition of substances on the heat exchanger surface can reduce heat transfer rates as well as inhibit fluid flow in the exchanger. In other cases, it will degrade the heat exchanger such that it can no longer be used.

Methods for addressing fouling are numerous and include filtering contaminated streams, constructing the exchanger with advanced materials, increasing heat exchanger surface areas, and designing the heat exchanger for easy access and cleaning. Nevertheless, the problem of fouling remains a significant challenge in thermal science. A 1992 study by Pacific Northwest National Laboratories examined 231 patents dealing with fouling. The significant patent activity and continued antidotal reports indicate that fouling remains an unresolved problem; moreover, a large portion of the research is reactive, involving methods for easily cleaning fouling, rather than methods for preventing fouling.[11]

Figure 3 - Abandoned Recuperator from an - Aluminum Melting Furnace (Source: ORNL)

2.4 *Minimum Allowable Temperature*

The minimum allowable temperature for waste streams is often closely connected with material corrosion problems. Depending on the fuel used, combustion related flue gases contain varying concentrations of carbon dioxide, water vapor, NO_X, SO_X, unoxidized organics, and minerals. If exhaust gases are cooled below the dew point temperature, the water vapor in the gas will condense and deposit corrosive substances on the heat exchanger surface. Heat exchangers designed from low-cost materials will quickly fail due to chemical attack. Therefore, heat exchangers are generally designed to maintain exhaust temperatures above the condensation point. The minimum temperature for preventing corrosion depends on the composition of the fuel. For example, exhaust gases from natural gas might be cooled as low as ~250°F [~120°C], while exhaust gases from coal or fuel oils with higher sulfur contents may be limited to ~300 °F [~150ºC] to ~350°F [~175°C].[12] Minimum exhaust temperatures may also be constrained by process-related chemicals in the exhaust stream; for example, sulfates in exhaust gases from glass melting furnaces will deposit on heat exchanger surfaces at temperatures below about 510ºF [270ºC].

The most common method for preventing chemical corrosion is designing heat exchangers with exhaust temperatures well above the dew point temperature. However, there are some cases where heat exchangers use advanced alloys and composite materials to further recover low-temperature heat. These systems have not seen much commercial application due to challenges such as high material costs, large surface areas required for heat exchange, and lack of an available end-use for low-temperature waste heat. Heat recovery at low temperatures is discussed further in Section 3.3.

2.5 *Economies of Scale, Accessibility, and Other Factors*

Several additional factors can determine whether heat recovery is feasible in a given application. For example, small-scale operations are less likely to install heat recovery, since sufficient capital may not be available, and because payback periods may be longer. Operating schedules can also be a concern. If a waste heat source is only available for a limited time every day, the heat exchanger may be exposed to both high and low temperatures. In this case, one must ensure that the heat exchange material does not fatigue due to thermal cycling. Additionally, it is important that the schedule for the heat source match the schedule for the heat load. If not, additional systems may be required to provide heat when the waste heat source is not available.

Another concern is the ease of access to the waste heat source. In some cases, the physical constraints created by equipment arrangements prevent easy access to the heat source, or prevent the installation of any additional equipment for recovering the heat. Additionally, constraints are presented by the transportability of heat streams. Hot liquid streams in process industries are frequently recovered, since they are easily transportable. Piping systems are easy to tap into and the energy can be easily transported via piping to the recovery equipment. In contrast, hot solid streams (e.g., ingots, castings, cement clinkers) can contain significant amounts of energy but their energy is not easily accessible or transportable to recovery equipment. As a result, waste energy recovery is not widely practiced with hot solid materials.

3.0 Waste Heat Recovery Options and Technologies

Methods for waste heat recovery include transferring heat between gases and/or liquids (e.g., combustion air preheating and boiler feedwater preheating), transferring heat to the load entering furnaces (e.g., batch/cullet preheating in glass furnaces), generating mechanical and/or electrical power, or using waste heat with a heat pump for heating or cooling facilities. Sections 3.1 and 3.2 discuss technologies for heat exchangers and for load preheating systems, while Section 3.3 addresses challenges and opportunities specific to low-temperature waste heat recovery. Section 3.4 discusses power generation options, and Section 3.5 contains summary tables comparing different recovery technologies.

The terminology for heat recovery technologies frequently varies among different industries. Since this report addresses multiple industries, the terminology used below is the basis for all subsequent discussion of heat exchange technologies in different industries.

3.1 Heat Exchangers

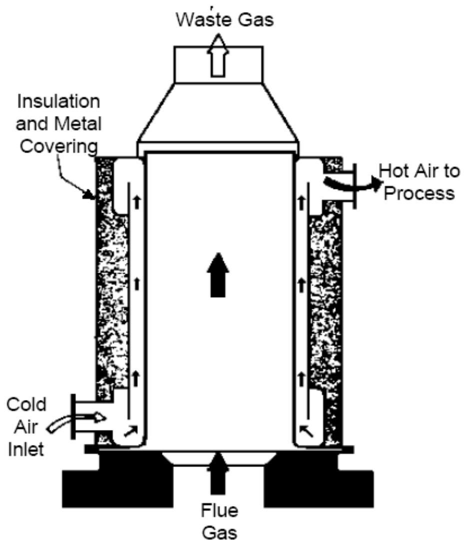
Heat exchangers are most commonly used to transfer heat from combustion exhaust gases to combustion air entering the furnace. Since preheated combustion air enters the furnace at a higher temperature, less energy must be supplied by the fuel. Typical technologies used for air preheating include recuperators, furnace regenerators, burner regenerators, rotary regenerators, and passive air preheaters.

3.1.1 Recuperator

Recuperators recover exhaust gas waste heat in medium- to high-temperature applications such as soaking or annealing ovens, melting furnaces, afterburners, gas incinerators, radiant-tube burners, and reheat furnaces. Recuperators can be based on radiation, convection, or combinations:

- A simple radiation recuperator consists of two concentric lengths of ductwork, as shown in Figure 4a. Hot waste gases pass through the inner duct and heat transfer is primarily radiated to the wall and to the cold incoming air in the outer shell. The preheated shell air then travels to the furnace burners.
- The convective or tube-type recuperator, Figure 5a (heat exchanger) passes the hot gases through relatively small diameter tubes contained in a larger shell. The incoming combustion air enters the shell and is baffled around the tubes, picking up heat from the waste gas.
- Another alternative is the combined radiation/convection recuperator, shown in Figure 4b and 5b. The system includes a radiation section followed by a convection section in order to maximize heat transfer effectiveness.

Recuperators are constructed out of either metallic or ceramic materials. Metallic recuperators are used in applications with temperatures below 2,000ºF [1,093ºC], while heat recovery at higher temperatures is better suited to ceramic-tube recuperators. These can operate with hot-side temperatures as high as 2,800ºF [1,538ºC] and cold-side temperatures of about 1,800°F [982ºC].[13]

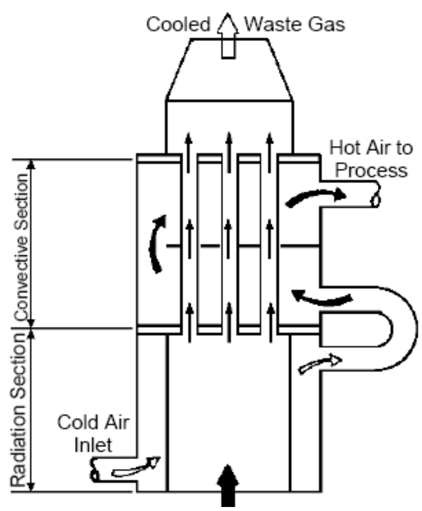


(a)

(b)

Figure 4 - (a) Metallic Radiation Recuperator Design (Source: PG & E)**,**
(b) Radiation Recuperator Installed at Glass Melter (Source: ALSTOM)

(a)



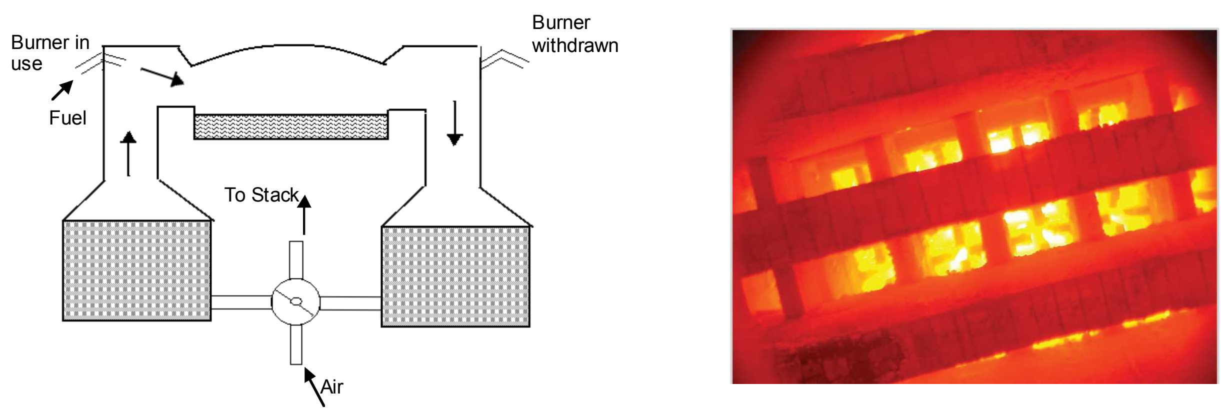
(b) -

Figure 5 - (a) Convection Recuperator (Source: Allstom, 2007)**, -**
(b) Combined Radiation/Convection Recuperator (Source: PG&E)

3.1.2 Regenerator

3.1.2.1 Furnace Regenerator

Regenerative furnaces consist of two brick "checkerwork" chambers through which hot and cold airflow alternately (Figure 6). As combustion exhausts pass through one chamber, the bricks absorb heat from the combustion gas and increase in temperature. The flow of air is then adjusted so that the incoming combustion air passes through the hot checkerwork, which transfers heat to the combustion air entering the furnace. Two chambers are used so that while one is absorbing heat from the exhaust gases, the other is transferring heat to the combustion air. The direction of airflow is altered about every 20 minutes. Regenerators are most frequently used with glass furnaces and coke ovens, and were historically used with steel open-hearth furnaces, before these furnaces were replaced by more efficient designs. They are also used to preheat the hot blast provided to blast stoves used in ironmaking; however, regenerators in blast stoves are not a heat recovery application, but simply the means by which heat released from gas combustion is transferred to the hot blast air (see - Section 4.3.1.2 Blast Furnace). Regenerator systems are specially suited for high-temperature applications with dirty exhausts. One major disadvantage is the large size and capital costs, which are significantly greater than costs of recuperators.[14]



(a) (b)

Figure 6 - (a) Regenerative Furnace Diagram,
(b) Checkerwork in Glass Regenerative Furnace (Source: GS Energy & Environment, 2007)

3.1.2.2 Rotary Regenerator/Heat Wheel

Rotary regenerators operate similar to fixed regenerators in that heat transfer is facilitated by storing heat in a porous media, and by alternating the flow of hot and cold gases through the regenerator. Rotary regenerators, sometimes referred to as air preheaters and heat wheels, use a rotating porous disc placed across two parallel ducts, one containing the hot waste gas, the other containing cold gas (Figure 7). The disc, composed of a high heat capacity material, rotates between the two ducts and transfers heat from the hot gas duct to the cold gas duct. Heat wheels are generally restricted to low- and medium-temperature applications due to the thermal stress created by high temperatures. Large temperature differences between the two ducts can lead to differential expansion and large deformations, compromising the integrity of duct-wheel air seals. In some cases, ceramic wheels can be used for higher-temperature applications. Another challenge with heat wheels is preventing cross contamination between the two gas streams, as contaminants can be transported in the wheel's porous material.

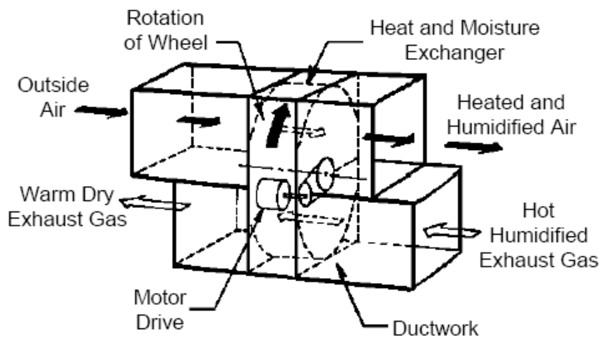


Figure 7 - (a) Rotary Regenerator (Source: PG&E, 1997)**,**
(b) Rotary Regenerator on a Melting Furnace (Source: Jasper GmbH, 2007)

One advantage of the heat wheel is that it can be designed to recover moisture as well as heat from clean gas streams. When designed with hygroscopic materials, moisture can be transferred from one duct to the other. This makes heat wheels particularly useful in air conditioning applications, where incoming hot humid air transfers heat and moisture to cold outgoing air. Besides its main application in space heating and air conditioning systems, heat wheels are also used to a limited extent in medium-temperature applications. They have also been developed for high-temperature furnace applications such as aluminum furnaces, though they are not widely implemented in the United States due to cost.[15] They are also occasionally used for recovery from boiler exhausts, but more economical recuperators and economizers are usually preferred.

3.1.3 Passive Air Preheaters

Passive air preheaters are gas-to-gas heat recovery devices for low- to medium-temperature applications where cross-contamination between gas streams must be prevented. Applications include ovens, steam boilers, gas turbine exhaust, secondary recovery from furnaces, and recovery from conditioned air.

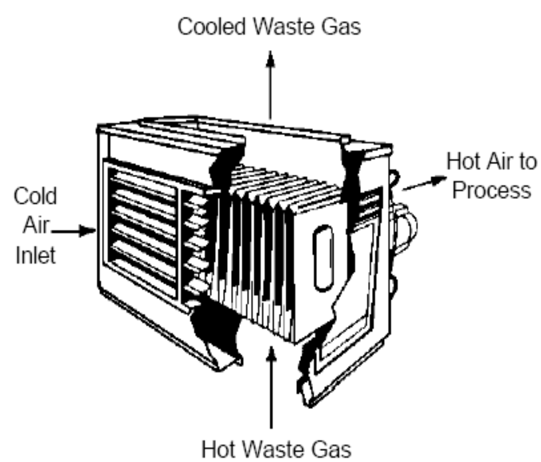


Figure 8 - Passive Gas to Gas Air Preheater
(Source, PG & E, 1997)

Passive preheaters can be of two types – the plate-type and heat pipe. The plate-type exchanger (Figure 8) consists of multiple parallel plates that create separate channels for hot and cold gas streams. Hot and cold flows alternate between the plates and allow significant areas for heat transfer. These systems are less susceptible to contamination compared to heat wheels, but they are often bulkier, more costly, and more susceptible to fouling problems.

The heat pipe heat exchanger consists of several pipes with sealed ends. Each pipe contains a capillary wick structure that facilitates movement of the working fluid between the hot and cold ends of the pipe. As shown in Figure 9 below, hot gases pass over one end of the heat pipe, causing the working fluid inside the pipe to evaporate. Pressure gradients along the pipe cause the hot vapor to move to the other end of the pipe, where the vapor condenses and transfers heat to the cold gas. The condensate then cycles back to the hot side of the pipe via capillary action.

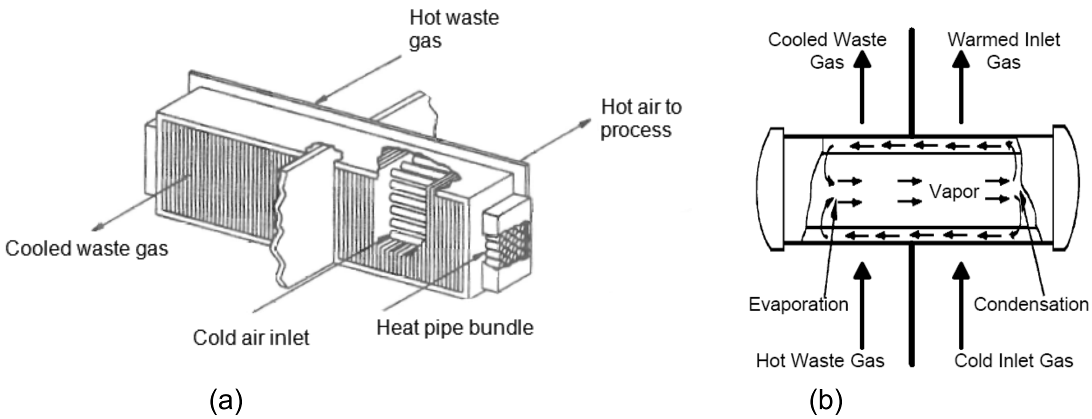


Figure 9 - (a) Heat Pipe Heat Exchanger (Source: Turner, 2006)**,**
(b) Heat Pipe (Source: PG&E, 1997)

3.1.4 Regenerative/Recuperative Burners

Burners that incorporate regenerative or recuperative systems are commercially available. Simpler and more compact in design and construction than a stand-alone regenerative furnaces or recuperators these systems provide increased energy efficiency compared to burners operating with ambient air. A self-recuperative burner incorporates heat exchange surfaces as part of the burner body design in order to capture energy from the exiting flue gas, which passes back through the body. Self-regenerative burners pass exhaust gases through the burner body into a refractory media case and operate in pairs similar in manner to a regenerative furnace. Typically, recuperative burner systems have less heat exchange area and regenerative burner systems lower mass than stand-alone units. Hence, their energy recovery is lower but their lower costs and ease of retrofitting make them an attractive option for energy recovery.

3.1.5 Finned Tube Heat Exchangers/Economizers

Finned tube heat exchangers are used to recover heat from low- to medium-temperature exhaust gases for heating liquids. Applications include boiler feedwater preheating, hot process liquids, hot water for space heating, or domestic hot water. The finned tube consists of a round tube with attached fins that maximize surface area and heat transfer rates. Liquid flows through the tubes and receive heat from hot gases flowing across the tubes. Figure 10 illustrates a finned tube exchanger where boiler exhaust gases are used for feedwater preheating, a setup commonly referred to as a boiler "economizer".

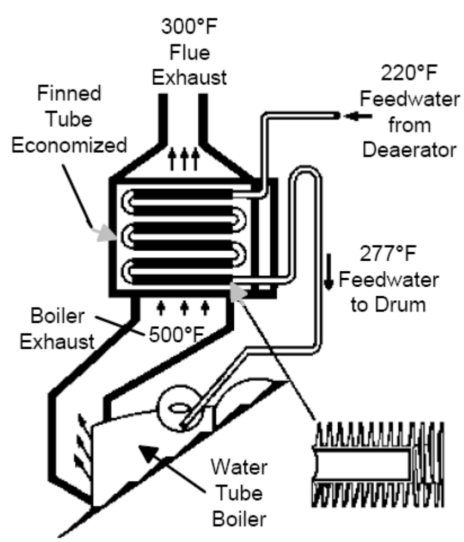


Figure 10 - Finned Tube Exchanger/ - Boiler Economizer (Source: PG&E 2007) -

3.1.6 Waste Heat Boilers

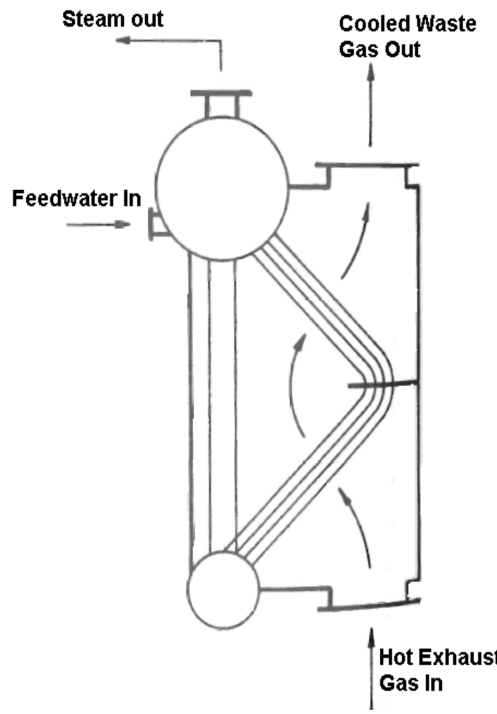


Figure 11 - Waste Heat Boiler

Waste heat boilers, such as the two-pass boiler shown in Figure 11, are water tube boilers that use medium- to high-temperature exhaust gases to generate steam. Waste heat boilers are available in a variety of capacities, allowing for gas intakes from 1000 to 1 million ft^3/min. In cases where the waste heat is not sufficient for producing desired levels of steam, auxiliary burners or an afterburner can be added to attain higher steam output. The steam can be used for process heating or for power generation. Generation of superheated steam will require addition of an external superheater to the system.

3.2 Load Preheating

Load preheating refers to any efforts to use waste heat leaving a system to preheat the load entering the system. The most common example is boiler feedwater preheating, where an economizer transfers heat from hot combustion exhaust gases to the water entering the boiler (Section 3.1.4). Other applications utilize direct heat transfer between combustion exhaust gases and solid materials entering the furnace. For example, in the aluminum metal casting industry, stack melters can replace reverberatory furnaces to reduce energy consumption. With stack melters, ingots and scrap are charged through the top of the furnace and preheated by exhaust gases leaving the furnace. Figure 12 shows a stack melter at a die casting facility that has successfully reduced energy consumption to about 47% below conventional furnaces.[16]

Figure 12 - Stack Melter in a Die - Casting Facility -

While boiler feedwater preheating is a standard practice, load preheating of material prior to melting in direct-fired systems is not as widely used. This is due to a variety of factors, including difficulties in controlling product quality, issues associated with environmental emissions, and the increased complexity and cost of building advanced furnace loading/heat recovery systems. Nevertheless, heat recovery via load preheating has received increased attention over the last 10 years. The available technologies and barriers for different load preheating furnaces will vary substantially depending on the type of furnace and load in question. These considerations are discussed in more detail in Section 4, which describes process-specific constraints on heat recovery equipment.

3.3 Low-Temperature Energy Recovery Options and Technologies

While economics often limit the feasibility of low-temperature waste heat recovery, there are various applications where low-grade waste heat has been cost-effectively recovered for use in industrial facilities. The large quantities of waste heat available in the range of 100-400°F [38-200°C] and the inherent challenges to its recovery and use warrant a separate and in-depth investigation of low-temperature waste heat recovery.

Much industrial waste heat is in the low-temperature range. For example, combustion systems such as boilers frequently use recovery technologies that exhaust gases at around 300-350°F [150°-180°C], accounting for at least 460 TBtu of waste heat per year (see - Section 4 Evaluating Selected Applications). Meanwhile, large quantities of waste heat can be found in industrial cooling water and cooling air; for example cooling of air compressors alone accounts for about 18 TBtu of waste heat per year. One integrated steel mill in Japan successfully installed a power generation plant with a 3.5 MW capacity using cooling water at only 208°F [98°C].[17]

In the case of combustion exhaust gases, substantial heat can be recovered if water vapor contained in the gases is cooled to lower temperatures. Minimum temperature limits around 250-300°F [120-150°C] are frequently employed in order to prevent water in the exhaust gases from condensing and depositing corrosive substances on the heat exchanger surface. However, cooling the flue gas further could significantly increase heat recovery by allowing the latent heat of vaporization to be recovered. A pound of water requires 1,000 Btu of energy to evaporate. Conversely, if a pound of water vapor condenses, it transfers 1,000 Btu to its environment. This latent heat comprises a significant portion of the energy contained in exhaust gases. Technologies that can minimize chemical attack while cooling exhaust gases below the condensation point can achieve significant increases in energy efficiency via recovering the latent heat of evaporation. Figure 13 below displays the energy recovered per pound of fuel with different stack exit temperatures. If gases are cooled from 300°F [150°C] to 140°F [60°C], then the facility can obtain a 3% efficiency increase. Cooling gases further to 100°F [38ºC] captures a portion of the latent heat and can provide an 11% efficiency increase.

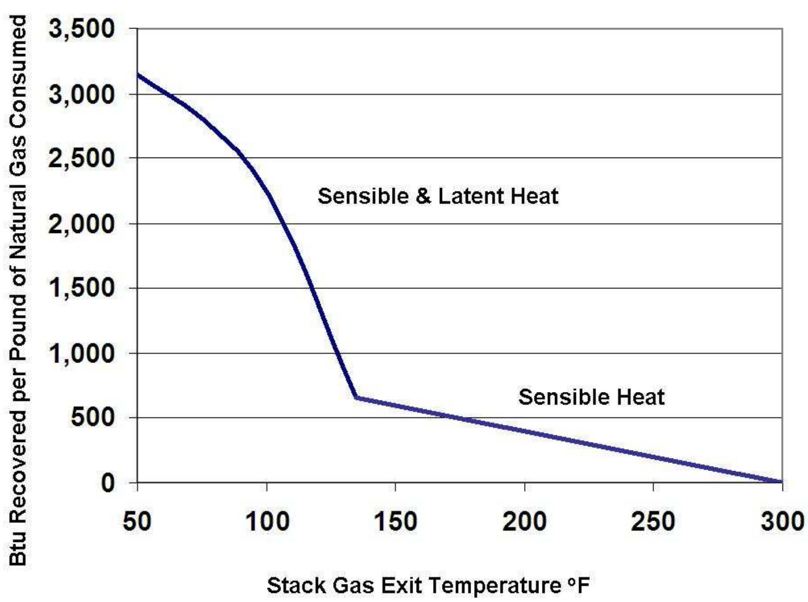


Figure 13 - Heat Recovery Curve for Natural Gas-Fired Boiler (Source: Goldstick, 1986)

3.3.1 Challenges to Recovering Low-Temperature Waste Heat

Low-temperature heat recovery faces at least three challenges:

- Corrosion of the heat exchanger surface: As water vapor contained in the exhaust gas cools, some of it will condense and deposit corrosive solids and liquids on the heat exchange surface. The heat exchanger must be designed to withstand exposure to these corrosive deposits. This generally requires using advanced materials, or frequently replacing components of the heat exchanger, which is often uneconomical.

- Large heat exchange surfaces required for heat transfer: Heat transfer rates are a function of the thermal conductivity of the heat exchange material, the temperature difference between the two fluid streams, and the surface area of the heat exchanger. Since low-temperature waste heat will involve a smaller temperature gradient between two fluid streams, larger surface areas are required for heat transfer. This limits the economics of heat exchangers.

- Finding a use for low-temperature heat: Recovering heat in the low-temperature range will only make sense if the plant has a use for low-temperature heat. Potential end-uses include domestic hot water, space heating, and low-temperature process heating. Other options include using a heat pump to "upgrade" heat to a higher temperature to serve a load requiring higher temperatures (Section 3.3.2). Additionally, low-temperature power generation technologies are slowly emerging (Section 3.4.1).

Technologies are available that can cool gases below dew point temperatures to recover low-temperature waste heat. Options include deep economizers, indirect contact condensation recovery, direct contact condensation recovery, and recently developed transport membrane condensers. These technologies are discussed below. Commercialization has been limited due to high costs and because facilities lack an end-use for the recovered heat. When facilities lack an end-use for waste heat, some have found other means for recovery, including heat pumps and low-temperature power generation. These technologies are also frequently limited by economic constraints.

3.3.2 Low-Temperature Heat Exchange

3.3.2.1 Deep Economizers

Deep economizers are designed to cool exhaust gas to 150-160ºF [65ºC-71ºC] and to withstand the acidic condensate depositing on its surface. Designs include the following options:

- Installing a "throwaway" section on the cold end of the economizer. The tubing in the cold end will degrade over time and will need to be repeatedly replaced. The frequency of replacements will depend on the flue gas composition and the material of construction.
- Designing the economizer with stainless steel tubes. Stainless steel can withstand acidic gases better than the mild steel typically used in construction.
- Using carbon steel for the majority of the heat exchanger, but using stainless steel tubes in the cold end where acidic deposits will occur.
- Using glass-tubed heat exchangers (mainly for gas-gas applications such as air preheaters).
- Using advanced materials such as Teflon.[18]

3.3.2.2 Indirect Contact Condensation Recovery

Indirect contact condensation recovery units cool gases to 100 to 110ºF [38-43ºC]. In this range, the water vapor in gases will condense almost completely. Indirect contact exchangers consist of a shell & tube heat exchangers. They can be designed with stainless steel, glass, Teflon, or other advanced materials.

3.3.2.3 Direct Contact Condensation Recovery

Direct contact condensation recovery involves direct mixing of the process stream and cooling fluid. Since these systems do not involve a separating wall across which heat must be transferred, they avoid some of the challenges of large heat transfer surfaces required for indirect contact units. An example system is shown in Figure 14. As flue gases enter the heat exchanger, they are cooled by cold water introduced at the top of the unit. The heated water stream exits through the bottom of the exchanger and provides heat to an external system. A challenge with direct contact condensation is that the water can be contaminated by substances in the flue gas.

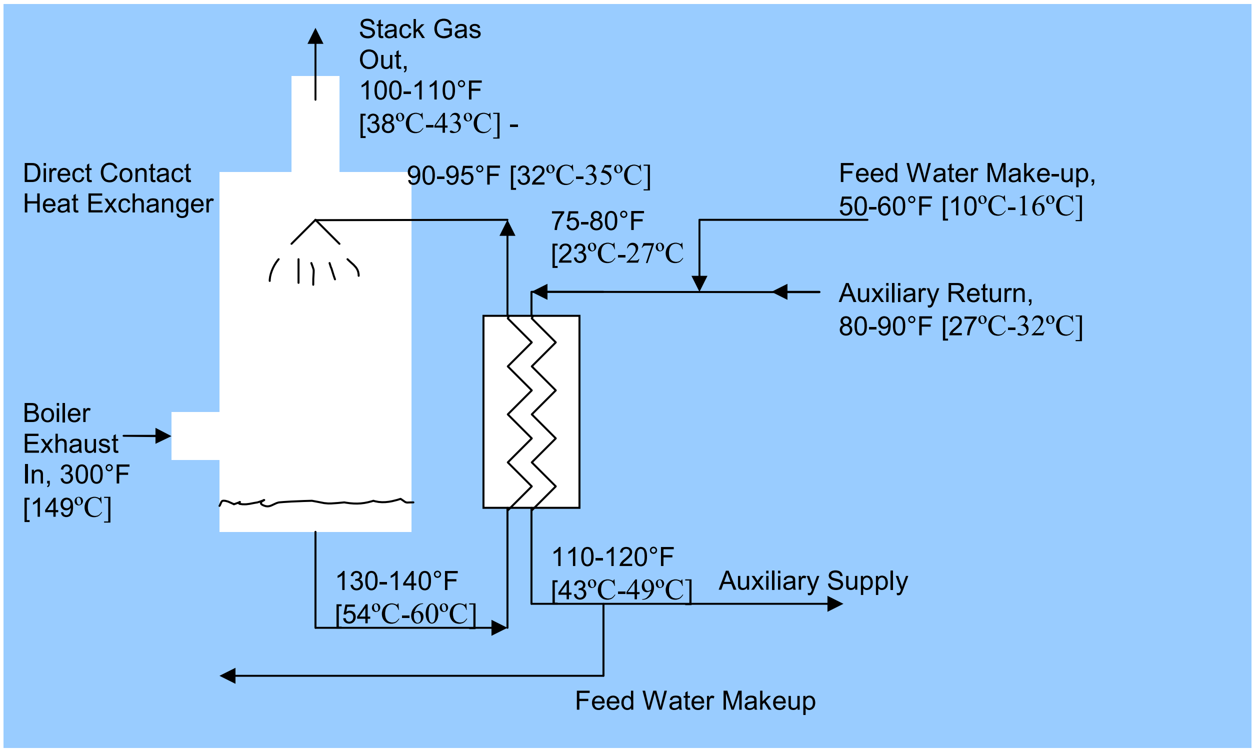


Figure 14 - Direct Contact Condensation Heat Recovery (Adapted from Goldstick, 1986)

3.3.2.4 Transport Membrane Condenser

Transport Membrane Condensers (TMCs) are a developing technology for capturing water (along with water's latent heat) from the water vapor in gas exhaust streams. Water is extracted from the flue gas at temperatures above dew point by employing capillary condensation and recycled into the boiler feedwater. A schematic of the TMC in operation is shown Figure15.[19] Like direct contact heat recovery units, TMCs extract hot water directly from the flue gas; however, since TMCs recover the water via transport thorough a membrane, the recovered water does not become contaminated as in a direct contact unit. The technology has been demonstrated for clean exhaust streams in a natural gas-fired boiler; however, TMCs require more research in advanced materials before widespread implementation for dirtier waste streams is possible. Needed areas of RD&D for enhancement include TMC strength and resistance to contaminants.

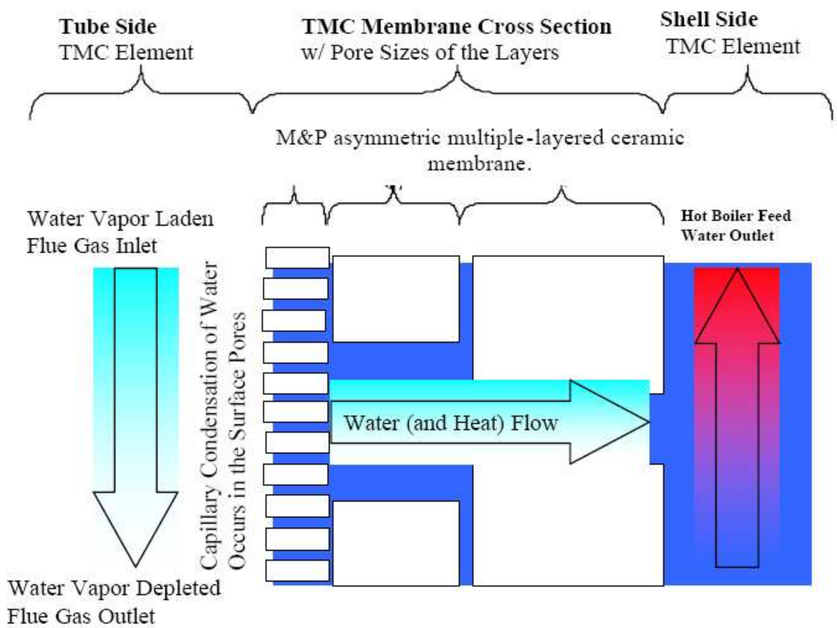


Figure 15 - Transport Membrane Condenser (Source: Liu, 2006)

3.3.2.5 Heat Pumps (Upgrading Low-Temperature Waste Heat)

Heat exchange technologies described above involve flow of energy "downhill" from a high temperature to a lower-temperature end-use. This can place limitations on opportunities for heat recovery when the waste heat temperature is below the temperature needed for a given heating load. (For example, waste heat may be available in the form of hot water at 90ºF [32ºC], while hot water at 180ºF [82ºC] is needed elsewhere in the facility). In such cases, a heat pump may provide opportunities for "upgrading" heat to the desired end-use temperature. Heat pumps use external energy inputs to drive a cycle that absorbs energy from a low-temperature source and rejects it at a higher temperature. Depending on the design, heat pumps can serve two functions: either upgrading waste heat to a higher temperature, or using waste heat as an energy input for driving an absorption cooling system. Heat pumps are most applicable to low-temperature product streams found in process industries including chemicals, petroleum refining, pulp and paper, and food processing.

Upgrading heat can be economical in some cases depending on the temperature differential required and the relative costs of fuel and electricity. If a facility has a heat load at a slightly higher temperature than the waste heat source, the heat can sometimes be provided more efficiently by a heat pump than if it were obtained from burning additional fossil fuels. Figure 16 displays typical energy losses associated with a heat pump and a steam boiler. In this example, the boiler requires 1.25 million Btu fuel input to provide 1 million Btu of heat. Meanwhile, the heat pump requires an input of only 0.72 Million Btu for electricity generation in conjunction with the 0.78 Million Btu already available from the waste heat stream.

The analysis below assumes a coefficient of performance (COP) of 4.5 and a boiler efficiency of 80%. The COP is a measure of heat pump performance, determined from the heat output and work input:

$$COP = \frac{Q}{W} \qquad \text{Equation (5)}$$

where Q is the useful heat output from heat pump, and W is the work input. -

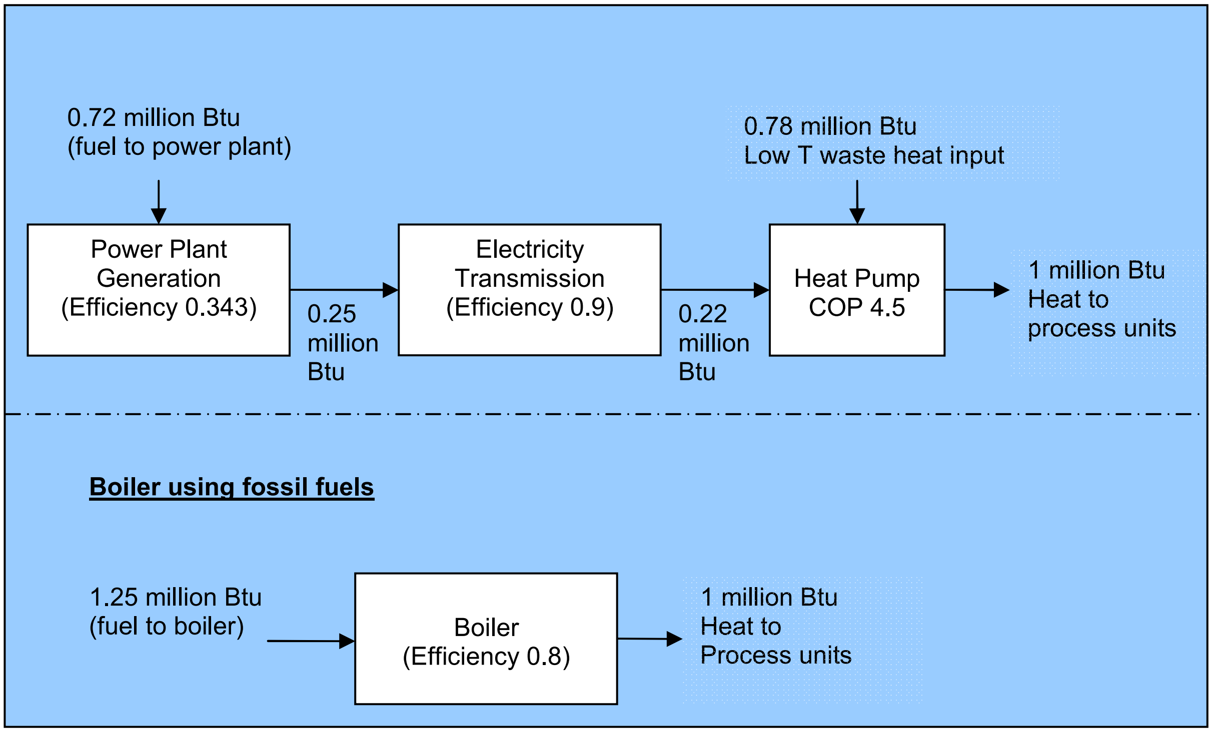


Figure 16 - Energy Losses from a Boiler versus a Heat Pump.

Note: *The heat pump receives heat from a low-temperature source and rejects it at a higher temperature. The heat pump uses waste heat plus an additional 0.22 million Btu of electrical energy to provide 1 million Btu of useful heat, while the boiler requires an input of 1.25 million Btu to provide 1 million Btu of steam heat.*

An important consideration in determining the feasibility of heat pumps is the waste heat temperature and the desired "temperature lift." The type of cycle used and the type of working fluid chosen will influence the temperatures at which the heat pump can receive or reject heat, as well as determine the maximum temperature lift achievable. The efficiency of a heat pump decreases as the desired temperature lift increase. An overview of different heat pump types, their operating parameters and associated costs is provided in Table 6. Research to develop advanced cycles and novel fluids to increase heat pump performance and flexibility in different temperature ranges could enhance the use of heat pumps for waste heat recovery.

Table 6 - Operating Parameters and Costs for Different Heat Pumps -

Heat Pump Type	Maximum Sink Temperature	Maximum Temperature Lift	Installation Costs (US$/kW) by Heat Pump Size		
			0.5 MW	1 MW	4 MW
Electric Motor Closed Compression Cycle	248°F [120°C]	176°F [80°]	450-700	320-550	240-420
Diesel Motor Closed Compression Cycle	266°F [130°C]	194°F [90°C]	520-770	390-620	300-490
Mechanical Vapor Recompression	374°F [190°C]	194°F [90°C]	520-770	390-620	300-490
Thermal Vapor Recompression	302°F [150°C]	104°F [40°C]	Not Available	210-270	100-120
Absorption Cycle (Type I, Heat Pump)	212°F [100°C]	122°F [50°C]	340-390	300-350	250-290
Absorption Cycle (Type II, Heat Transformer)	302°F [150°C]	140°F [60°C]	800-900	720-830	590-680

Source: IEA CADDET 1997

3.3.2.6 Closed Compression Cycle

Figure 17 displays an example use of a closed compression cycle to recover heat from cooling water leaving a sterilizer in a dairy plant. The sterilizer in the plant discharges cooling water at 127°F [53°C]. A heat pump is used to lower the temperature of the cooling water, while using the heat extracted to increase the temperature of process water used elsewhere in the plant. The heat pump consists of an evaporator, compressor, condenser, and expansion valve. In the evaporator, energy is transferred from the waste heat source to the refrigerant. Then the refrigerant enters the compressor, where its temperature increases. Superheated refrigerant then enters the condenser and transfers heat to the heat sink. Finally, refrigerant is throttled in an expansion valve before returning to the evaporator.

3.3.2.7 Open Cycle Vapor Recompression

These systems use compression to increase the pressure (and consequently the temperature) of waste vapor. Mechanical vapor recompression (MVR) uses a mechanical compressor, while thermal vapor recompression (TVR) uses a steam ejector, and therefore is heat-driven rather than mechanically driven.

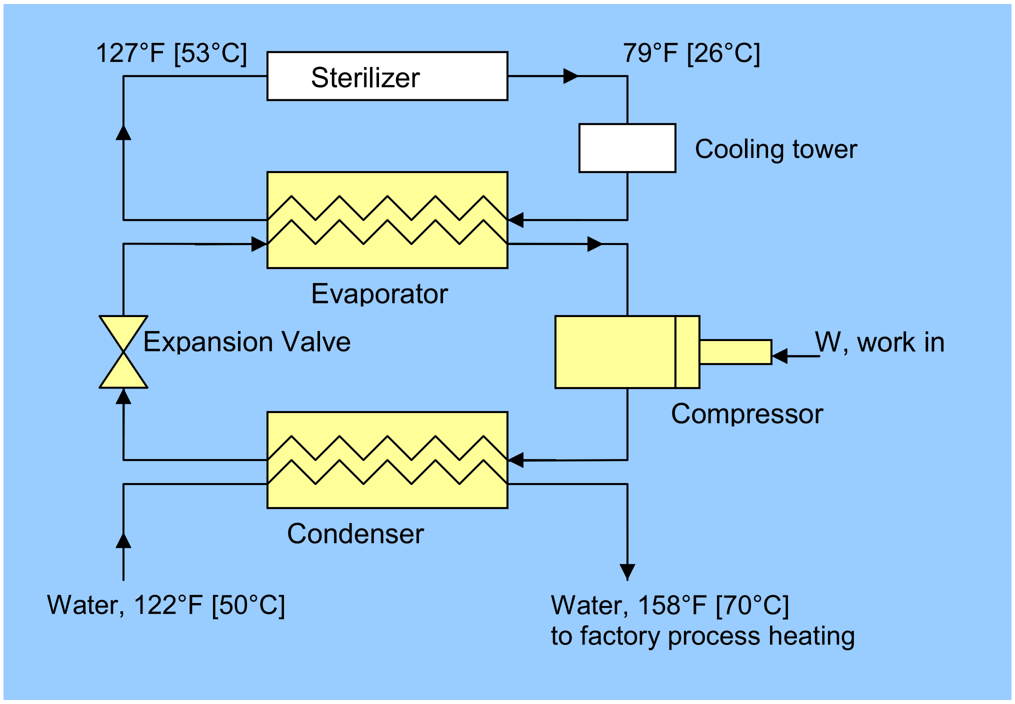


Figure 17 - Example Heat Pump Application in a Dairy
Note: *Heat pump components are highlighted in yellow. Based on successful heat pump application reported by CADDET, 1997.*

3.3.2.7 Absorption Heat Pumps

Absorption heat pumps are very similar to the closed compression cycle, except the compressor is replaced by a more complex, heat-driven absorption mechanism. Depending on the plant needs, the system can be configured in multiple ways. A "Type I" heat pump can use a lower- and a higher-temperature heat input to reject heat at an intermediate level (e.g., upgrade the low-temperature heat). A "Type II" heat pump can use a medium-temperature input to reject heat in one lower-temperature stream and one higher-temperature stream. This second application can be used for air conditioning and/or refrigeration. Chilling cycles can be valuable for applications such as food refrigeration or for cryogenic processes in various industries.

3.4 Power Generation

Generating power from waste heat typically involves using the waste heat from boilers to create mechanical energy that then drives an electric generator. While these power cycles are well-developed, new technologies are being developed that can generate electricity directly from heat, such as thermoelectric and piezoelectric generation. When considering power generation options for waste heat recovery, an important factor to keep in mind is the thermodynamic limitations on power generation at different temperatures. As discussed in Section 2, the efficiency of power generation is heavily dependent on the temperature of the waste heat source. In general, power generation from waste heat has been limited to only medium- to high-temperature waste heat sources. However, advances in alternate power cycles may increase the feasibility of generation at low temperatures. While maximum efficiency at these temperatures is lower, these systems can still be economical in recovering large quantities of energy from waste heat. Table 7 summarizes different power generation technologies.

Table 7- Options for Heat Recovery via Power Generation

Thermal Conversion Technology	Temperature Range	Typical Sources of Waste Heat	Capital Cost
Traditional Steam Cycle [a]	M,H	Exhaust from gas turbines, reciprocating engines, incinerators, and furnaces.	$1100-1,400/kW[f]
Kalina Cycle [d]	L,M,	Gas turbine exhaust, boiler exhaust, cement kilns	$1100-1,500/kW[f]
Organic Rankine Cycle [c,e]	L,M	Gas turbine exhaust, boiler exhaust, heated water, cement kilns	$1,500-3,500/kW[f]
Thermoelectric Generation [b]	M-H	Not yet demonstrated in industrial applications	$20,000-30,0000/kW[b]
Piezoelectric generation [b]	L	Not yet demonstrated in industrial applications	$10,000,000/kW[b]
Thermal Photovoltaic	M-H	Not yet demonstrated in industrial applications	N/A

a. Sean Casten, 2003. Update on US Steam Turbine technology, Presented to Canadian District Energy Association 8th Annual Conference June 20th 2003.
b. BCS, Inc., Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery
c. Daniel Duffy, "Better Cogeneration through Chemistry: the Organic Rankine Cycle
d. based on cement kiln waste heat recovery project economics. Mark Mirolli, "The Kalina Cycle for Cement Kiln Waste Heat Recovery Power Plants." Cement Industry Technical Conference, 2005. 15-20 May 2005.
e. "Organic Rankine Cycle for Electricity Generation. http://www.stowa-selectedtechnologies.nl
f. Paul Cunningham, "Waste Heat/ Cogen Opportunities in the Cement Industry" Cogeneration and Competitive Power Journal. Vol 17, No 3 p. 31-50

3.4.1 Generating Power via Mechanical Work

3.4.1.1 Steam Rankine Cycle

The most frequently used system for power generation from waste heat involves using the heat to generate steam, which then drives a steam turbine. A schematic of waste heat recovery with a Rankine cycle is shown in Figure 18. The traditional steam Rankine cycle is the most efficient option for waste heat recovery from exhaust streams with temperatures above about 650-700°F [340-370°C]. [20] At lower waste heat temperatures, steam cycles become less cost-effective, since low-pressure steam will require bulkier equipment. Moreover, low-temperature waste heat may not provide sufficient energy to superheat the steam, which is a requirement for preventing steam condensation and erosion of the turbine blades. Therefore, low-temperature heat recovery applications are better suited for the organic Rankine Cycle or Kalina cycle, which use fluids with lower boiling point temperatures compared to steam.

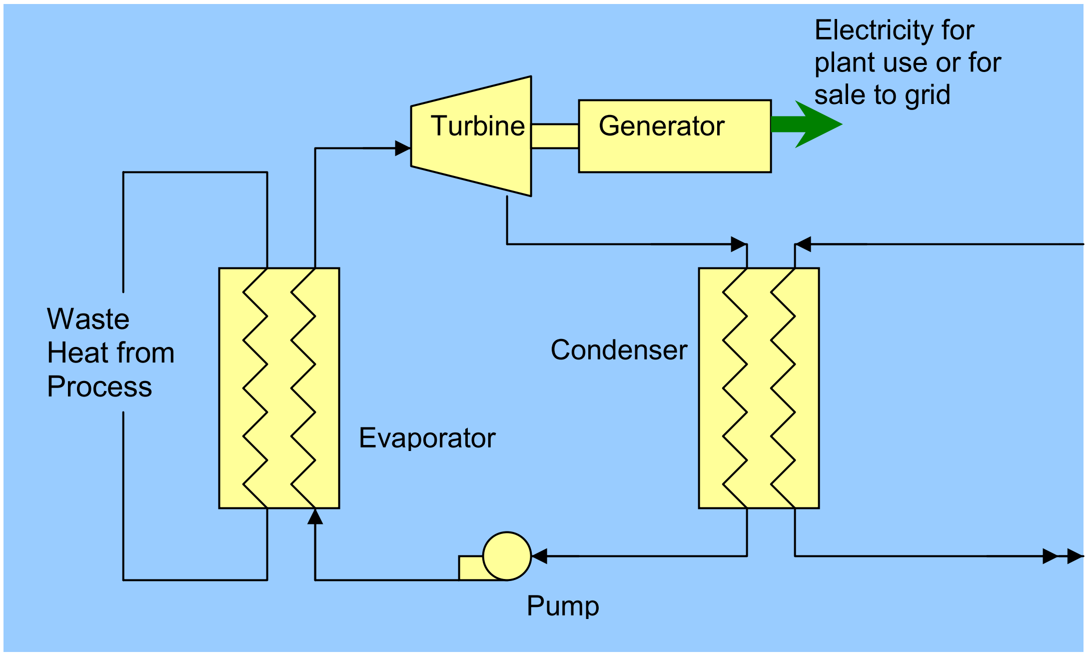


Figure 18 - Waste Heat Recovery with Rankine Cycle -

3.4.1.2 Organic Rankine Cycle

The Organic Rankine Cycle (ORC) operates similar to the steam Rankine cycle, but uses an organic working fluid instead of steam. Options include silicon oil, propane, haloalkanes (e.g., "freons"), iso-pentane, iso-butane, p-xylene, and toluene, which have a lower boiling point and higher vapor pressure than water. This allows the Rankine cycle to operate with significantly lower waste heat temperatures—sometimes as low as 150ºF [66ºC]. The most appropriate temperature range for ORCs will depend on the fluid used, as fluids' thermodynamic properties will influence the efficiency of the cycle at various temperatures.

In comparison with water vapor, the fluids used in ORCs have a higher molecular mass, enabling compact designs, higher mass flow, and higher turbine efficiencies (as high as 80-85%).[21,22] However, since the cycle functions at lower temperatures, the overall efficiency is only around 10-20%, depending on the temperature of the condenser and evaporator. While this efficiency is much lower than a high-temperature steam power plant (30-40%), it is important to remember that low-temperature cycles are inherently less efficient than high-temperature cycles. Limits on efficiency can be expressed according to Carnot efficiency—the maximum possible efficiency for a heat engine operating between two temperatures. A Carnot engine operating with a heat source at 300ºF [150ºC] and rejecting it at 77ºF [25ºC] is only about 30% efficient. In this light, an efficiency of 10-20% is a substantial percentage of theoretical efficiency, especially in comparison to other low-temperature options, such as piezoelectric generation, which are only 1% efficient.

ORC technology is not particularly new; at least 30 commercial plants worldwide were employing the cycle before 1984.[23] Its applications include power generation from solar, geothermal, and waste heat sources. As per an article published in Distributed Energy, ORCs are most useful for waste heat recovery among these three applications.[24] Waste heat recovery can be applied to a variety of low- to medium-temperature heat streams. An example of a recent successful installation is in Bavaria, Germany, where a cement plant installed an ORC to recover waste heat from its clinker cooler, whose exhaust gas is at about 930ºF [500°C]. The ORC provided 12% of the plant's electricity requirements and reduced CO_2 emissions by approximately 7,000 tons.[25] Although the economics of ORC heat recovery need to be carefully analyzed for any given application, it will be a particularly useful option in industries that have no in house use for additional process heat or no neighboring plants that could make economic use of the heat.

3.4.1.3 Kalina Cycle

The Kalina cycle is a variation of the Rankine cycle, using a mixture of ammonia and water as the working fluid. A key difference between single fluid cycles and cycles that use binary fluids is the temperature profile during boiling and condensation. For single-fluid cycles (e.g., steam or organic Rankine), the temperature remains constant during boiling. As heat is transferred to the working medium (e.g., water), the water temperature slowly increases to boiling temperature, at which point the temperature remains constant until all the water has evaporated. In contrast, a binary mixture of water and ammonia (each of which has a different boiling point) will increase its temperature during evaporation. This allows better thermal matching with the waste heat source and with the cooling medium in the condenser. Consequently, these systems achieve significantly greater energy efficiency.

Figure 19 – Kalina Cycle - Installation -

The cycle was invented in the 1980s and the first power plant based on the Kalina cycle was constructed in Canoga Park, California in 1991. It has been installed in several other locations for power generation from geothermal energy or waste heat. Applications include a 6 million metric tons per year steelworks in Japan (1999),[26] heat recovery from a municipal solid waste incinerator (1999), and from a hydrocarbon process tower (2003).[27] The steelworks application involved using a Kalina cycle to generate power from cooling water at 208°F [98°C]. With a water flow rate of 1,300 metric tons per hour, the electric power output was about 4,500 kW. The total investment cost was about $4 million or about $1,100/kW.[28]

3.4.2 Direct Electrical Conversion Devices

Whereas traditional power cycles involve using heat to create mechanical energy and ultimately electrical energy, new technologies are being developed that can generate electricity directly from heat. These include thermoelectric, thermionic, and piezoelectric devices. There is no evidence that these systems have been tested in industrial waste heat recovery applications, although a few have undergone some prototype testing in applications such as heat recovery in automotive vehicles.

3.4.2.1 Thermoelectric Generation

Thermoelectric (TE) materials are semiconductor solids that allow direct generation of electricity when subject to a temperature differential. These systems are based on a phenomenon known as the Seebeck effect: when two different semiconductor materials are subject to a heat source and heat sink, a voltage is created between the two semiconductors. Conversely, TE materials can also be used for cooling or heating by applying electricity to dissimilar semiconductors. Thermoelectric technology has existed for a long time (the thermoelectric effect was first discovered in 1821), but has seen limited use due to low efficiencies and high cost. Most TE generation systems in use have efficiencies of 2 to 5%; these have mainly been used to power instruments on spacecraft or in very remote locations. However, recent advances in nanotechnology have enabled advanced TE materials that might achieve conversion efficiencies 15% or greater.

A recent study by PNNL and BCS, Incorporated examines the opportunity for TE generation in various industrial waste heat streams and identifies performance requirement and RD&D needs.[29] The study concluded that advanced TE packages would be appropriate in medium- to high-temperature, high flow-rate exhaust streams where facilities have little use for recovered waste heat. Two example opportunities are glass furnaces and molten metal furnaces. Before TE materials can be used in these applications, advances are needed in both TE production technology and in heat transfer systems. Competing with current electricity costs will mandate a TE package cost of about $5/watt instead of the current $30/watt.[30] Low-cost, high-volume production methods for TE materials must be developed in order to achieve this goal. Meanwhile, maintaining a high temperature differential across thin TE devices will present a significant engineering challenge. Obtaining high heat transfer rates will require advances in heat transfer materials and heat exchange systems with high heat transfer coefficients.

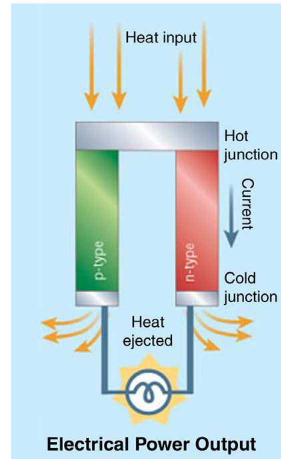


Figure 20 - Thermoelectric - Generation Unit -

3.4.2.2 Piezoelectric Power Generation

Piezoelectric Power Generation (PEPG) is an option for converting low-temperature waste heat (200-300ºF or [100-150°C]) to electrical energy.[31] Piezoelectric devices convert mechanical energy in the form of ambient vibrations to electrical energy. A piezoelectric thin-film membrane can take advantage of oscillatory gas expansion to create a voltage output. A recent study[32] identified several technical challenges associated with PEPG technologies:

- low efficiency: PEPG technology is only about 1% efficient; difficulties remain in obtaining high enough oscillatory frequencies; current devices operate at around 100 Hz, and frequencies closer to 1,000 Hz are needed,
- high internal impedance,
- complex oscillatory fluid dynamics within the liquid/vapor chamber,
- need for long term reliability and durability, and
- high costs ($10,000/W).

While the conversion efficiency of PEPG technology is currently very low (1%), there may be opportunities to use PEPG cascading, in which case efficiencies could reach about 10%.[33] Other key issues are the costs of manufacturing piezoelectric devices, as well as the design of heat exchangers to facilitate sufficient heat transfer rates across a relatively low temperature difference.[34]

3.4.2.3 Thermionic Generation

Thermionic devices operate similar to thermoelectric devices; however, whereas thermoelectric devices operate according to the Seebeck effect, thermionic devices operate via thermionic emission. In these systems, a temperature difference drives the flow of electrons through a vacuum from a metal to a metal oxide surface. One key disadvantage of these systems is that they are limited to applications with high temperatures above 1,800°F [1,000°C]. However, some development has enabled their use at about 210-570°F [100-300°C].[35]

3.4.2.4 Thermo Photo Voltaic (TPV) Generator

TPV Generators can be used to convert radiant energy into electricity. These systems involve a heat source, an emitter, a radiation filter, and a PV cell (like those used in solar panels). As the emitter is heated, it emits electromagnetic radiation. The PV cell converts this radiation to electrical energy. The filter is used to pass radiation at wavelengths that match the PV cell, while reflecting remaining energy back to the emitter. These systems could potentially enable new methods for waste heat recovery. A small number of prototype systems have been built for small burner applications and in a helicopter gas turbine.[36]

3.5 Summary of Heat Recovery Technologies

The selection of heat recovery method will depend on key factors such as the temperature, phase, and chemical composition of the exhaust stream, as well as the nature of the desired end-use for recovered heat. Table 8 compares conventional heat exchange technologies according to applicable temperature ranges, waste heat sources, end-uses, type of heat exchange, moisture recovery, temperature differentials permitted, resistance to cross-contamination, and adaptability to corrosive gases. Table 9 summarizes the use of different recovery methods (heat exchange, power generation, etc.) in different applications included in this study (Section 4).

Table 8 - Comparison of Heat Recovery Technologies [a]

Recovery Method	Temperature Range	Typical Sources of Waste Heat	Typical Uses	Type of Heat Exchange (Gas-Gas, Gas-Liquid, etc.)	Recovers Moisture	Large Temperature Differentials Permitted	No Cross-Contamination	Corrosive Gases Permitted with Special Construction
Radiation Recuperator	H	Soaking or annealing ovens, melting furnaces, incinerators, radiant-tube burners, reheat furnace	Combustion air preheat	G-G		X	X	X
Convection Recuperator	M-H	Soaking or annealing ovens, melting furnaces, incinerators, radiant-tube burners, reheat furnace	Combustion air preheat	G-G		X	X	X
Metallic Heat Wheel	L-M	Boiler exhaust, curing and drying ovens	Combustion air preheat, space heat	G-G	b		c	x
Hygroscopic Heat Wheel	M	Boiler exhaust, curing and drying ovens	Combustion air preheat, space heat	G-G	X		c	X
Ceramic Heat Wheel	M-H	Large boilers, incinerator exhaust, melting furnaces	Combustion air preheat,	G-G		X		X
Plate-type Heat Exchanger	L,M	Exhaust from boilers, incinerators, & turbines Drying, curing, and baking ovens	Combustion air preheat, space heat	G-G, L-L		X	X	
Heat Pipe	L-H	Waste steam, air dryers, kilns (secondary recovery), reverberatory furnaces (secondary recovery) Drying, curing & baking ovens	Combustion air preheat, boiler makeup water preheat, domestic hot water, space heat	G-G,G-L		d	X	X
Finned-tube Heat Exchanger	L,M	Boiler exhaust	Boiler feedwater preheat	G-L		X	X	e
Waste-heat Boilers	L-H	Exhaust from gas turbines, reciprocating engines, incinerators, furnaces	Hot water or steam generation	G-L			X	e
Tube Shell-and Tube Exchanger	L,M	Refrigeration condensates, waste steam distillation condensates, waste steam distillation condensates, coolants from engines, air compressors, bearings & lubricants	Liquid feed flows requiring heating	G-L, L-L		X	X	

a. Sources: W. Turner. *Energy Management Handbook,* 2007; *PG&E Energy Efficiency Information* "Industrial Heat Recovery Strategies," 1997
b. claimed by some vendors
c. with a purge section added, cross-contamination can be limited to less than 1% by mass
d. allowable temperatures and temperature differential limited by the phase equilibrium properties of the internal fluid
e. can be constructed from corrosion-resistant materials, but consider possible extensive damage to equipment caused by leaks or tube ruptures

Table 9. Status of Waste Heat Recovery Technologies in Selected Applications

	Iron/Steel																	
	Coke Oven						Blast Furnace						BOF			EAF		
	Coke Oven Gas			Waste Gas			Blast Furnace Gas			Hot Blast Stove Exhaust			Basic Oxygen Furnace Gas			Electric Arc Furnace Offgas		
	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic
Regenerator	-	-	-	+	+	+	-	-	-	n	n	-	x	x	x	x	x	x
Recuperator	-	-	-	n	-	-	-	-	-	n	n	-	x	x	x	x	x	x
Heat Wheel	-	-	-	n	m	-	n	n	n	+	+	+	x	x	x	x	x	x
Passive Air Preheater	-	-	-	-	o	o	n	n	n	+	+	+	x	x	x	x	x	x
Thermal Medium System	o	o	-	n	m	-	n	n	n	+	+	+	n	n	n	n	n	n
Waste Heat Boiler	-	-	-	-	-	-	n	-	n	n	-	-	o	+	o	n	-	n
Low T Power Cycle	-	-	-	n	m	-	-	n	n	-	m	n	x	x	x	x	x	x
Solid State Generation	-	-	-	-	m	-	-	-	-	-	m	-	-	-	-	-	-	-
Load preheat																+	+	o
Process Specific/Other2	o	o	-	o	o	-	o	+	-									

	Glass Industry						Cement			Aluminum						Metal Casting			Cross-cutting		
	Glass Melting																				
	Gas-fired Melting Furnace			Oxyfuel Melting Furnace			Cement Kiln			Hall-Heroult Cells			Melting Furnaces			Iron Cupola			Steam Boiler		
	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic
Regenerator	+	+	o	-	o	-	n	n	n	-	-	-	+	+	o	n	n	n	-	+	-
Recuperator	+	+	+	-	o	-	n	n	n	-	-	-	+	+	o	+	+	+	+	+	+
Heat Wheel	o	o	-	n	o	-	n	n	n	-	-	-	o	+	o	n	n	n	+	+	+
Passive Air Preheater	n	n	n	-	o	-	n	n	n	-	-	-	n	n	n	n	n	n	+	+	+
Thermal Medium System	n	n	n	n	n	n	n	n	n	-	-	-	n	n	n	n	n	n	+	+	+
Waste Heat Boiler	o	+	-	o	+	-	+	+	+	-	-	-	n	n	n	n	n	n	x	x	x
Low T Power Cycle	x	x	x	x	x	x	o	+	o	-	-	-	x	x	x	n	n	n	-	m	n
Solid State Generation	-	m	-	-	m	-	-	m	-	-	m	-	-	m	-	-	m	-	-	m	-
Load preheat	n	m	n	o	o	o	+	+	+	n	n	n	+	+	o				+	+	+
Process Specific/Other2							+	+	+												

1. This table is reproduced in Appendix B with detailed notes

2. "Process-specific" includes coal moisture control for coke making, dry-type top pressure recovery turbines for blast furnaces, and recovery from cement clinker cooler.

Key:	Commercialization Status	Technical Feasibility	Economic Feasibility
	+ Frequently used in US	+ No technical barriers	+ Cost-effective
	o Limited commercialization	o Proven in limited applications	o Application-specific
	- Not deployed	m May be feasible, but not demonstrated	- Cost-prohibitive
		- Not technically feasible	
	n Not addressed in available literature		
	x Not applicable		

Part B: -

Waste Heat Losses and Recovery Practices -

4.0 Evaluating Selected Applications for Waste Heat Opportunities and Practices

Multiple energy-intensive processes were investigated in order to identify recovery practices and quantity of unrecovered waste heat. Processes selected for evaluation in this study were chosen by focusing on the most energy-intensive industries (e.g., glass, cement, iron/steel) and identifying some of the largest energy-consuming processes.

This investigation helped highlight trends in waste heat losses and opportunity areas for waste heat recovery. For each process analyzed, waste heat quantity was evaluated by estimating the typical percent of energy inputs lost to flue gas waste heat, estimating total energy consumed by that process in the United States, and then calculating approximate total waste heat losses from that application. The percent of waste heat loss varies for different furnaces, depending on the flue gas composition and exhaust temperature. In many cases, the processes analyzed already include waste heat recovery. In these cases, efforts were made to estimate the fraction of production currently using waste heat recovery. In cases where heat recovery is already in place, estimates of waste heat evaluate the heat contained in flue gases exiting the recovery device. Therefore, this study only evaluates the unrecovered waste heat.

The basis for waste heat calculations and documentation of waste heat estimates are provided in Appendix A. In general, estimates of waste heat loss in exhaust gases were based on estimated fuel consumption and expected specific enthalpy (Btu/lb) of exhaust streams, which depends on temperature and chemical composition of the exhaust stream. Waste heat loss in a given application can be expressed as:

$$\dot{E}_{ex} = \left(\dot{m}\,h(t)\right)_{ex} = \dot{m}_{ex}\sum_i \left(x_i h_i(t)\right)_{ex} \qquad \text{Equation (6)}$$

where $\dot{E}_{ex}$ is the exhaust gas waste heat, m_{ex} is the exhaust gas mass flow rate, x_i is the mass fraction of each species in the exhaust gas, and $h_i(t)$ is the enthalpy of each species *i* in the exhaust at the exhaust temperature. Enthalpy is not an absolute term, but must be measured against a reference state (for example, the enthalpy of a substance at room temperature and atmospheric pressure). In this report, the enthalpy of waste heat streams is calculated at two reference temperatures: 77°F [25°C] and 300°F [150°C]. A reference of 77°F [25°C] was used to provide a basis for estimating the maximum heat attainable if a gas is cooled to ambient temperatures. Meanwhile, a reference of 300°F [150°C] was also used, since the majority of industrial heat recovery systems do not cool below this temperature.

In addition to evaluating the quantity of waste heat, the work potential was also estimated. The work potential is the maximum work that could be obtained by using the waste heat to drive a heat engine. The work potential is given by:

$$WP = \eta\,\dot{E} = \left(1 - \frac{T_o}{T_H}\right)\dot{E} \qquad \text{Equation (7)}$$

where T_H is the waste heat temperature, and T_O is the atmospheric temperature (assumed here to be 77°F, [25°C]). An overview of industry-specific recovery practices and estimated heat losses is contained in the sections below.

4.1 Glass Manufacturing

The glass industry consumes approximately 300 TBtu/yr,[37] and some sources estimate that as much as 70% of this energy consumption is devoted to glass melting and refining processes in high-temperature furnaces.[38] Furnaces vary widely in the energy required to melt a ton of glass. The theoretical minimum energy for melting glass is only about 2.2 million Btu per ton. However, some furnaces consume as much as 20 million Btu/ton.[39]

Furnaces used in large glass melting operations include direct-fired, recuperative, regenerative, unit melters, oxy-fuel, and mixed-fuel furnaces. In the United States, more than half of all glass furnaces are natural gas-fired regenerative furnaces, which account for over 90% of the tonnage produced. Best practice furnaces have efficiencies of about 40%, with stack heat losses about 30% and structural losses accounting for another 30%.[40]

Regenerators and recuperators are the most frequently used systems for waste heat recovery in the glass industry. Glass melting is a high-temperature operation providing several opportunities for recovery of high-grade waste heat. Without heat recovery, stack exhaust temperatures typically exceed 2,400°F [1,315°C].[41] Recuperators and regenerators for combustion air preheating are the most common methods for waste heat recovery.

Regenerative furnaces employ two chambers with checker bricks. These chambers alternately absorb heat from exhaust gases and transfer heat to the incoming combustion air. The direction of airflow changes approximately every 20 minutes so that one chamber receives heat from the stack exhaust while the other one rejects heat to incoming air. Final exhaust temperatures vary between about 600 and 1,000°F [316-538°C] throughout the cycle.[42] Recuperators are a less-efficient option more commonly employed in smaller operations that cannot afford the large costs of regenerative furnaces. A metallic recuperator is used to indirectly preheat combustion air. Preheat temperatures usually do not exceed about 1,470°F [800°C], and exhaust temperatures are reduced to about 1,800°F [982°C].

In addition to combustion air preheating, methods for waste heat recovery in glass manufacturing include preheating batch and cullet material and using waste heat boilers for electricity generation. However, these systems are most likely to be used in oxyfuel furnaces, where combustion air preheat is not used. Oxy-fuel furnaces use oxygen-enriched air or pure oxygen for combustion. This saves fuel by reducing the energy needed to heat nitrogen carried in atmospheric air. When furnaces are adapted to oxy-fuel firing, the regenerators are removed, which can lead to higher exhaust temperatures around 2,660°F [1,460°C]. Although the waste heat is at a high temperature, the mass of exhaust gases is much lower, leading to lesser waste heat loss as a percentage of fuel input.

Preheating batch material is used in one plant in the United States;[43] it is more common in Europe, where energy costs are higher. About 13 new batch/cullet preheaters have been installed since the 1980s, nine of which were located in Germany.[44] Challenges with batch preheating include the large amount of material that must be handled and the desire to maintain a homogeneous glass product. Fluid beds and special silos are used to agglomerate the batch and simplify heat transfer. Further improvements that reduce the capital costs and simplify operation of these systems may create opportunities for increased implementation of batch preheating.

Analysis of glass furnaces in the United States shows that while heat recovery is a common practice, about 43 TBtu of medium- to high-temperature waste heat provide additional opportunities for recovery (Table 10, see Appendix A – Documentation of Waste Heat Estimates). Waste heat losses from regenerative furnaces total about 15 TBtu/yr, losses from recuperative melters total about 7 TBtu/yr, from electric boost melters 9 TBtu/yr, and from oxy-fuel furnaces 3 TBtu/yr.

Table 10 - Unrecovered Waste Heat and Work Potential from Exhaust Gases in Glass Melting

Source	Energy Consumption	Assumed Average Exhaust Temperature		Waste Heat 77°F/25°C *Ref*	Waste Heat 300°F/150°C *Ref*	Carnot Efficiency	Work Potential
	TBtu/yr	°F	°C	TBtu/yr	TBtu/yr		TBtu/yr
Regenerative	54.4	800	427	15.1	6.5	0.6	8.7
Recuperative	13.6	1,800	982	7.6	5.4	0.8	5.8
OxyFuel	12.8	2,600	1,427	4.2	2.7	0.8	3.4
Electric Boost	34.9	800	427	8.6	3.7	0.6	4.9
Direct Melter	10.1	2,400	1,316	7.5	5.8	0.8	6.1
Total	125.8			43.0	24.1		28.9

Note: Sources and assumptions in Appendix A: Documentation of Waste Heat Estimates

4.2 Cement Manufacturing

The cement industry consumes about 550 TBtu/yr[45] to produce about 110 million tons of cement annually.[46] The major process steps include mining and quarrying raw materials (mainly limestone and chalk), crushing and grinding materials in preparation for the kiln, clinker production (pyroprocessing), and cement milling. Clinker is the solid nodular material exiting kilns and used for production of cement. Clinker production in kilns is by far the most energy-intensive process in the cement industry, responsible for about 90% of delivered energy consumption and 74% of total energy consumption (when electricity-related losses are included).

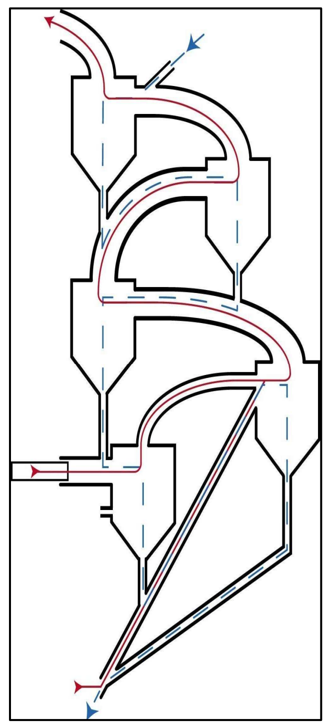


Figure 21 - Cement - Kiln Preheater

Rotary cement kilns are long refractory-lined steel tubes with lengths varying from 200 to 1,000 feet.[47] The fuel most commonly used is coal, though some kilns use natural gas, oil, and various waste fuels. Raw meal (limestone and other materials) enter at the top of the kiln and gradually passes through increasingly hot zones toward the flame at the bottom of the kiln. Rotary kilns can be divided into two main groups: wet process and dry process. In a wet kiln, the raw meal has a moisture content of 30-40%,[48] requiring larger energy expenditures for evaporating the water. These kilns are no longer being constructed and comprise only 20% of U.S. clinker production capacity. Dry process kilns use dry powder meal. The kiln typically has a "chain section" which absorbs heat from the exhaust gases and enhances heat transfer to the meal. Exhaust temperatures without heat recovery are about 840°F [450°C].[49]

Options for heat recovery from stack exhausts include preheating meal and power generation. Preheating is accomplished through countercurrent flow of raw materials and exhaust gases in cyclones as shown in Figure 21. The most common systems are series four-stage preheaters, which have exhaust gases leaving at approximately 640°F [340°C].[50] Exhaust gases are in the medium-temperature range, where there are still opportunities for waste heat recovery. Additional stages of preheaters can further lower temperatures. If 5-6 stages are used, exhaust temperatures can be reduced to 400 to 570°F [204-300°C].[51] The number of preheat stages is often limited by increasing complexity and structural limitations associated with each additional stage. Exhaust gases can also be used for drying and preheating kiln feed in the raw grinding stages.

Cogeneration, instead of meal preheating is another option of heat recovery. Currently, four plants in the United States have cogeneration systems, generating 486 million kWh (1.66 TBtu) annually.[52] All these systems use steam cycles for electricity generation.[53] However, alternative cycles, including the organic Rankin cycle and Kalina cycles are receiving increased attention for their ability to work more efficiently with low- to medium-temperature exhausts.[54] These can be used for recovering heat from combustion exhaust gases (i.e., after meal preheaters) or from the clinker cooler.

While heat recovery from cement kilns is common, about 83 TBtu/yr of medium-temperature waste heat is still unrecovered from kiln off-gases in the United States cement industry (Table 11). These waste heat losses can be reduced through the installation of additional preheating stages or by using cogeneration technologies.

Table 11 - Unrecovered Waste Heat and Work Potential from Exhaust Gases in Cement Kilns

Source	Energy Consumption	Assumed Average Exhaust Temperature		Waste Heat 77°F [25°C] *Ref*	Waste Heat 300°F[150°C] *Ref*	Carnot Efficiency	Work Potential
	TBtu/yr	°F	°C	TBtu/yr	TBtu/yr		TBtu/yr
Wet kiln	98.0	640	338	18.8	9.4	0.5	9.6
Dry kiln							
No Preheater or Precalciner	80.2	840	449	20.6	12.8	0.6	12.1
Preheater (only)	67.8	640	338	13.9	7.0	0.5	7.1
Precalciner	143.4	640	338	29.7	15.1	0.5	15.2
Total	388			82.0	44.3		44.0

Note: Sources and assumptions in Appendix A: Documentation of Waste Heat Estimates

Another opportunity for increasing kiln efficiency is through optimizing waste heat recovery in the clinker cooler. Clinker is discharged red-hot from the kiln and transferred to clinker coolers, which perform the dual function of cooling the clinker for downstream transport and processing, as well as recovering heat energy contained in the clinker. The most common clinker cooler designs are grate- type designs. Recirculating air cools the clinker from about 1,800°F [1,200°C] to 200°F [100°C]. The hot air discharged from coolers is used to heat secondary air in the kiln combustion or tertiary air for the precalciner. These systems typically recover about 1-1.3 million Btu per ton of clinker.[55] The recovery efficiency of clinker coolers can be enhanced through reducing excess air volumes, properly controlling the clinker bed depth, optimizing grate designs, and controlling the air distribution over the grate. These measures can save an additional 0.1 million Btu/ton.[56] Meanwhile, organic Rankin cycles and Kalina cycles are also emerging opportunities for heat recovery from clinker cooler exhausts.

4.3 Iron and Steel Manufacturing

The U.S. iron and steel industry consumes approximately 1,900 TBtu of energy per year,[57] with an average energy intensity of 17.4 million Btu/ton.[58] The industry employs several high-temperature furnaces for sinter, coke, iron, and steel production, which account for about 58% of the industry's energy consumption.[59] While recovery from clean gaseous streams in the industry is common, heavily contaminated exhaust gases from coke ovens, blast furnaces, basic oxygen furnaces, and electric arc furnaces continue to present a challenge for economic waste heat recovery. Heat recovery techniques from these dirty gaseous streams are available, yet implementation has been limited due to high capital investment costs.[60]

This study investigated waste heat losses in both integrated steel mills and mini-mills. In integrated steel mills, which account for about 54% of U.S. raw steel production in 1999,[61] processes analyzed included coke making, blast furnace ironmaking, and basic oxygen furnace steelmaking. In the mini-mill, exhaust gases from electric arc furnaces were analyzed. Waste heat from these processes total about 79 TBtu/yr based on a reference temperature of 77°F [25°C] (Table 12).

Table 12 - Unrecovered Waste Heat and Work Potential from Selected Process Exhaust Gases in the Iron and Steel Industry

Source	Energy Consumption	Assumed Average Exhaust Temperature		Waste Heat 77°F [25°C] *Ref*	Waste Heat 300°F [150°C] *Ref*	Carnot Efficiency	Work Potential
	TBtu/yr	°F	°C	TBtu/yr	TBtu/yr		TBtu/yr
Coke Oven	65.5						
Coke Oven Gas		1,800	980	15.8	13.9	0.8	12.1
Coke Oven Waste Gas		392	200	11.2	10.0	0.4	4.1
Blast Furnace	642.3						
Blast Furnace Gas		200	430	5.3	-	0.19	1.0
Blast Stove Exhaust							
no Recovery	36.2	482	250	10.6	1.9	0.4	4.6
with Recovery	34.1	266	130	3.2	-	0.3	0.8
Basic Oxygen Furnace	49.7	3,100	1,700	27.1	26.0	0.8	23.0
Electric Arc Furnace							
no Recovery	57.7	2,200	1,200	5.8	5.4	0.8	4.6
with Recovery	13.3	400	204	0.2	0.1	0.4	0.1
Total	828.6			79.1	57.3		49.2

Note: Sources and assumptions in Appendix A: Documentation of Waste Heat Estimates

4.3.1 Integrated Steel Mills

4.3.1.1 Coke Oven

Producing coke, an essential fuel for blast furnace operation, is a key step in the iron-making process. Coke is produced in coke ovens, where coal is heated in an oxygen-limited environment. There are two methods for producing coke: the byproduct process and the non-recovery process. In the byproduct process, chemical byproducts (tar, ammonia, and light oils) in the coke oven gas are recovered, while the remaining coke oven gas is cleaned and recycled within the steel plant. In the non-recovery process, all the coke oven gas is burned in the process. The most common type of process is still the byproduct process, which is the focus of our discussion here.

Byproduct coke-making process (Figure 22) has two sites of sensible heat loss: a) coke oven gas that is cooled in the gas cleaning process and b) waste gas exiting the coke oven. The coke making process employs several coke oven chambers separated by heating flues. Recycled coke oven gas (COG), and sometimes other gases such as blast furnace gas, are used as the fuel source in the heating flue and supply heat to the oven chamber where coal pyrolysis takes place. As coal is pyrolyzed in the oven chamber, gas and moisture (accounting for about 8-11 mass % of charged coal) are driven off and exit through the ascension pipes. Typical compositions of this coke oven gas (COG) are shown in Table 13. The COG has a high heat content ranging from around 500-700 Btu/scf therefore it can be recycled for use as a fuel after undergoing a rigorous cleaning process.

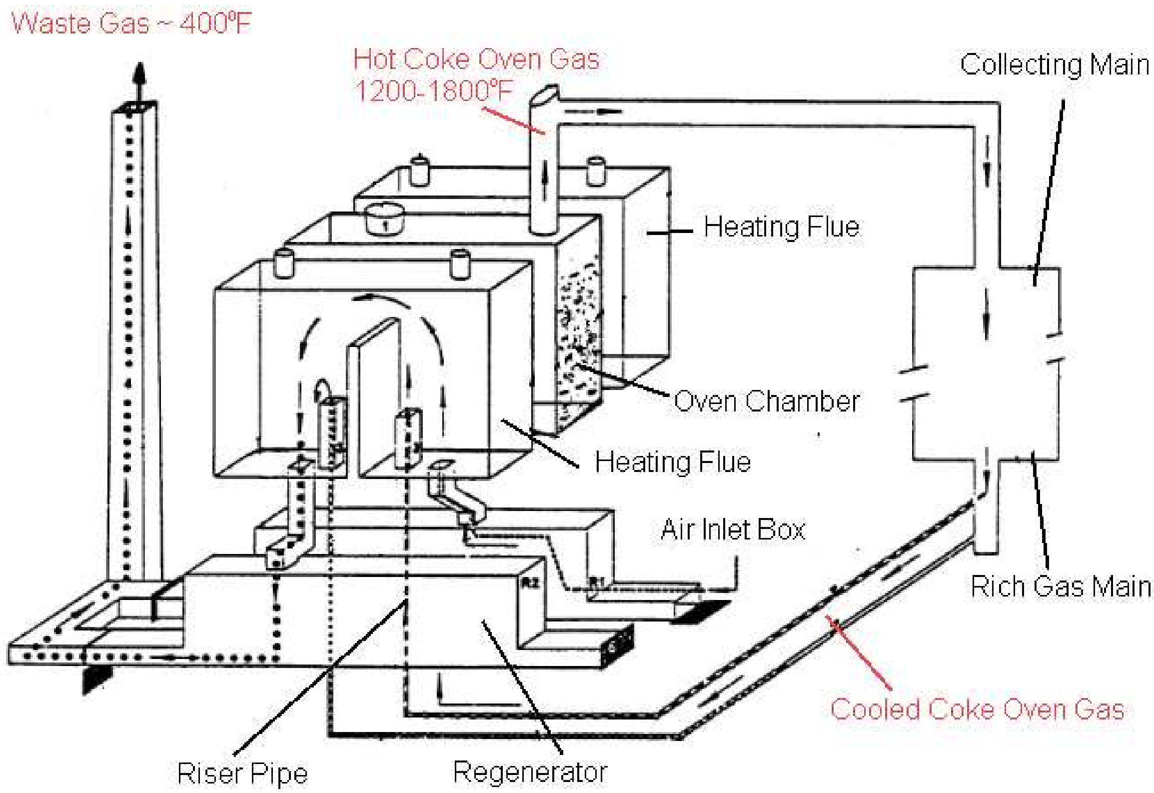


Figure 22 - Coke Oven (Source: IPCC, p. 113)

The temperature of the crude COG at the oven outlet ranges from 1,200°F [649°C] to 1,800°F [982°C].[62,63] At this point, the COG gas is a source of sensible heat; however the heat is universally wasted due to the high level of tars and other materials that would build up on heat exchanger surfaces. Upon leaving the oven, the COG is cooled by ammonia liquor spray followed by primary coolers. Various technologies are then used for removing tar, sulfur compounds, ammonia, and light oils. After cleaning, the COG is used as a fuel throughout the plant. In this arrangement, only the chemical energy of the COG is recovered when recycled, while the sensible heat is wasted. The total sensible heat lost from COG in the United States is approximately 16 TBtu/yr.

Table 13 - Typical Coke Oven Gas Composition -

Compound	Volume %
H_2	39-65
CH_4	32-42
C_xH_y	3.0-8.5
CO	4.0-6.5
H_2S	3-4
BTX	23-30
PAH	nd
NH_3	6-8
CO_2	2-3

Source: IPCC

While facilities in the United States do not employ heat recovery from COG, a limited level of heat recovery from COG is possible, as demonstrated by the success of this practice in Japan. Facilities in Japan have successfully applied heat recovery through use of a low-pressure heat transfer medium. In general, the minimum allowable temperature for the COG in the heat exchanger is about 840°F [450°C]; at lower temperatures, tar condenses and leads to soot formation on the heat exchanger surface.[64] Cooling to 840°F [450°C] enables only about one-third of the sensible heat to be recovered. It is unlikely that integrated steel mills in the United States would pursue new technologies for heat recovery from crude coke oven gas. Not only will the industry face cost barriers with heat recovery from dirty exhaust streams, but the byproduct coke making process may become irrelevant in future years. It is likely that the industry will move away from the byproduct process to the non-recovery process due to environmental considerations.[65] In the non-recovery process, the COG gas will be burned within the process, and a waste heat boiler used to recover the sensible heat in the off-gases.

Another source of sensible heat loss in coke ovens is the waste gases from the combustion of recycled (clean) COG. The recycled COG is used as a fuel in the heating flue, which is adjacent to the oven chamber. Combustion of the COG generates hot exhaust gases which leave the oven flue and pass through a regenerator to transfer heat to incoming combustion air and/or fuel.[66, 67] Waste gases leave the regenerator at temperatures averaging around 400°F [200°C].[68] In some cases, mainly outside the United States, the heat content of the waste gases are further recovered by use of a heat pipe[69] or for preheating coal charge and reducing its moisture content. In this case, the temperature of the exhaust gases drops about 110°F [60°C].[70] The waste heat loss from coke oven waste gas in the United States is estimated at about 11 TBtu/yr (Table 13).

4.3.1.2 Blast Furnace

The major unit in integrated steel mills is the blast furnace, which converts iron ore (iron oxide, FeO) into pig iron (Fe). Raw materials are charged from the top, including iron-containing materials (lump iron ore, sinter, or pellets), additives (flux), and coke, while hot air and supplemental fuels are injected into the bottom of the furnace. The burden moves down through the blast furnace and meets a rising current of hot gases. The hot air entering the furnace is provided by several auxiliary hot blast stoves (also known as furnace cowpers). In the blast stove, fuels such as blast furnace gas (BFG) and COG are combusted. The heat from the combustion exhausts is transferred to a checkerwork regenerator. When the regenerator reaches an appropriate temperature, the flow of air is reversed and cold air is forced through the regenerator, which transfers heat to the cold air. The heated air is then injected into the furnace. The system operates according to the same principles as a regenerator used for heat recovery; however in this case, the regenerator is not a "waste heat" recovery device, but rather the mechanism for transferring heat from the stove to the hot blast. Sources of off-gas waste heat in blast furnaces include both the exhaust gases from the hot blast stove and the BFG leaving the blast furnace.

Sensible heat loss from BFG in the United States is estimated at about 5 TBtu/yr. BFG consists of approximately 20-28% CO, 1–5% H_2, inert compounds (50-55% N_2, 17-25% CO_2), as well as dust, sulfur, cyanide compounds, and other contaminants.[71] Older blast furnaces had high exhaust temperatures around 900°F [400°C].[72] New furnaces have been designed for more efficient heat transfer; consequently, hot gases are in the low-temperature range.[73] Several plants recover blast furnace gas for use as a fuel in blast air heating, hot mill reheating furnaces, coke oven heating, power production, and steam generation. Since its heat content is only 80 to 90 Btu/scf,[74] it is often mixed with other fuels such as natural gas or COG. As with COG, BFG must be cleaned before it can be used as a fuel, and the sensible heat contained in the gas is rarely recovered. In some cases, blast furnaces operate at a sufficiently high pressure (2.5 atm or higher) to economically use a top pressure recovery turbine (TRT) to recover the "pressure energy" of the BFG. The gas must be cleaned before entering the TRT, which is generally accomplished via wet cleaning, with the result that sensible heat of the off-gas is lost. An alternative to wet-cleaning technology is dry-cleaning, in which the temperature of the gas entering the TRT can be raised to about (250°F, [120°C]).[75] Dry-type TRT technology is already commercial; however, being significantly more expensive (it requires an additional $28/ton instead of $20/ton) this technology will most likely not be implemented in the U.S in the near term.[76]

Another opportunity for waste heat recovery is from the combustion exhaust gases leaving hot blast stoves. The gases are at temperatures of approximately 480°F [250°C]. The blast stove exhaust gas is relatively clean and is more compatible with heat recovery devices, making heat recovery from blast stoves a more common practice. The heat can be used to preheat combustion air and/or fuel gas. Heat exchangers used include rotary regenerators, fixed plate heat exchangers, and circulating thermal medium systems.[77] Recovery from these systems is typically 73,000 Btu/ton of pig iron (69,000 Btu/ton steel).[78]

4.3.1.3 Basic Oxygen Furnace

The basic oxygen furnace (BOF) uses oxygen to oxidize impurities in the pig iron such as carbon, silicon, phosphorus, sulfur, and manganese. Operation is semi-continuous: hot metal and scrap are charged to the furnace, oxygen is injected, fluxes are added to control erosion, and then the metal is sampled and tapped. The temperature required to melt the metal is supplied by the exothermic oxidation reaction; therefore, no external heat source is needed (energy consumption in the BOF is to power auxiliary processes only).

The off-gases from the BOF are at a high temperature and account for about 27 TBtu/yr of waste heat in the United States. BOF gas has a high concentration of carbon monoxide, and like coke oven gas and blast furnace gas, BOF gases offer opportunities for recovery of chemical energy and sensible heat. Challenges to waste heat recovery include high capital costs and the substantial maintenance problems resulting from hot dirty gases. Contaminants include iron oxides, heavy metals, SO_x, NO_x, and fluorides. The typical gas composition of BOF gas is shown in Table 14.

Table 14 - Basic Oxygen Furnace Off-gas Composition

Compound	Volume %	
	Range	Average
CO	55-80	72.5
H_2	2-10	3.3
CO_2	10-18	16.2
N_2+Ar	8-26	8

Source: IPCC,233

In the United States, the most common practice is to simply flare BOF off-gases;[79] however, various commercial methods for waste heat recovery are used in Europe and Japan. The two main methods for heat recovery are "open combustion" and "suppressed combustion." In open combustion systems, air is introduced to the BOF gas duct to combust the CO. The heat generated is recovered with a waste heat boiler. In the "suppressed combustion" method, a skirt is added to the converter mouth to reduce air infiltration and inhibit combustion of the CO. The gas is then cleaned, collected, and used as a fuel.[80] It is also possible to recover both the gas and the sensible heat via a combined boiler/suppressed combustion gas recovery system, which can recover about 169,000 Btu/ton of crude steel.[81] The capital cost for these systems is approximately $22/ton of crude steel.[82]

4.3.2 Electric Arc Furnaces

The steel industry has experienced significant growth in manufacture from recycled scrap via electric smelting, which accounts for about 46% of U.S. steel production. Electric arc furnaces (EAF) are used to melt ferrous scraps derived from cutoffs from steelworks and product manufacturers as well as from post-consumer scrap. The furnace is refractory lined and typically covered by a retractable roof, through which carbon electrodes are lowered. Charge materials (consisting of scrap metal as well as direct reduced iron, hot briquetted iron, and cold pig iron) are lowered through the roof. Fluxes and alloying agents are also added to help control the quality of the material. The electrodes are then lowered to about an inch above the metal, and the current provides heat for melting the scrap.[83] During furnace operation, several gases and particulate emissions are released, including CO, SO_x, NO_x, metal oxides, volatile organic compounds (VOCs), and other pollutants. Off-gas temperatures at peak loads can equal anywhere from

2,500-3,500°F [1,370-1,925°C].[84] Exhaust gases are responsible for losses of about 20% of the power input. Half of these losses are due to the chemical energy in the gases, while the other half is sensible heat. Total sensible heat loss via exhaust gases is estimated at about 6 TBtu/yr. Additionally, about 8-10% of energy input is also lost to EAF cooling water "jacket", totaling an additional 6 TBtu/yr.[85]

The most common method for heat recovery is scrap preheating, which has been widely used in Europe and Japan for the last thirty years[86] and is seeing increased use in the United States. The use of off-gases to preheat scrap can save from 5 to 10% of total EAF energy consumption.[87] Initial designs for scrap preheat required piping off-gases to the charging bucket, as shown in Figure 23. Some of the challenges with these systems include the need to transport preheated scrap containing semi-burned non-scrap materials (e.g., plastics), as well the evaporation of volatiles which create odor and environmental control problems.[88,89] Alternatives to the bucket preheating system include the Consteel process, the Fuchs shaft furnace, and the Twin shell furnace; retrofit costs range from $4.4 to $6/ton.[90] These processes have been installed at various plants in the United States, including Florida Steel, New Jersey Steel, Nucor, North Star, Birmingham Steel, Chapparrel, Gallatin Steel, Steel Dynamics, and Tuscaloosa Steel.[91] The Consteel process involves continuous charging of scrap and uses a scrap conveyer, a feeding system, and a preheater. The preheater is a refractory-lined tunnel. Off-gases flow opposite the flow of scrap charge. Air is introduced into the preheater to burn the CO and CO_2; consequently both the chemical and sensible heat in the off-gas is used. An afterburner is sometimes installed to burn remaining CO and other compounds.[92] The Fuchs shaft furnace involves a shaft immediately above the arc furnace roof. The charge is loaded via baskets in three stages. The baskets are refractory-lined and designed with a seal that prevents the escape of fumes. Scrap heating is further assisted by auxiliary oxy-fuel burners. Additionally, afterburners are installed to completely combust all carbon monoxide. One additional benefit of the system is that charge acts as a dust filter, capturing about 40% of dust and returning it to the furnace, thus enabling slight increases in yield.[93]

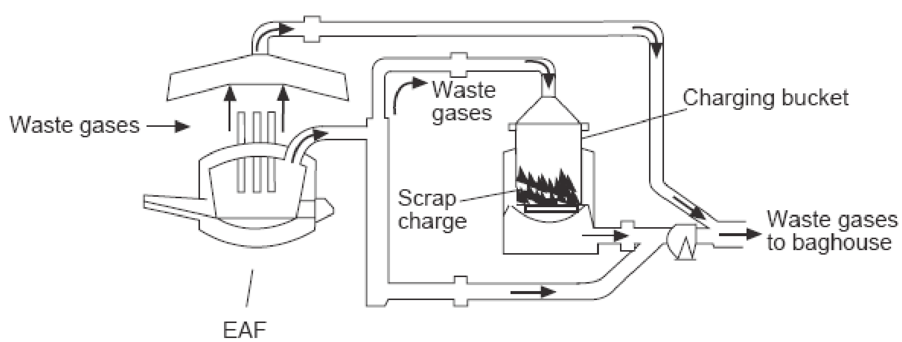


Figure 23 - Scrap Preheat System Using a Charging Bucket (source: AISE p. 629)

The benefits and drawbacks of scrap preheating systems depend on the specific operation. In some cases, it enables reduced electricity consumption and increased productivity. In other cases, scrap preheating systems are difficult to maintain. As EAFs become increasingly efficient and tap-to-tap times are reduced, scrap handling may reduce productivity and possibly create burdensome maintenance demands. In one case, the energy savings enabled by scrap preheating were reduced by about one half when tap-to-tap times were reduced by a third.[94]

4.3.3 Waste Heat from Solid Streams

In addition to waste heat losses from off-gases, solid streams and cooling water are sources of additional sensible heat losses. Solid products and byproducts with significant waste heat losses include hot cokes, byproduct fuels (BF) slag, BOF slag, cast steel, and hot rolled steel. Waste heat losses from these systems were analyzed by de Beer, et. al.[95] and are summarized in Table 15. Though the heat from solid streams are often more difficult to recover, the heat losses are high, totaling about 500 TBtu/yr. The sensible heat loss from coke can be partially recovered by coke dry quenching (CDQ) as an alternative to wet quenching. CDQ involves catching incandescent coke in a specially designed bucket, which is discharged into the CDQ vessel. An inert gas such as nitrogen passes over the coke and recovers its sensible heat. The hot gas is then passed through a waste heat boiler.[96] Energy savings are approximately 0.7 to 1 million Btu/ton of coke. Retrofit costs of these systems are high ($70/ton of coke) and thus are seldom installed.[97] There have also been attempts to recover heat from other solid flows via radiant heat boilers. This was unsuccessful for BF and BOF slag, but has been commercialized for recovering heat from cast steel in a few locations in Japan and Germany.[98]

Another option for reducing heat losses from cast steel is hot charging, in which slabs are charged to the reheating furnace while still hot. The feasibility of hot charging often depends on the distance between the caster and hot rolling mill. Hot charging is done at a few plants in the United States; however, it is usually applied only to a fraction of production (e.g., 10-15%)[99] due to logistical reasons, such as mismatched capacities in the caster and rolling mill.[100] Hot charging can save about 0.5 million Btu/ton.[101] Finally, sensible heat loss from hot rolled steel can be partially recovered by using water-cooling. Since the final temperature of the cooling water is generally low (around 180°F or 80°C), it can be upgraded for other heating applications with a heat pump.[102]

Table 15 - Unrecovered Sensible Heat Losses from Hot Solid Streams in Iron/Steel Production

Waste Heat Source	Max Temp [a]	Sensible Heat (Btu/ton) [a]	Applicable Steel Production (million tons /year)	Recovery Technology [a]	Stage of Development [a]	Waste Heat (TBtu/yr)
Hot Coke	2000°F [1100°C]	0.21	56.47 [b]	Dry coke quenching	Commercial, not widely used in US	12
BF Slag	2400°F [1300°C]	0.34	56.47 [b]	Radiant heat boiler(RHB)	Prototype, R & D stopped since end of 1980s	19
BOF Slag	2700°F [1500°C]	0.02	56.47 [b]	RHB	Prototype, R & D stopped since end of 1980s	1
Cast Steel	2900°F [1600°C]	1.20	104.58 [c]	RHB with heat pipes, slab cooler boiler, hot charging.	RHBs are commercial, but not used in US. Hot charging is used for a small % of production.	125
Hot Rolled Steel	1700°F [900°C]	4.76	104.58 [c]	Water spraying and heat pumps	Commercial, not widely used in US	497
Total		-				497

a. adapted from de Beer, p. 189

b. based on steel production at integrated steel mills in the United States (USGS Mineral Yearbook, 2005)

c. based on total steel production in the United States

4.4 Aluminum Production

The United States has over 300 aluminum production plants in 35 States[103] and consumes about 770 TBtu of energy per year.[104] Aluminum manufacturing is divided between primary refining of aluminum from bauxite (about 2.5 million tons of aluminum per year) and secondary production of recycled scrap (about 3 million tons of aluminum per year). Primary aluminum production relies on energy-intensive electrolytic cells that account for about 15.6 kWh/kg or 60% of the energy associated with primary aluminum production. A small quantity of heat is lost via off-gases, while the majority of heat is lost through the cell sidewalls.

Secondary aluminum production requires only about one-sixth of the energy required for primary production, which has contributed to the increased demand of aluminum recycling. A key step in secondary production is scrap melting in high-temperature furnaces, where waste heat recovery is employed in only about one-third of high-capacity furnaces. Total exhaust gas losses from primary refining and secondary melting total about 9 TBtu/yr (Table 16).

Table 16 - Unrecovered Waste Heat and Work Potential from Exhaust Gases in Aluminum Refining and Melting

Source	Energy Consumption	Assumed Average Exhaust Temperature		Waste Heat 77°F [25°C] *Ref*	Waste Heat 300°F [150°C] *Ref*	Carnot Efficiency	Work Potential
	TBtu/yr	°F	°C	TBtu/yr	TBtu/yr		TBtu/yr
Hall Hèroult Cells	134.6	1,292	700	2.6	2.2	69%	1.8
Secondary Melting							
no Recovery	9.3	2,100	1,150	6.1	4.2	79%	4.8
with Recovery	2.2	1,000	538	0.8	0.4	63%	0.5
Total	146.1			9.5	6.7		7.1

Note: Sources and assumptions in Appendix A: Documentation of Waste Heat Estimates

4.4.1 Primary Aluminum Production

Primary aluminum production is carried out in Hall-Hèroult cells (Figure 24) where alumina is electrolyzed in a molten bath of fluoride compounds known as cryolite. Furnace operating temperatures are typically around 1,290°F [960°C].[105] Waste heat losses in aluminum cells include off-gases as well as unusually high sidewall losses. Off-gas losses account for a small percentage of waste losses in aluminum cells, accounting for only about 1% of electricity inputs to the cell. Off-gases are primarily due to anode reactions and air burning, which cause the production of about 1.5 tons of CO_2 per ton of aluminum. Dilution air is usually used to lower the temperature of the heat before the gases are ducted away from the furnace. Losses total about 2.6 TBtu/yr of waste heat. At this time, no plants have developed economical means for recovering off-

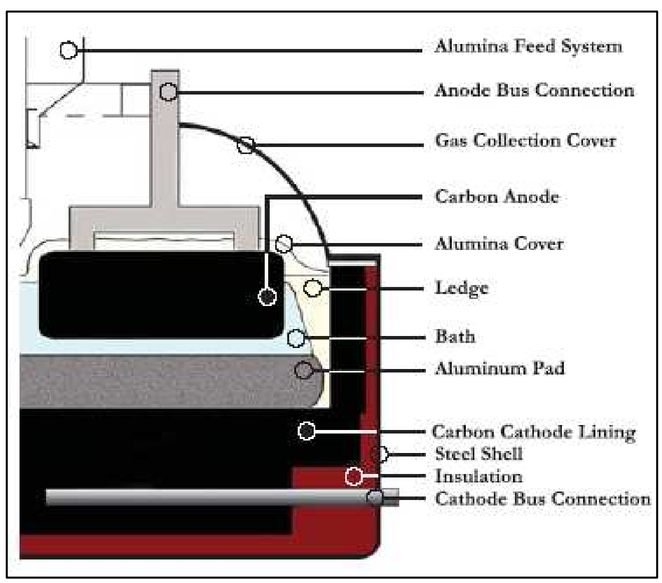


Figure 24 – Hall-Hèroult Cell (Choate, 2003)

gas waste heat. The waste heat loss is a small fraction of total energy inputs; therefore recovery installations are unlikely to have desired payback periods. Moreover, the physical arrangement of cells would make it difficult to retrofit any heat exchange equipment.

Meanwhile, sidewall losses in aluminum cells are unusually high compared to other process furnaces. Molten cryolite is highly corrosive; therefore, cells maintain a "frozen ledge," where the cryolite adjacent to the cathode lining is kept solid. This requires high rates of heat transfer away from the furnace. Consequently, the furnace is controlled so that as much as 45% of the energy input to the cell is lost via conduction, convection, and radiation from the sidewall. This accounts for about 55 TBtu of waste heat per year. Despite the high level of waste heat loss, no technologies have been developed for recovering this heat. There also do not appear to be any ongoing efforts to develop recovery methods. However, there may be possibilities to explore new methods of waste heat recovery, such as using thermoelectric technologies to control furnace heat losses. By closing or opening the electrical circuit connected to the thermoelectric device, it may be possible to control heat losses in order to control the frozen ledge, while recovering a portion of the heat lost. There may also be opportunities for other technologies — such as thermophotovoltaic generation — to recover waste heat.

4.4.2 Secondary Aluminum Production

Secondary aluminum production involves recycling aluminum scraps, both "new" scrap (created in aluminum processing steps including scrap from drilling and machining of castings, scrap from aluminum fabrication, etc.) and "old" scrap or post-consumer scrap. Scrap is first pretreated to remove paints, oils, etc. before it is sent to a melting furnace. In the melting furnace, impurities are further removed via fluxing, in which NaCl and/or KCl is mixed with the molten metal in order to both separate impurities and to prevent the molten aluminum from oxidizing. The most common furnace used in secondary melting is the reverberatory furnace (Figure 25), though other options include round-top melters, induction furnaces, tower melters, vortex melters, and flotation melters.[106] Reverberatory furnaces can have energy intensities ranging anywhere from about 1,200 to over 2,500 Btu/lb[107] with typical values around 1,800 Btu/lb without heat recovery.[108, 109] In many cases, the actual energy consumption associated with producing a final pound of product is much higher, since yield losses in shape casting can be as high as 45%, essentially requiring that 2 pounds of aluminum must be melted for every pound of final cast product. Exhaust gas temperatures leaving the furnace are as high as 2,000-2,200°F [1,090°C-1,200°C], which can lead to as much as 60% of the energy input being lost to flue gas waste heat.[110]

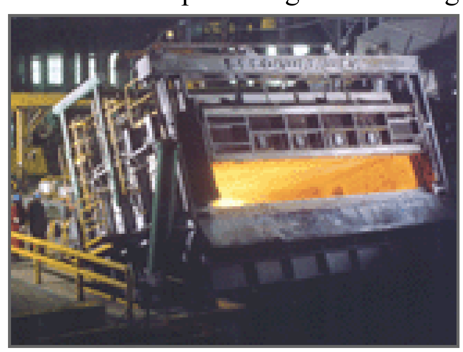


Figure 25 - Gas-Fired Aluminum - Reverberatory Tilting Furnace -
(Source: Seco/Warwick Corporation)

There are about 400 aluminum melting furnaces in operation,[111] of which over 300 have capacities greater than 40,000 lbs. Of these, only about one-third employ waste heat recovery technologies, due to the increased complexity and capital costs associated with heat recovery.[112] The secondary aluminum industry has historically struggled with heat recovery technologies; several plants have previously attempted recovery techniques such as recuperative air preheating, only to quickly abandon these systems when maintenance costs proved burdensome.[113] Challenges originally faced by the industry included corrosion from chlorides and fluorides released during fluxing operations, secondary combustion of volatiles in the recuperator, and overheating.[114] Several of these issues have been partially addressed, thanks to improved operations and increased field experience with recuperators. Secondary combustion of volatiles is less common, since many producers now delaquer scrap before the melting process. Meanwhile, waste-gas bypasses can be used during the fluxing operation to prevent corrosive gases from coming in contact with the heat exchanger. Overheating can also be prevented by both carefully monitoring furnace operations and by introducing dilution air before the recuperator.[115]

Alternatives to recuperators include fixed and rotary regenerators, as well as charge preheat (at least one system for charge preheating has been commercialized in the United States). The use of fixed regenerators is becoming increasingly common in the United States. Meanwhile, rotary regenerators for heat recovery from aluminum and other high-temperature furnaces have been developed and commercialized in Europe. However, efforts to commercialize them in the United States have been unsuccessful due to their high capital costs.[116]

4.5 Metal Casting

Metal casting involves pouring molten metal into molds to produce consumer goods such as engine blocks, suspension parts for motor vehicles, structural and metal fittings for appliances, and pipes and valves. Metal casting relies on high-temperature, and often inefficient, furnaces for heating and melting metals. The industry consumed approximately 257 TBtu/yr in 2002.[117] Approximately 55% of the industry's energy costs are for melting processes.[118] The industry relies on a variety of melting furnaces including reverberatory furnaces, cupola furnaces, crucible furnaces, electric induction furnaces and electric arc furnaces for melting. It also uses several holding and heat treating furnaces. In order to concentrate on the largest opportunity areas, the metal casting activities analyzed include only aluminum and iron casting industries since these two products account for over 80% of the energy use in the metal casting industry.[119] The exhaust gas waste heat from fuel-fired melting processes in these industries is estimated to be approximately 33 TBtu/yr from a reference temperature of 77°F [25°C] (Table 17).

Table 17 - Unrecovered Waste Heat and Work Potential from Selected Process Exhaust Gases in - Metal Casting -

Source	Energy Consumption TBtu/yr	Assumed Average Exhaust Temperature °F	°C	Waste Heat 77°F [25°C] *Ref* TBtu/yr	Waste Heat 300°F [150°C] *Ref* TBtu/yr	Carnot Efficiency	Work Potential TBtu/yr
Aluminum							
Reverb Furnace	19.0	2,100	1,150	12.5	8.5	0.8	9.9
Stack Melter	1.1	250	121	0.2	-	0.2	0.0
Iron Cupola							
no Recovery	46.7	1,650	900	19.3	15.3	0.7	14.4
with Recovery	7.8	400	204	0.8	0.2	0.4	0.3
Total	74.6			32.8	24.0	2.2	24.6

Note: Sources and assumptions in Appendix A: Documentation of Waste Heat Estimates

The major barrier to heat recovery in the metal casting industry is economic rather than technical. Barriers to waste heat recovery include the inertia of inefficient, "status quo" operations, the large number of small facilities, and a general decline in metal casting profitability. The metal casting industry is a struggling industry, largely dominated by small operations.[120] Due to the economic limitations on the metal casting industry, facilities are most likely to implement projects with very short payback periods. With payback periods ranging from 1 to 3 years, waste heat recovery is often not implemented.

The most common uses for waste heat in the metal casting industry are preheating charge material and preheating combustion air. Another good use for recovered heat is space heating, especially in the Midwest, where space heating bills can contribute as much as half of the total energy bill in the winter (Figure 26). In other cases, more creative options have been found; for example, one metal casting facility has installed a system for using waste heat to evaporate wastewater. Initially the facility had to spend about $22,000 per year to dispose of 48,000 gallons of wastewater consisting of 90% water and 10% oil. It was discovered that exhaust gases from a reverberatory furnace could be used to evaporate the water, thereby significantly reducing waste disposal costs.

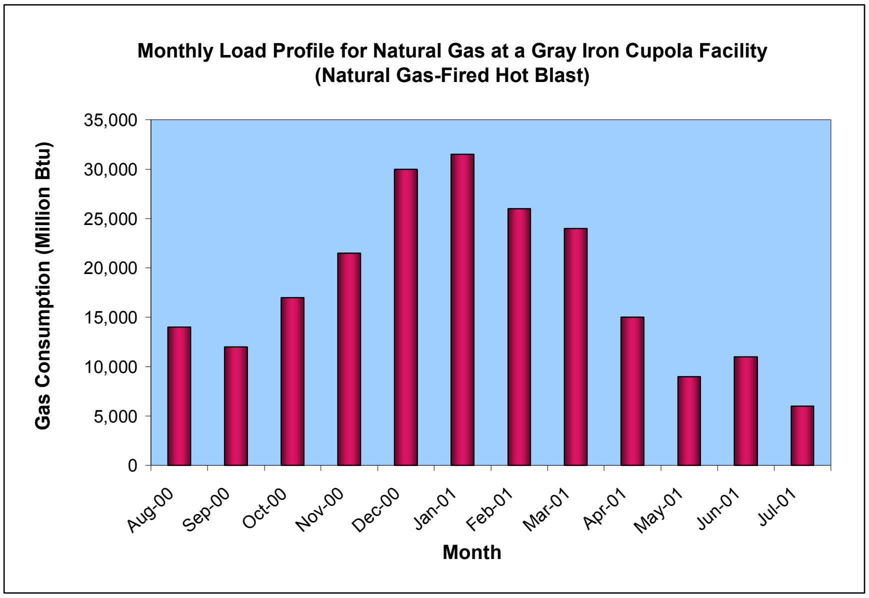


Figure 26 – Example of Monthly Load Profile for Natural Gas at a - Casting Facility Located in the Midwest -

4.5.1 Aluminum Casting

Aluminum casting facilities consume about 34% of the energy consumed by the metal casting industry.[121] They consume from 60 to 100 million Btu tacit energy per ton of casting shipments.[122] Melting furnaces include reverberatory furnaces, stack melters, crucible furnaces, and induction furnaces.

Reverberatory furnaces are the most commonly used melting furnaces among high-volume aluminum foundries and account for melting 90% of aluminum produced in the United States.[123] Aluminum reverberatory furnaces have exhaust temperatures of about 2,000-2,400°F [1,090°C-1,316°C] and thermal efficiencies around 30-35%.[124] A more efficient option is the stack melter, which has a better seal and uses hot flue gases to preheat the metal charge, enabling efficiencies of 40-45%.[125] The temperature of exhaust gases leaving stack melters ranges from about 250 to 400ºF [120-204°C].

Despite the greater efficiency of stack melters, they are used in only about 5 to 15% of aluminum production.[126] Some barriers to implementation include:

- *Increased maintenance costs:* Charges loaded at the top of the stack melter drop to the bottom and cause additional wear and tear on the refractory lining. The additional labor and materials required to maintain the refractory can limit the financial savings achieved through energy efficiency.[127] However, some progress has been achieved in advanced refractory materials that can better withstand impacts from falling charge material.
- *Charge Requirements:* Due to the stacking requirements for the charge material, facilities are often unable to take advantage of lower cost charge materials.[128]

However, rising natural gas costs and further improvements in stack melter design may increase the cost-effectiveness of stack melters and reduce the magnitude of these barriers.

Another option for waste heat recovery is recuperators, which have the potential to save as much as 30% of current energy consumption. Recuperators would be most appropriate for a reverberatory furnace, rather than a stack melter, which has low exhaust temperatures. If all reverberatory furnaces installed recuperators, it would achieve energy savings comparable to that achieved by installing stack melters.[129] Aluminum reverberatory furnaces lose approximately 13 TBtu/yr via exhaust gases.

4.5.2 Iron Casting

Iron casting is responsible for 50% of energy consumption in the metal casting industry.[130] Melting furnaces include induction furnaces, electric arc furnaces, and cupola furnaces. There are about 70 cupolas operating in the United States, making up about 60% of the total melting capacity in the industry.[131] The efficiency of cupola furnaces has improved substantially in recent years. Older, low-efficiency cupolas have a specific energy consumption of about 5 million Btu/ton, while more modern systems including energy-efficient designs can achieve about 3.4 million Btu/ton.[132] According to an analysis of cupola energy efficiencies by Kuttner, LLC of Port Washington, typical “low efficiency” cupolas lose about 50% of their heat in flue gases.[133] However, newer, “high efficiency” cupolas incorporate a recuperative unit for preheating air, reducing stack losses to only 37%.[134] The exhaust gas temperature from a cupola furnace can range from about 1,500-1,800°F (816-982°C), whereas the temperature leaving a recuperative unit is approximately 400°F (204°C). Iron cupola furnaces in the metal casting industry lose approximately 20 TBtu/yr via exhaust gases.

4.6 Industrial Boilers

Steam is critical to several manufacturing sectors, and it is estimated that approximately 43,000 industrial boilers consume about 6,500 TBtu of fuels annually.[135] Fuel consumption for steam generation is greatest in the chemicals, refining, food, paper, and primary metals industries (Figure 27)[136] where steam generation can account for anywhere from 10 to 80% of total energy consumption.[137] Total unrecovered heat from industrial boiler exhaust gases is estimated at about 1,200 TBtu/yr (Table 18), most of which is low-temperature heat.

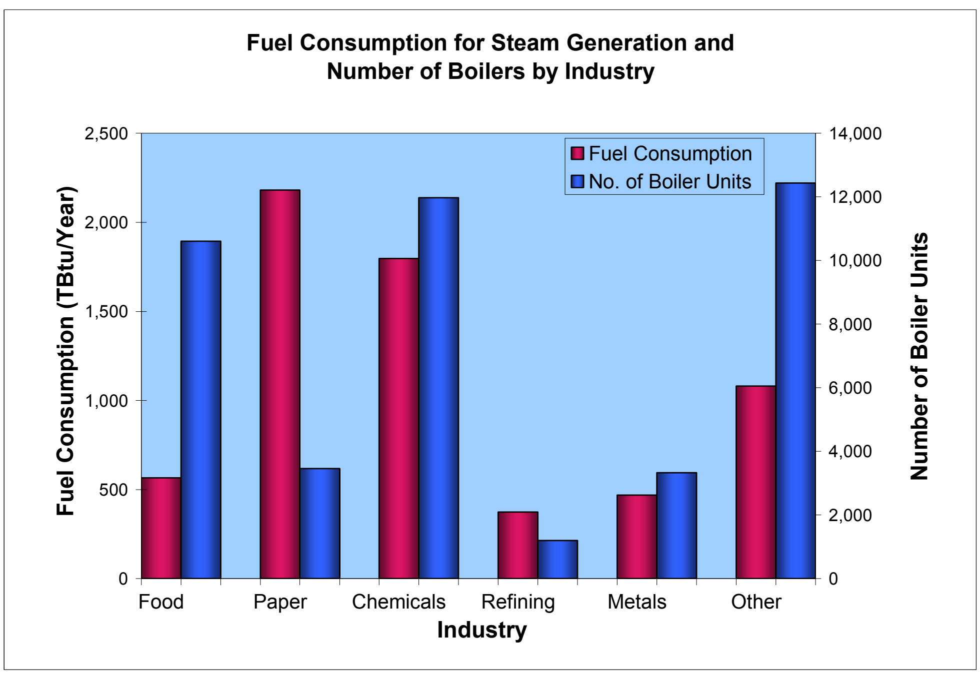


Figure 27. Fuel Consumption for Steam Generation and Number of Boilers - by Industry (Source: EEA, 2005) -

Table 18 - Unrecovered Waste Heat and Work Potential from Industrial Boiler Exhaust Gases -

Source	Energy Consumption	Assumed Average Exhaust Temperature		Waste Heat 77°F [25°C] *Ref*	Waste Heat 300°F [150°C] *Ref*	Carnot Efficiency	Work Potential
	TBtu/yr	°F	°C	TBtu/yr	TBtu/yr		TBtu/yr
Boilers							
No Recovery	1,625	500	260	348	73	44%	153
With Recovery	4,875						
Conventional Fuels	2,438	300	150	394	-	30%	117
Byproduct Fuels	2,438	350	177	428	27	34%	144
Total	6,500			1,170	100		414

Note: Sources and assumptions in Appendix A: Documentation of Waste Heat Estimates

The most significant fuel sources for boilers are natural gas (2,141 TBtu/yr) and byproduct fuels (3,249 TBtu/yr). Byproduct fuels include black liquor and wood waste in the paper industry, refinery byproducts (e.g., still gas), and coke oven and blast furnace gases in primary metals manufacturing. Exhaust temperatures will depend on the pressure of steam required for a given industrial process. In this study, average exhaust temperatures are assumed to be around 500°F [260°C] without heat recovery. Heat recovery is quite common for boilers. Options include economizers, air preheaters, or both. Average exhaust temperatures from boiler economizers using conventional fuels are likely to be around 300°F [150°C].[138] Meanwhile, boilers burning byproduct fuels (e.g., black liquor) would be likely to have minimum final exhaust temperatures around 350-400°F [180-200°C].[139] Typical efficiencies for natural gas boilers range from 80-85%, while boilers firing black liquor have efficiencies as low as 70%.[140, 141]

According to conversations with boiler manufacturers, most boilers with capacities greater than about 25 million Btu/hr include economizers. Though there are a large number of small boilers in different facilities, total U.S. industrial boiler capacity is dominated by boilers with energy consumption greater than 50 million Btu/hr;[142] therefore, the use of economizers can be considered a fairly typical practice. A very small number of facilities also use condensing economizers (Section 3.3.2) to cool exhaust gases to temperatures as low as 100-150°F [38-66°C], where the latent heat contained in water vapor can be recovered. Boilers incorporating condensation recovery have been commercially available for several decades; however, they are only used in a small fraction of the boiler market. According to a market study of commercial boilers, only about 2% of the boilers sold included condensation recovery.[143] Conversations with boiler manufacturers indicate that condensing systems make up a similarly small fraction of the industrial boiler market. A key barrier is the high capital cost of condensing economizers, which can be almost three times as much as a conventional economizer.[144] Additionally, it is necessary that return water is at a sufficiently low-temperature (e.g.,100-150°F or [38°-66°C]) to enable heat transfer from the exhaust gas to the return water. This is often not available.

Exhaust gas waste heat losses from industrial boilers are estimated at about 1,200 TBtu/yr. This is largely low-quality waste heat. Nevertheless, it is noteworthy that because the quantity of heat available is so large, the work potential of this waste heat source is about 400 TBtu, which considerably exceeds the work potential of waste heat exhausted by other higher-temperature sources. Considering the large number of industrial boilers (43,000) and the high quantity of energy consumed for steam generation, incremental improvements in boiler efficiency could have an appreciable impact on total energy consumption. It should also be noted that commercial boilers are also significant energy consumers, responsible for another 1,630 TBtu/yr of energy consumption, and responsible for 263 TBtu/yr of low-temperature waste heat loss. Any technology improvements that reduce the cost of condensing economizers in the industrial sector could extend to the commercial sector and facilitate further energy savings.

4.7 Ethylene Furnaces

Ethylene is the largest volume petrochemical product in the United States and functions as a key building block for many other chemical products. Over 28.3 million tons of ethylene were produced in 2004[145] requiring about 645 TBtu of energy input. A key component of the production process is the pyrolysis furnace (Figure 28), where hydrocarbon feedstocks are cracked at temperatures around 1400-1600°F [760-870°C].[146]

The energy intensity of ethylene production varies depending on the feedstocks used: it requires about 16.7 million Btu/ton to produce ethylene from ethane and around 27.4 million Btu/ton when produced from naphtha/gas oil feedstocks. Based on the mix of feedstocks used in the United States, the average energy intensity for ethylene production is about 22.8 million Btu/ton, corresponding to a total of 654 TBtu/yr. It is estimated that about 58% of energy consumption or about 374 TBtu is consumed in the ethylene furnace alone.[147]

Figure 28 - Ethylene Furnace
(Source: Selas Fluid)

Ethylene crackers rely on fired gas or oil to provide heat to the pyrolysis reaction. The furnace consists of both a radiant section and convection section. The radiant section contains reactor tubes where the pyrolysis reaction takes place. The convection section consists of several heat exchangers where heat is exchanged between flue gases and process fluids such as steam and reactor feed. The flue gases leaving the convection section are at relatively low temperatures. As with other systems such as conventional steam boilers, typical furnace exhaust temperatures are around 300°F [150°C].[148] It is fairly common for furnaces to be designed for higher efficiencies via cooling of the exhaust gases to lower temperature. In this case fouling on the outside of the heat exchanger is cleaned by steam lancing, while fouling on the inside is addressed by burning.[149] Based on an assumed average exhaust temperature of 300°F [150°C], the unrecovered waste heat from these ethylene cracking furnaces is about 60 TBtu/yr (Table 19).

Table 19 - Unrecovered Waste Heat and Work Potential from Ethylene Furnaces

Source	Energy Consumption TBtu/yr	Assumed Average Exhaust Temperature °F	Assumed Average Exhaust Temperature °C	Waste Heat 77°F [25°C] *Ref* TBtu/yr	Waste Heat 300°F [150°C] *Ref* TBtu/yr	Carnot Efficiency	Work Potential TBtu/yr
Ethylene Furnace	374.0	300	149	60.5	-	29%	17.8

Note: Sources and assumptions in Appendix A: Documentation of Waste Heat Estimates

Part C: -
Results -

5.0 Industrial Waste Heat Losses and Research Development, and Demonstration Needs

5.1 Estimates of Exhaust Gas Waste Heat Losses from Selected Processes

This study investigated several industrial processes, consuming a total of ~8,400 TBtu/yr, in order to estimate waste heat recovery opportunities. Estimates of unrecovered waste heat are shown in Figure 29 and Table 20. It should be noted that though the figure displays results by industry; these are not estimates of total waste heat losses by industry, but of the waste heat losses from selected processes analyzed in Section 4 of this report (e.g., iron/steel includes coke ovens, blast furnaces, basic oxygen furnaces, and electric arc furnaces, but not annealing furnaces). Of the 8,400 TBtu/yr analyzed, about 1,500 TBtu/yr is lost as waste heat in exhaust gases, based on a reference enthalpy of 77°F [25°C]. The work potential of this waste heat is about 600 TBtu/yr. Waste heat losses were also estimated based on a reference enthalpy of 300°F [150°C], since many facilities do not cool exhaust gases below this temperature. Waste heat losses with a 300°F [150°C] reference total about 660 TBtu/yr.

The red column in Figure 29 shows waste heat losses calculated from a reference temperature of 77°F [25°C], while the green column shows waste losses calculated from a reference temperature of 300°F [150°C]. For low-temperature sources analyzed, the green column is significantly lower compared to other high-temperature sources. Meanwhile, the blue column displays work potential, which provides a means for better comparing heat sources with different temperatures. For low-temperature sources, work potential will be a smaller fraction of total waste heat losses, whereas for high-temperature sources work potential will be a larger fraction of total waste heat losses. The blue column in Figure 29 can be used to better compare waste heat losses in different processes, since it accounts for the varying value of low- and high-temperature heat.

Total waste heat losses depend largely on energy consumed by each system and on the typical range of exhaust temperatures for each system. For example, Figure 29 shows that steam boilers are significant sources of waste heat; however, most of this waste heat is at low temperatures (e.g., 300-450°F). Large industry steam boilers typically have high efficiencies (80-85%), which significantly exceed the efficiencies of other fired systems (e.g., glass furnaces have efficiencies as low as 30%). Boilers are used across a wide array of industries (food, paper, chemicals, refining, and metals), and it is estimated that industry relies on a total of 43,000 or more boilers. Therefore, even though boilers are one of the most efficient fired systems included in this study, the large number of boilers in operation leads to significant waste heat losses. When comparing opportunities available in industrial boilers, it is better to compare the green or blue columns in Figure 29, since these better reflect the low quality of waste heat from boilers. In doing so, one finds that heat recovery opportunities from industrial boilers my still be significant, since the work potential of boilers' waste heat exceeds that of other sources. An appropriate conclusion would be that due to the large magnitude of steam boilers in industry, incremental improvements in boiler efficiency may continue providing additional opportunities for energy efficiency. Meanwhile, several other systems (glass furnaces, aluminum furnaces, cement kilns) are sources of medium- to high-temperature heat and also prevent significant opportunities for heat recovery.

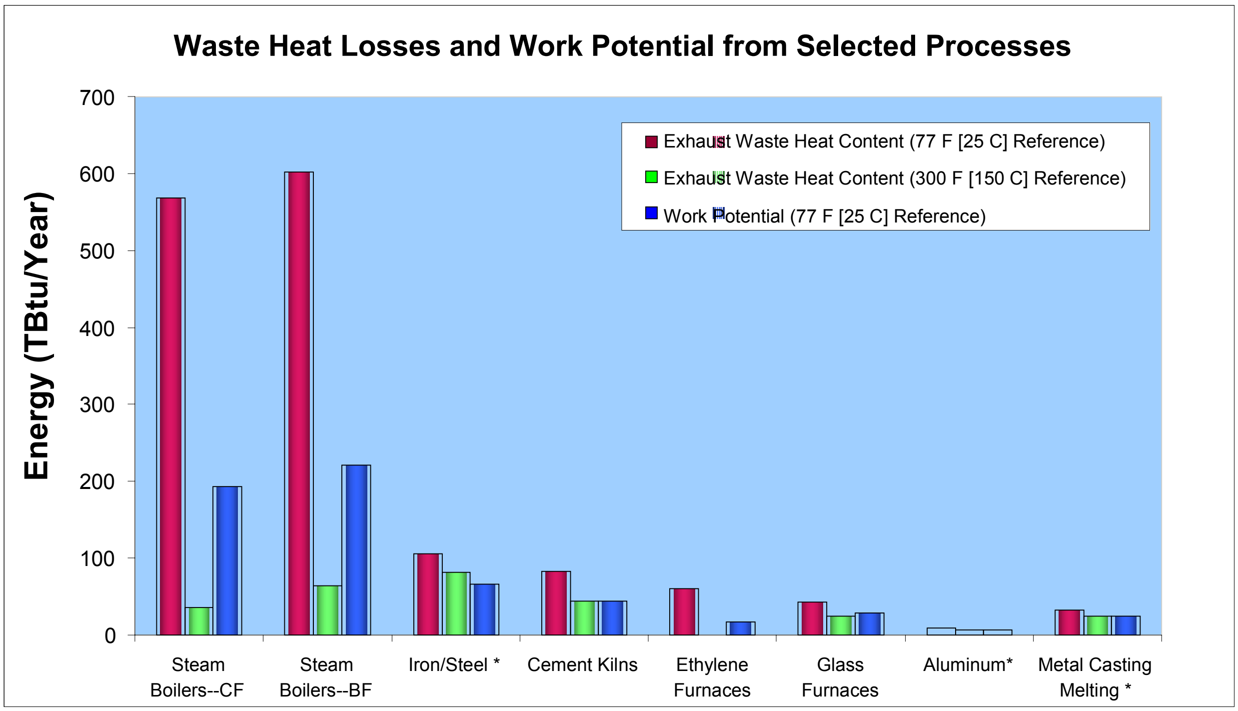


Figure 29. Waste heat losses and work potential from selected process exhaust gases.

*NOTE: Steam boilers are divided into conventional fuels (CF) and BF. It is important to note that while steam boilers have higher waste heat losses, this is due to the large number of industrial boilers (about 43,000 total units) rather than due to boiler inefficiency. Typical boiler efficiencies (80-85%) are much higher than other fired units such as glass furnaces. Heat losses from boilers are in the low-temperature range, as evidenced by the low heat content from a 300°F [150°C] reference. *Also note that values reported above do not reflect total waste heat losses by industry, but rather the waste heat losses from selected processes. Iron/Steel includes coke ovens, blast furnaces, basic oxygen furnaces, and electric arc furnaces. Aluminum includes primary refining cells and secondary melting furnaces. Metal casting melting includes aluminum reverberatory furnaces, stack melters, and iron cupolas in metal casting facilities. Aluminum includes primary and secondary refining furnaces.*

Table 20 - Unrecovered Waste Heat and Work Potential from Selected Process Exhaust Gases

Source	Energy Consumption	Assumed Average Exhaust Temperature		Waste Heat 77°F [25°C] R*ef*	Waste Heat 300°F [150°C] *Ref*	Carnot Efficiency	Work Potential
	TBtu/yr	°F	°C	TBtu/yr	TBtu/yr		TBtu/yr
Aluminum Primary	146.1			9.47	6.73		7.11
Hall Heroult Cells	134.6	1,292	700	2.6	2.2	69%	1.8
Aluminum Secondary							
no Recovery	9.3	2,100	1,150	6.1	4.2	79%	4.8
with Recovery	2.2	1,000	538	0.8	0.4	63%	0.5
Iron/Steel Making	828.6			79.1	57.3		52.3
Coke Oven	65.5						
Gas		1,800	980	15.8	13.9	76%	12.1
Waste Gas		392	200	11.2	10.0	37%	4.1
Blast Furnace	642.3						
Blast Furnace Gas		200	430	5.3	-	19%	1.0
Blast Stove Exhaust							
no Recovery	36.2	482	250	10.6	1.9	43%	4.6
with Recovery	34.1	266	130	3.2	-	26%	0.8
Basic Oxygen Furnace	49.7	3,100	1,700	27.1	26.0	85%	23.0
Electric Arc Furnace							
no Recovery	57.7	2,200	1,200	5.8	5.4	80%	4.6
with Recovery	13.3	400	204	0.2	0.1	38%	0.1
Glass Melting	125.8			43.0	24.1		28.9
Regenerative	54.4	800	427	15.1	6.5	57%	8.7
Recuperative	13.6	1,800	982	7.6	5.4	76%	5.8
OxyFuel	12.8	2,600	1,420	4.2	2.7	82%	3.4
Electric Boost	34.9	800	427	8.6	3.7	57%	4.9
Direct Melter	10.1	2,400	1,316	7.5	5.8	81%	6.1
Cement	389.5			83.1	44.3		44.1
Wet kiln	98.0	640	338	18.8	9.4	51%	9.6
Dry kiln	80.2	840	449	20.6	12.8	59%	12.1
Preheater (only)	67.8	640	338	13.9	7.0	51%	7.1
Precalciner	143.4	640	338	29.7	15.1	51%	15.2
Metal Casting	74.6			32.8	24.0		24.6
Aluminum							
Reverb Furnace	19.0	2,100	1,150	12.5	8.5	79%	9.9
Stack Melter	1.1	250	121	0.2	-	24%	0.0
Iron Cupola							
no Recovery	46.7	1,650	900	19.3	15.3	75%	14.4
with Recovery	7.8	400	204	0.8	0.2	38%	0.3
Boilers	6,500.0			1,169.7	100.0		414.2
Conventional Fuels							
no Recovery	812.5	500	260	173.8	36.5	44%	76.6
with Recovery	2,437.5	300	150	394.3	-	30%	116.5
Byproduct Fuels							
no Recovery	812.5	500	260	173.8	36.5	44%	76.6
with Recovery	2,437.5	350	177	427.8	27.0	34%	144.4
Ethylene Furnace	374.0	300	149	60.5	-	29%	17.8
Total	8,439			1,478	257		589

5.2 Waste Heat Recovery Opportunity Areas

Based on estimates of waste heat losses in selected applications, several trends were identified regarding opportunity areas and RD&D needs for waste heat recovery. Opportunity areas are listed below and further elaborated in Sections 5.3-5.6.

Key opportunity areas:

- **Low-temperature waste heat sources** - Based on a 77°F [25°C] reference, most unrecovered waste heat is at low temperatures. About 60% of waste heat losses are at temperatures below 450°F [230°C].
- **Systems already including waste heat recovery that can be further optimized to reduce heat losses** - The extent of heat recovery from existing systems is often constrained by costs and temperature limits for the heat recovery system. In many cases, such as cement preheater kilns and recuperative glass furnaces, exhaust gases exiting the recovery device are still in the medium- to high-temperature range. This represents an opportunity for additional waste heat recovery. Opportunities are also available to maximize the quality of heat recovered, since facilities often use dilution air to lower the temperature of waste heat streams.
- **High-temperature systems where heat recovery is less common** - There are market segments where waste heat recovery is less common; this is due to barriers such as chemical constituents in exhaust gases that interfere with heat exchange, as well as limitations on economies of scale for smaller waste heat streams.
- **Alternate waste heat sources typically not considered for waste heat recovery** - This study focused on combustion and process exhaust gases. However, alternate sources of waste heat were also found to be significant. These alternates include heat radiated, convected, and conducted from heated products (e.g., cast steel, hot cokes), as well as heat lost in aluminum cell sidewalls and after pyro-processes where slag or after materials are solidified to protect the vessel walls.

5.3 Waste Heat Opportunity

Figure 30 displays estimated waste heat losses in different temperature groups. The temperature groups are defined as:

High	1200ºF [650°C] and higher -
Medium	450ºF [230°C] to 1,200ºF [650°C] -
Low	450ºF [230°C] and lower [150 -]

Based on a reference temperature of 77°F [25°C], approximately 60% of waste heat analyzed is low-temperature heat below 450°F [230°C], and nearly 90% of waste heat is below 600°F [316°C]. It is already well-known that low-temperature heat is abundant; however a unique element in this study is its analysis of the work potential of waste heat, which allows a better comparison of waste heat at different temperatures. As shown in Table 21 and Figure 30, the work potential of low-temperature waste heat (based on a 77°F reference) exceeds that of medium- and high-temperature heat. Therefore, even when accounting for the lesser value of low-temperature heat, the sheer magnitude of low-temperature heat available makes it worthy of further investigation.

The analysis above is based on the quantity of heat estimated using a reference temperature of 77°F [25°C]. This reflects the maximum heat recoverable if exhaust gases are cooled to room temperature. However, many facilities only cool exhaust gases to about 300°F [150°C] in order to prevent flue gas condensation. Based on a 300°F [150°C] reference, more heat is recoverable in the medium- to high-temperature range. The relative merits of low-, medium-, and high-temperature recovery efforts depend on the ability of industries to cost-effectively cool exhaust gases to sub-dewpoint temperatures and on the availability of end-uses for low-temperature waste heat. While low-temperature heat recovery technologies are available, significant reductions in cost or completely different approaches will be required in order to tap the potential of this heat source.

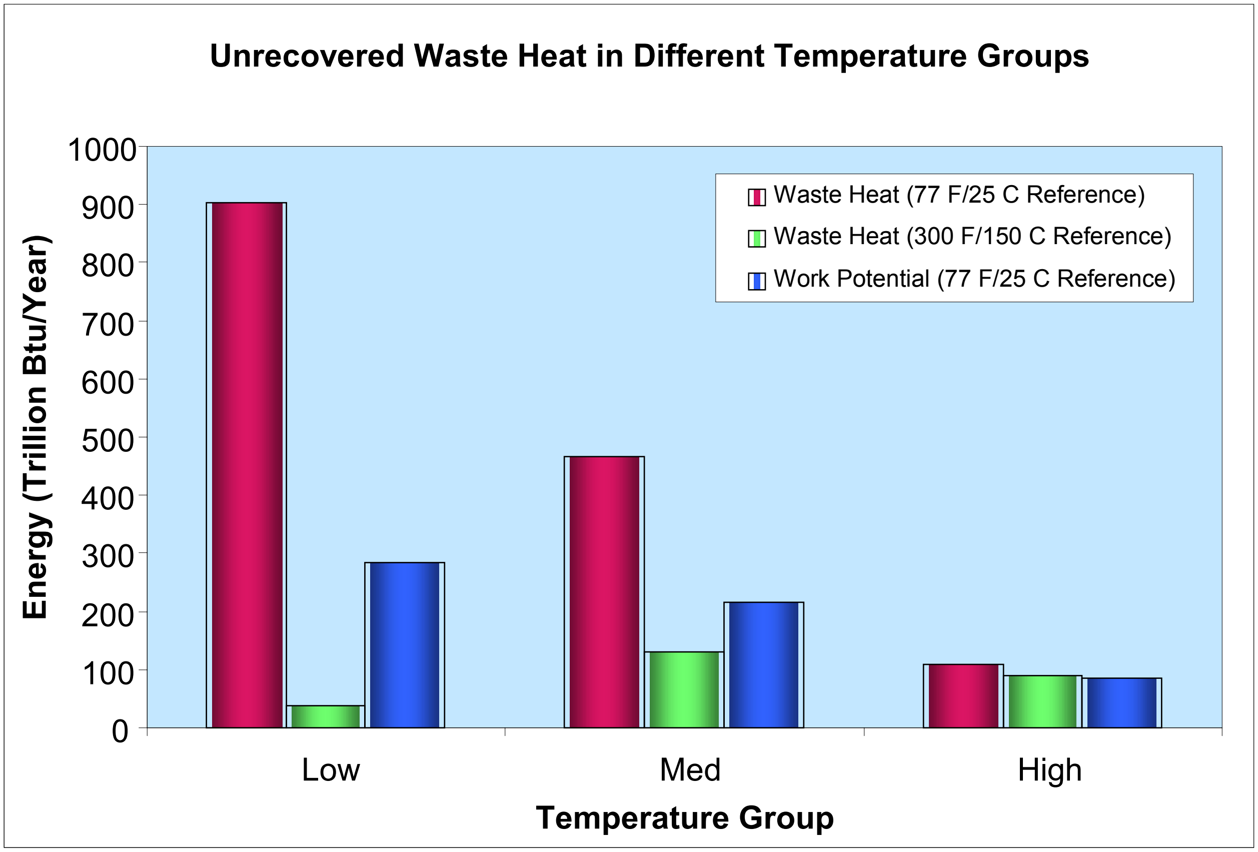


Figure 30 - Unrecovered Waste Heat in Different Temperature Groups.
The graph above indicates that the majority of waste heat losses (based on a 77°F [25°C] reference) are in the low-temperature range. Though low-temperature waste heat is a lower-quality heat source, it is present in sufficiently large magnitudes that its work potential exceeds that of other waste heat sources.

Table 21 - Unrecovered Waste Heat in Different Temperature Groups

	Temperature Range		Waste Heat (TBtu/yr)		Work Potential (TBtu/yr)
	°F	°C	77°F [25°C] *Reference*	300°F [150°C] *Reference*	77°F [25°C] *Reference*
Low	<450	<230	903	37	287
Med	450-1200	230-650	466	130	216
High	>1200	>650	108	89	86
Total	-	-	1,478	256	589

5.3.1 RD&D Needs for Low-Temperature Waste Heat Recovery

Developing Heat Exchangers for Low Temperatures

A major challenge for low-temperature heat recovery from exhaust gases is the condensation and corrosion caused by cooling exhaust gases below their dew point temperature. Condensation heat recovery requires significantly higher capital and operating costs, which usually are not worth the energy saving benefits. While condensing economizers are commercially available, capital costs can be as much as three times that of conventional boilers.[151] Alternate technologies, such as transport membrane condensers are being developed and may have lower costs.[152]

Recovery at low temperatures becomes increasingly challenging with chemically laden gas streams. These waste heat sources will have greater limitations that prevent cooling flue gases to low temperatures. In order to enable expansion of low-temperature heat recovery, RD&D might involve improving methods for cleaning exhaust streams, developing low cost advanced heat exchangers that can withstand corrosive environments, developing heat exchangers that can be easily cleaned, or perhaps modifying process technologies in order to prevent introduction of chemicals that would prevent heat exchange. Another challenge for heat exchangers when working with low-temperature fluids is the large heat transfer area required, especially if heat is to be recovered from gaseous exhausts. Developments that increase heat transfer coefficients in heat recovery systems could partially address this issue. Some examples of commercially available technology for improving heat technology coefficients are ceramic inserts used in radiant heating tubes, dimpled or finned tubes and heat pipes.

End-Use Technologies for Low-temperature Heat

A further challenge for low-temperature waste heat recovery is the limitations on available end-uses. Potential end-uses for low-temperature heat include low-temperature process heating, domestic water heating, and space heating. Additionally, as discussed in Sections 3.3-3.4, heat pumps and low-temperature power generation are options for recovery from low-temperature heat sources. Heat pumps can be used to "upgrade" waste heat if a heat load is available at a temperature slightly higher than the waste heat temperature. Heat pump technology is well-developed, but improvements could be made that lower capital costs or improve heat pump performance (for example, innovative working fluids could be developed to increase heat pump efficiency). Low-temperature power generation technologies are an emerging opportunity. Power cycles such as organic Rankin cycles and the recently developed Kalina cycle have been successfully installed in low-temperature industrial applications. Longer-term technologies under investigation, such as piezoelectric generation, are not yet economical. Efforts can be made in further demonstrating emerging power cycles, improving these power cycles, and developing alternative generation systems.

5.4 Optimization of Systems Already Incorporating Waste Heat Recovery

5.4.1 Heat Losses from Units Already Including Waste Heat Recovery

Many of the applications analyzed in this study already include waste heat recovery technologies, especially in large systems with relatively clean exhaust gases. For the processes analyzed, Table 22 and Figure 31 display estimated current industrial energy consumption and waste heat losses from units using heat recovery technologies and those not using heat recovery. Example units incorporating heat recovery include boilers, ethylene furnaces, cement preheater kilns, glass regenerative and recuperative furnaces, recuperative aluminum melting furnaces, etc.

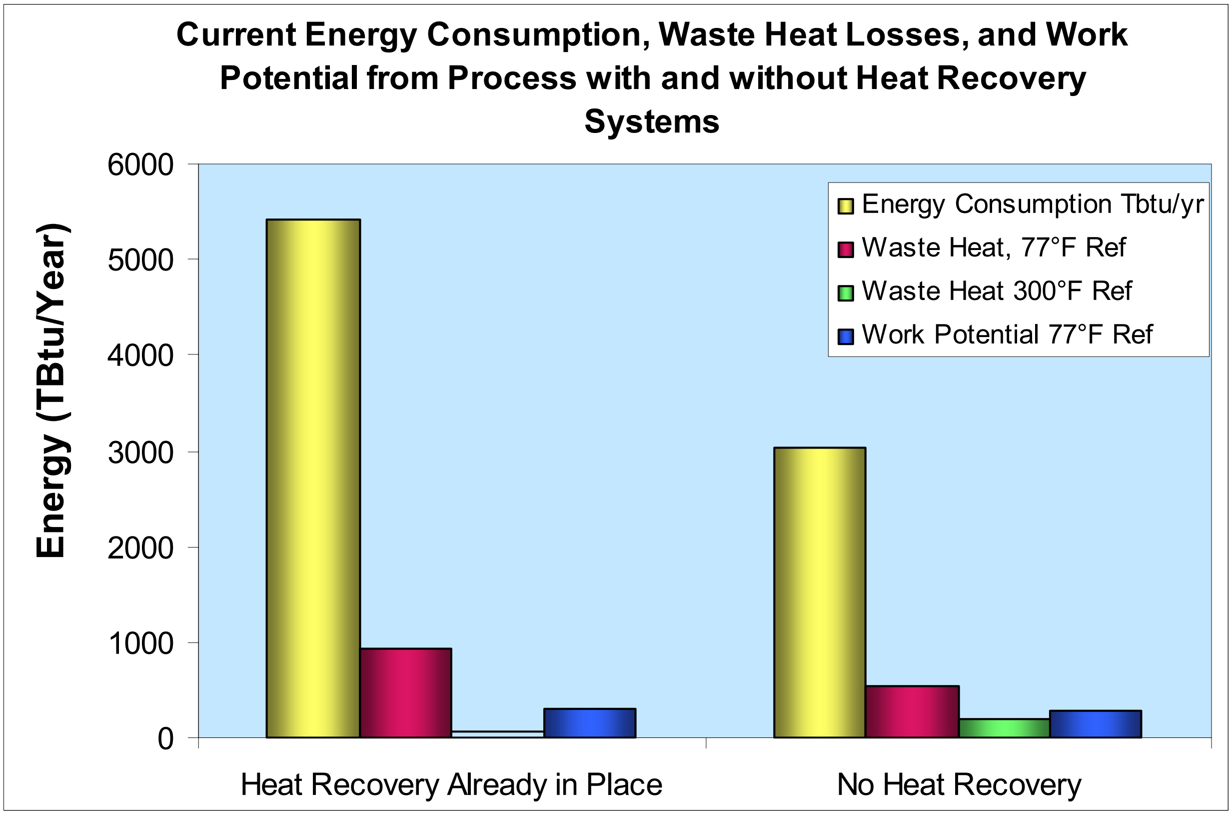


Figure 31 - Waste Heat Losses and Work Potential from Processes with and without Heat Recovery

Note: The category "Heat Recovery in Place" estimates the waste heat enthalpy of gas streams exiting heat recovery equipment currently installed in furnaces, boilers, etc.

Table 22 - Comparison of Current Units with and without Heat Recovery

	Energy Consumption TBtu/yr	Waste Heat, 77°F [25°C] *Ref*	Waste Heat 300°F [150°C] *Ref*	Work Potential 77°F [25°C] *Ref*
Heat Recovery Already in Place	5,409.3	935.5	56.5	306.2
No Heat Recovery	3,029.4	542.2	199.9	282.9

While heat recovery systems successfully capture a portion of the waste heat in exhaust gases, additional opportunity remains in the exhaust gases exiting recovery units. Exhaust gases exiting waste heat recovery systems have temperatures ranging anywhere from 250°F [121°C] to 1,800°F [982°C]. As discussed in Section 4, economizers on waste heat boilers have typical exhaust temperatures of 300°F [150°C], four-stage cement preheater kilns have exhaust temperatures around 640°F [340°C], and recuperative glass furnaces have exhaust temperatures around 1,800°F [982°C]. Therefore, significant quantities of unrecovered waste heat are still available.

A number of factors prevent more comprehensive recovery of waste heat in existing installations. In the case of relatively clean combustion exhaust gases, typical minimum exhaust temperature limits are about 300°F [150°C], to prevent flue gas condensation. In other cases, process-specific chemicals in the exhaust stream can inhibit the extent of cooling possible. Examples include sulfates in glass melting and tars in coke ovens, which increase the complexity of heat recovery at temperatures below 510°F [270°C] and 840°F [450°C], respectively.

In addition to temperature constraints, there are practical and economic limitations on heat recovery equipment. For example, larger surface areas required for further recovery will increase capital costs, as well as increase the pressure drop in the flue gas. The increased pressure drop in turn increases requirements for auxiliary power consuming equipment. In other cases, such as cement preheater kilns, structural engineering load limitations prevent additional preheat stages. Additionally, a concern in some combustion air preheat applications is the increase in NO_X emissions resulting from higher flame temperatures. This may influence the final design temperatures of the waste heat source and the preheated combustion air. Finally, there may be insufficient end-uses available on-site for the recovered waste heat. These factors all contribute to the large quantities of unrecovered waste heat exiting recovery devices.

5.4.2 RD&D Needs for Optimizing Existing Recovery Systems

Optimizing Recovery Systems

Efforts to improve heat recovery systems encompass many of the same efforts listed in Section 5.3. Development opportunities could involve low-cost solutions that address chemical attack to heat exchanger materials, increase heat transfer efficiency, and enable heat recovery at low-temperature ranges.

Beyond optimizing heat recovery systems to increase the quantity of recovered energy, there are also opportunities to increase the quality of energy recovered. In many high-temperature applications, dilution air is introduced into the waste heat stream in order to protect ducts and heat exchanger materials from damage. Advanced materials are available that can withstand high temperatures; however, typically these are very costly. Most options for recovery of high-quality heat will require the availability of low-cost manufacturing technologies for advanced materials for use in high-temperature applications. It is often more economical for facilities to introduce dilution air that reduces the waste heat temperature. In these cases, there is no loss in the quantity of heat in the exhaust stream; however, since the temperature is reduced, it is of lower quality. An alternative to air bleeding is using more advanced alloys and composite materials for heat exchangers and ducts. RD&D that reduces costs of these materials will maximize the efficiency of recovery systems.

End-Use Technologies for Low-Temperature Heat

As discussed in Section 5.3, limitations on available end-use applications for waste heat can prevent heat recovery in a number of cases. Any developments that create alternative end-uses for waste heat may increase opportunities for energy efficiency.

5.5 Expanding Heat Recovery in Certain Market Segments

5.5.1 Applications Where Heat Recovery is Less Common

Approximately 5,400 TBtu out of the 8,400 TBtu of energy consumption analyzed are consumed in systems that already have some level of waste heat recovery leaving nearly 3,000 TBtu are consumed in systems that are not currently using heat recovery. These systems account for about 540 TBtu of waste heat annually (Table 23). Economies-of-scale and process-related chemicals in exhaust streams are key factors in the decision not to include heat recovery.

Economies-of-scale dictate the economic viability of many heat recovery systems. This can be due to lack of capital available in smaller operations, as well as relatively longer payback periods involved for heat recovery installations. A good example of the relationship between furnace size and recovery practices is in the glass melting industry. As shown in Figure 32 and Table 23, typical furnace capacities vary in different segments of the glass industry. Flat glass and container glass melting is performed in large furnaces, while average capacities for pressed/blown glass, insulation fiber glass, and textile fiber glass are much smaller. One can note that smaller capacity furnaces typically have a higher percentage of waste heat losses.

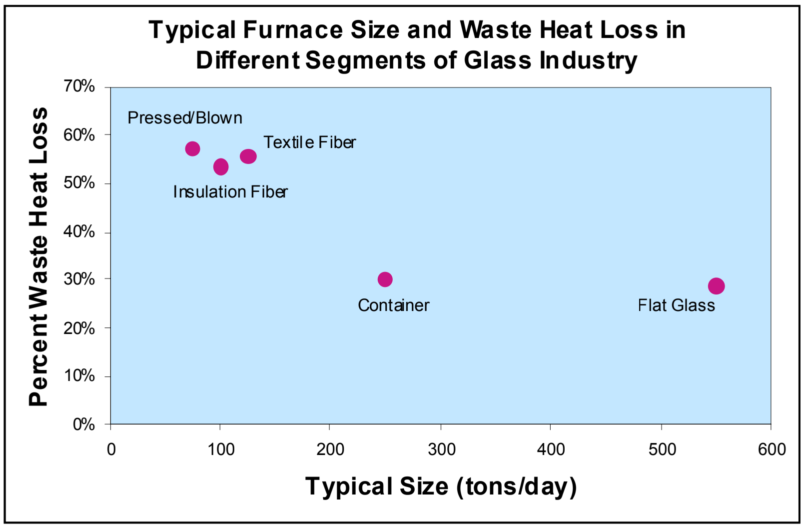


Figure 32 - Relationship between Typical Furnace Size and Average Waste Heat Losses in Different Segments of the Glass Industry (Note: Table 21)

Table 23 - Typical Furnace Capacities and Waste Heat Losses in Different Segments of Glass - Industry -

Glass Industry Segment	Furnace Capacity Range [a]	Typical Furnace Capacity [a]	Natural Gas Consumption TBtu/yr	Waste Heat TBtu/yr	% Nat. Gas Input Lost to Waste Heat
Flat Glass	300-1000	550+	41.10	11.82	29%
Container Glass	50-550	250	45.49	13.65	30%
Pressed/ Blown Glass	1-300	75	16.82	9.63	57%
Insulation Fiber Glass	20-300	100	3.24	1.73	53%
Textile Fiber Glass	100-150	100-150	11.05	6.14	56%

a. Source: Energetics, Energy and Environmental Profile of the U.S Glass Industry, 2002, p. 54

Another key challenge to heat recovery is exhaust gas chemical composition. Heat recovery is more common with clean gaseous exhaust streams, including exhausts from boilers, ethylene furnaces, and hot blast stoves. Heat recovery is less common when process-related chemicals in exhaust streams increase the complexity of waste heat recovery. Examples include dust in steel electric arc furnaces, chlorides and fluorides in secondary aluminum melting, sulfates from glass melting, and tars in coke oven gas. In the case of coke oven gas, no current facilities in the United States use waste heat recovery. In other cases such as glass melting furnaces, steel electric arc furnaces, and secondary aluminum furnaces, some facilities are currently using waste heat recovery techniques, but only to a limited extent.

In addition to economies-of-scale and process-related chemical constituents, challenges to waste heat recovery include lack of available space for retrofit applications and discontinuous furnace operations that create problems with thermal cycling. Additionally, previous experience with failed heat exchanger installations can prevent interest in waste heat recovery. In some cases application-specific constraints may not have been addressed in the design of heat recovery systems. This leads to unexpected maintenance costs. In other cases, operator error could have resulted in heat exchanger failure. A facility with previous negative experience with heat recovery may be less likely to replace previous equipment or install new equipment, typically regardless of the cause of the failure. This may be a result of, among other factors, limited industry R&D staff and expertise for post mortem failure analysis.

5.5.2 Research, Development, and Demonstration Needs for Expanding Implementation of Recovery Technologies

Reduce Impact of Chemical Composition of Exhaust Gases

Efforts to address chemical-related barriers to heat recovery include:

- development of low-cost heat exchangers with advanced materials that can withstand harsh environments or that can be easily and cost effectively cleaned and maintained,
- development of low-cost gas cleanup systems that can operate at elevated temperatures, and
- identification of new industrial process concepts that avoid introducing chemical contaminants into exhaust streams.

Optimize Economies of Scale

Implementation of waste heat recovery by small-scale facilities will require the development of exchangers that minimize associated capital costs and payback periods. New designs to economically scale-down heat recovery equipment may help increase the practice of industrial heat recovery. Additional challenges for smaller operations may be the costs of energy efficiency opportunity evaluations and engineering and design services. Publicly available tools and resources for energy efficiency improvements can aid small-scale facilities in identifying cost-effective heat recovery opportunities.[†]

Tackle Other Barriers to Waste Heat Recovery

Additional barriers to waste heat recovery include lack of physical space available to incorporate retrofit systems, discontinuous furnace operations that prevent heat recovery, and previous experiences with failed heat recovery. Not much can be done to solve the problem of lack of physical space, although the decreasing costs of increasingly compact equipment might provide options. Discontinuous furnace operations can create problems by damaging heat exchangers due to thermal cycling. Addressing this issue requires lowering the cost of heat exchangers designed to withstand large fluctuations in temperatures. Lastly, the problem of previous negative experiences with heat exchangers can be addressed by proper distribution of success stories and best practice guidance. Resources that publicize industry successes with heat recovery can help mitigate perceived economic and technical risks of heat recovery. Additionally, federally funded post mortem analysis and lessons learned could be obtained and published.

[†] Resources available include the Department of Energy Industrial Technologies Program "Best Practice" resources (http://www1.eere.energy.gov/industry/bestpractices/), as well as Industrial Assessment Centers (http://www.iac.rutgers.edu/)

5.6 Alternate Waste Heat Sources

5.6.1 Waste Heat Losses from Alternate Sources

The focus of this study is on exhaust gases from high-temperature processes. However, during the course of this study it became apparent that other sources of waste heat also deserve further investigation into potential heat recovery opportunities. For example, conductive, convective, and radiative sidewall losses from primary aluminum cells (Section 4.4.1) and hot solid streams in the iron and steel industry (Section 4.3) total about 700 TBtu of waste heat (Table 24). This is equal to half of all the waste heat contained in gaseous exhaust streams analyzed in this study (~1.5 quadrillion Btu).

Table 24 - Waste Heat Losses from Other Sources in Addition to Exhaust Gases

Waste Heat Source	Waste Heat TBtu/yr (77°F/25°C *Ref*)	Work Potential TBtu/yr
Primary aluminum cell sidewall losses	59	41
Solid streams in iron/steel	654	501
Total	713	541

Note: Sources and assumptions in Appendix A: Documentation of Waste Heat Estimates

5.6.2 Research, Development, and Demonstration for Heat Recovery from Alternate Waste Heat Sources

Heat recovery from solid streams is practiced in only a small number of applications. One challenge with efficiency of recovery from solid streams is that recovery may require additional stages of heat exchange. A common example of heat recovery from solid streams is clinker cooling in cement kilns. Heat in a clinker exiting the kiln is transferred to cooling air, which is then used for combustion air preheat. Coke dry quenching is also implemented in some applications, though it is not very common in the United States. Other methods have been explored such as radiant heat boilers for recovering heat from blast furnace slag and basic oxygen furnace slag, but these have never been commercialized. Research could be done to further investigate waste heat losses from solid streams and opportunities for waste heat recovery.

In the case of aluminum sidewall losses, no efforts have been made to recover the heat losses inherent to the Hall-Hèroult manufacturing process. If more efficient methods for aluminum refining cannot be found, perhaps novel methods could be developed for recovering the heat lost through cell walls. For example, thermoelectric or TPV devices could potentially generate electricity from waste heat while frozen cryolite thickness remained constant. In contrast to other RD&D efforts described in this study (which mainly optimize the performance of existing systems), RD&D for nontraditional waste heat sources might require research into new technologies not yet tested in industrial applications.

5.7 Summary of Key Barriers to Waste Heat Recovery

Four opportunity areas for waste heat recovery, each with its concomitant barriers to waste heat recovery, have been discussed. While some of these barriers are specific to the given application, many are cross-cutting across several heat recovery applications. They reduce the effectiveness of existing heat recovery systems and, in some cases, prevent recovery systems from being installed. In this section, key restrictions are presented by cost, heat stream composition, temperature, process- and application-specific constraints, and inaccessibility/transportability of certain heat sources.

1) Costs
   i) Long payback periods - Costs of heat recovery equipment, auxiliary systems, and design services lead to long payback periods in certain applications. Additionally, several industry subsectors with high-quality waste heat sources (e.g., metal casting,) are renowned for small profit margins and intense internal competition for limited capital resources.
   ii) Material constraints and costs - Certain applications require advanced and more costly materials. Costly materials are required for high-temperature streams, streams with high chemical activity, and exhaust streams cooled below condensation temperatures. Overall material costs per energy unit recovered increase as larger surface areas are required for more-efficient, lower-temperature heat recovery systems.

2) Economies-of-Scale – Equipment costs favor large-scale heat recovery systems and create challenges for small-scale operations.
   i) Operation and maintenance costs – Corrosion, scaling and fouling of heat exchange materials lead to higher maintenance costs and lost productivity.

3) Temperature Restrictions
   i) Lack of an end-use – Many industrial facilities do not have an on-site use for low-temperature heat. Meanwhile, technologies that create end-use options (e.g., low-temperature power generation) are currently less developed and more costly.
   ii) Material constraints and costs –
      (a) High temperature – Materials that retain mechanical and chemical properties at high temperatures are costly. Therefore, waste heat is often diluted with outside air to reduce temperatures. This reduces the quality of energy available for recovery.
      (b) Low temperature – Liquid and solid components can condense as hot streams cool in recovery equipment, leading to corrosive and fouling conditions. The additional cost of materials that can withstand corrosive environments often prevents low-temperature recovery.
      (c) Thermal cycling – The heat flow in some industrial processes can vary dramatically and create mechanical and chemical stress in equipment.
   iii) Heat transfer rates- Smaller temperature differences between the heat source and heat sink lead to reduced heat transfer rates and require larger surface areas.

4) Chemical Composition
   i) Temperature restrictions – Waste heat stream chemical compatibility with recovery equipment materials will be limited both at high- and low-temperatures.
   ii) Heat transfer rates – Deposition of substances on the recovery equipment surface will reduce heat transfer rates and efficiency.
   iii) Material constraints and costs – Streams with high chemical activity require more advanced recovery equipment materials to withstand corrosive environments.

iv) Operation and maintenance costs – Streams with high chemical activity that damage equipment surfaces will lead to increased maintenance costs.
v) - Environmental concerns – Waste heat recovery from exhaust stream may complicate or alter the performance of environmental control and abatement equipment.
vi) Product/Process control – Chemically active exhaust streams may require additional efforts to prevent cross-contamination between streams.

5) Application-Specific Constraints
   i) Process-specific constraints – Equipment designs are process-specific and must be adapted to the needs of a given process. For example, feed preheat systems vary significantly between glass furnaces, blast furnaces, and cement kilns.
   ii) Product/ Process control – Heat recovery can complicate and compromise process/quality control systems

6) Inaccessibility/Transportability
   i) Limited space – Many facilities have limited physical space in which to access waste heat streams (i.e., limited floor or overhead space)
   ii) Transportability – Many waste heat gaseous streams are discharged near atmospheric pressure (limiting the ability to transport them to and through equipment without additional energy input).
   iii) Inaccessibility – It is difficult to access and recover heat from unconventional sources such as hot solid product streams (e.g., ingots) and hot equipment surfaces (e.g., sidewalls of primary aluminum cells). Safety and operational demands that require egress/access around/above most melting furnaces, boilers, heaters, and other high temperature equipment.

5.8 Summary of Research, Development, and Demonstration Opportunities for Waste Heat Recovery

In order to promote heat recovery practices, several efforts could be made to reduce system costs, optimize heat exchange materials, heat transfer rates, low-temperature recovery, and available end-uses for waste heat. Opportunities for RD&D that address technology and cost barriers are listed below.

- Low-cost, novel materials – Develop low-cost, novel materials for resistance to corrosive contaminants and to high temperatures.

- Reduce overall costs – Economically scale down heat recovery equipment and reduce relative costs for small-scale operations.

- Easier maintenance – Develop economic recovery systems that can be easily cleaned after exposure to gases with high chemical activity.

- Process improvements – Develop alternative manufacturing processes that generate less waste heat. Or, develop processes that avoid introducing contaminants into process off-gases, thereby enabling easier heat transfer from exhaust gases. Of course, both must retain acceptable product quality and financial returns.

- Gas cleaning – Develop low-cost methods for cleaning exhaust gases.

- Low-temperature recovery – Develop and demonstrate low-temperature heat recovery technologies, including heat pumps and low-temperature electricity generation. Develop new working fluids that can efficiently recover low-temperature heat.

- Alternate end-uses – Develop alternative end-uses for waste heat. In addition to new technologies for power generation, options could include converting waste heat into other transportable forms.

- Improve heat transfer – Develop novel heat exchanger designs with increased heat transfer coefficients, especially in gas-to-gas and gas-liquid heat exchangers.

- Process-specific technologies – Develop process-specific heat recovery technologies that address the unique constraints of various applications.

- Feed preheat systems – Reduce the cost, technical, and product-control challenges of process-specific feed preheating systems (e.g., batch/cullet preheating in the glass industry).

- Recovery from unconventional sources – Evaluate and develop opportunities for recovery from waste heat sources not typically considered for heat recovery. These include recovery equipment for sidewall losses (e.g., in primary aluminum cells, oxygen fired glass furnaces or glass industry forehearths) as well as losses from heated product and byproduct streams (e.g., hot rolled steel, blast furnace slag).

- New recovery technologies – Develop new heat recovery technologies such as solid-state generation.

- Low-cost manufacturing of recovery technologies – Promote low-cost manufacturing techniques for the technologies described above.

6.0 Conclusion

This study evaluated technologies and current waste heat recovery practices in a variety of applications: melting furnaces; boilers; coke ovens, blast furnaces, basic oxygen furnaces, and electric arc furnaces in the steel industry; glass melting furnaces, primary and secondary refining furnaces in the aluminum industry; cement kilns; and ethylene furnaces. The equipment evaluated consumes a total of 8,400 TBtu/yr, or about one third of the energy delivered to industrial facilities.[†] Systems analyzed varied significantly in terms of typical recovery practices. Industrial boilers account for about 70% of the energy analyzed, and these systems typically incorporate heat recovery. Meanwhile, analysis of other processes showed that heat recovery is frequently used with clean gaseous streams in high-capacity furnaces. However, heat recovery is less common in applications that have dirty exhaust streams and/or in small-scale applications. Several furnaces continue operating at efficiencies below 50% due to high exhaust temperatures. Additionally, while this study focused on gaseous exhaust streams, it was concluded that alternate sources of waste heat can be significant and require further investigation. Large quantities of low-temperature waste heat are available in cooling water. Additionally, significant heat is lost from hot equipment surfaces (e.g., aluminum cell sidewalls) and from product streams (e.g., cast steel, blast furnace slag, etc).

Waste Heat Losses

Energy content of waste streams was evaluated based on reference temperatures of 77°F [25°C] and 300°F [150°C]. Calculations based on a 77°F [25°C] reference reflect maximum heat recoverable by cooling heat streams to atmospheric temperatures. The 300°F [150°C] reference reflects the typical practice of cooling exhaust gases to no less than 300°F (150°C) in order to prevent flue gas condensation. Based on a reference temperature of 77°F [25°C], waste heat losses via sensible and latent heat contained in exhaust gases studied in this report are about 1.5 quadrillion Btu/yr. Only about 160 TBtu/yr are estimated as potentially recoverable energy based on a reference temperature of 300°F [150°C].

Work potential based on Carnot efficiency for energy conversion (mechanical or electrical) was also evaluated in order to better compare waste heat with different exhaust temperatures. Based on a 77°F [25°C] ambient reference temperature, the work potential of all the waste heat studied is about 600 TBtu/yr. Despite the very low Carnot efficiency for low-temperature energy conversions, about 75% of the work potential is contained in low-temperature waste heat streams (i.e., at less than 450°F [230°C]). This is a result of the very large mass flow rate of these low-temperature waste heat streams.

Waste Heat Opportunity Areas

Based on trends observed in this study, opportunity areas for waste heat recovery can be grouped as follows:

- *low-temperature waste heat sources,*
- *optimization of existing waste heat recovery systems,*
- *high-temperature systems where heat recovery is less common (chemical composition, material constraints, and cost/economies of scale are key barriers, and*
- *non-fluid sources typically not considered for heat recovery.*

[†] Based on 25 quadrillion Btu of energy consumption, which excludes losses associated with electricity generation. US DOE EIA *Annual Energy Review 2006.*

Waste Heat Recovery Barriers and RD&D Opportunities

Section 5 of this report outlines waste heat recovery barriers and technology opportunities that can promote heat recovery in the opportunity areas listed above. Key restrictions preventing heat recovery in a particular application can include cost, temperature restrictions, chemical composition of heat streams, application-specific constraints, and difficulty accessing and transporting non-fluid heat sources. Challenges for heat recovery under these constraints include material costs, maintenance costs, lack of a local end-use for low-temperature heat, environmental concerns, and the need for process and product quality control.

Table 25 summarizes the RD&D needed to address the various technology barriers determined from this investigation in order to impact significant waste heat recovery. RD&D opportunities encompass both optimizing existing heat recovery technologies, as well as promoting new technologies. Since cost is a key barrier to heat recovery, it is important that any efforts for technology development focus on reducing both the capital and operating costs of heat recovery equipment.

Optimizing Existing Technologies

Although several technologies are already available for heat recovery, constraints listed above may prevent the applicability of technologies to a given waste heat source, or may prevent it from being installed economically. RD&D focused on enhancing existing technologies will extend their applicability to diverse waste heat sources. This includes extending the range of temperatures over which heat recovery can be performed (i.e., including low-temperature heat recovery as well as high-temperature heat recovery), extending the use of heat recovery equipment to processes with high levels of chemical activity, and extending technologies into new applications.

Developing New Technologies

New technologies are emerging as options for heat recovery. An example of a recent technology is the Kalina cycle for low-temperature power generation, which has been successfully demonstrated in some applications and may have increasing relevance for heat recovery. Other technologies such as thermoelectric devices have not yet been tested in industrial applications, but further development could create future opportunities for heat recovery. Moreover, while this study focused on gaseous exhaust streams, further work should be done to investigate unconventional sources of waste heat that are not typically considered for waste heat recovery. Perhaps novel recovery technologies could provide new avenues for improved industrial efficiency.

Table 25 - Summary of RD&D Opportunities and Barriers Addressed -

	Barriers Addressed									
	Long Payback Periods	Material Constraints and Costs	Maintenance Costs	Economies of Scale	Lack of End-use	Heat transfer rates	Environmental Concerns	Process Control and Product Quality	Process-specific Constraints	Inaccessibility
Develop low-cost, novel materials for resistance to corrosive contaminants and to high temperatures		x	x							
Economically scale down heat recovery equipment	x	x		x						
Develop economic recovery systems that can be easily cleaned after exposure to gases with high chemical activity			x	x		x				
Develop novel manufacturing processes that avoid introducing contaminants into off-gases in energy-intensive manufacturing processes		x	x				x	x	x	
Develop low-cost dry gas cleaning systems		x	x			x	x	x		
Develop and demonstrate low-temperature heat recovery technologies, including heat pumps and low-temperature electricity generation		x			x					
Develop alternative end-uses for waste heat					x					
Develop novel heat exchanger designs with increased heat transfer coefficients	x	x				x				
Develop process-specific heat recovery technologies				x		x	x	x	x	x
Reduce the technical challenges and costs of process-specific feed preheating systems	x			x		x		x	x	
Evaluate and develop opportunities for recovery from unconventional waste heat sources (e.g., sidewall losses)									x	x
Promote new heat recovery technologies such as solid-state generation					x					x
Promote low-cost manufacturing techniques for the technologies described above	x	x	x	x	x	x	x	x	x	x

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Appendix A: Documentation for Waste Heat Estimates

A.1 Method for Calculating Flue Gas Waste Heat and Its Work Potential

Background

Figure 1 displays the energy balance for a typical industrial furnace. For most fired systems analyzed in this study, the following assumptions were made: all material flows and energy transfers are at steady state, furnace inputs are at standard temperature and pressure (STP), exhaust gases are at atmospheric pressure, the exhaust gases are ideal gases (with the exception of H2O), the furnace uses 10% excess air, and combustion is complete. Enthalpy of mass streams is measured from a reference of STP.

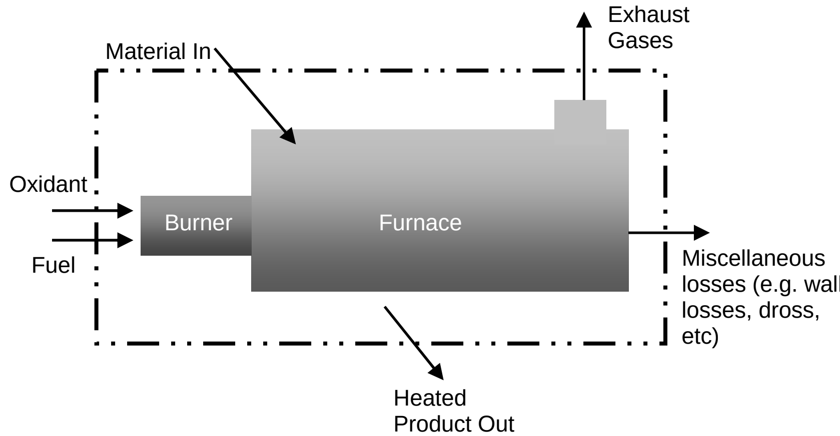

Figure A1. Energy balance in an industrial furnace

The energy balance for the furnace in Figure A1 is given by:

$$E_{in} = E_{ex} + E_p + E_{misc} \tag{A1}$$

Where E_{in} is the energy input, E_{ex} is the energy lost to exhaust gases, E_p is the heat contained in heated products leaving the furnace (e.g. heated metal), and E_{misc} is miscellaneous heat losses such as sidewall losses.

In this analysis, we are interested in quantifying the exhaust gas waste heat loss, E_{ex}, which is a function of the exhaust gas mass flow rate and its enthalpy, which is dependent on the chemical composition and temperature:

$$E_{ex} = \left(\dot{m}\, h(t) \right)_{ex} = \dot{m}_{ex} \sum_i \left(x_i h_i(t) \right)_{ex} \tag{A2}$$

Where $\dot{m}$ is the exhaust gas mass flow rate, h(t) is the gas enthalpy, x_i is the mass fraction of each species in the exhaust gas, and $h_i(t)$ is the enthalpy of each species i in the exhaust. The enthalpy $h_i(t)$ of each species is a function of the temperature (t). The enthalpy $h_i(t)$ of each species can be calculated based on its specific heat capacity and from reference tables. Enthalpy is not an absolute term, but must be measured against a reference state (for example, the enthalpy of a substance at room temperature and atmospheric pressure). In this report, the enthalpy of waste heat streams is calculated at two reference temperatures: 77°F (25°C) and 300°F (149°C). A reference of 77°F was used to provide a basis for estimating the maximum heat attainable if a gas is cooled to ambient temperatures. A reference of 300°F was also used, since the majority of industrial heat recovery systems do not cool below this temperature.

The mass flow rate of exhaust gases and the mass fraction of each species can be determined from fuel consumption and mass balances, based on reaction equations for the combustion of fuel. Therefore, another way to express Equation A2 would be:

$$E_{ex} = \dot{m}_{fuel} \left(\frac{\dot{m}_{ex}}{\dot{m}_{fuel}} \right) \sum_i \left(x_i h_i(t) \right)_{ex} \qquad \text{(A3)}$$

where $\dot{m}_{fuel}$ is the fuel input $\left(\frac{\dot{m}_{ex}}{\dot{m}_{fuel}} \right)$ and is the exhaust gas mass flow rate relative to the fuel input (as determined from the combustion equations).

Finally, the fraction of waste heat loss relative to energy input can be expressed as:

$$\frac{E_{ex}}{E_{in}} = \frac{\dot{m}_{fuel} \left(\frac{\dot{m}_{ex}}{\dot{m}_{fuel}} \right) \sum_i \left(x_i h_i(t) \right)_{ex}}{\dot{m}_{fuel}\, h_c} \qquad \text{(A4)}$$

$$= \frac{\left(\frac{\dot{m}_{ex}}{\dot{m}_{fuel}} \right) \sum_i \left(x_i h_i(t) \right)_{ex}}{h_c} \qquad \text{(A5)}$$

Where h_c is the higher heating value of the fuel.

Based on the equations above, the energy content of exhaust gases can be estimated by determining approximate values for the following parameters:

- Fuel consumption
- Exhaust gas chemical composition and mass flow rate relative to fuel input (calculated based on fuel consumed, assumed quantity of combustion air, and process-specific chemical reactions)
- Exhaust gas temperature
- Enthalpy $h_i(t)$ of each species (calculated)

Approach

1) Estimate fuel consumption

Fuel consumption was estimated based on the approximate energy intensity for different processes (Btu/lb of product), and estimated production values. For example, it is estimated that about 4,500,469 tons of flat glass are produced in regenerative furnaces. These have an average natural gas consumption of about 9 Million Btu/ton (Energetics, *Energy and Environmental Profile of the US Glass Industry*, p. 56. 2002) Therefore, total fuel consumption for regenerative furnaces in the glass industry is about 38 trillion Btu/year. Energy intensity of processes was determined from a literature review.

2) Estimate exhaust gas chemical composition and mass flow rate

Exhaust gas chemical composition

The mass fraction x_i of each species in the exhaust varies for different processes. In applications involving combustion (the majority of cases considered), exhaust gas is calculated based on the assumed composition of the fuel. Assumed compositions of various fuels are listed in Table A1.1 below.

Table A1.1 - Assumed Fuel Composition

				Natural Gas (% volume)	
Carbon	72.00%	Carbon	87.30%	Methane (CH_4)	93.27%
Hydrogen	4.40%	Hydrogen	12.60%	Ethane (C_2H_6)	3.79%
Sulfur	1.60%	Sulfur	0.22%	Propane C_3H_8	0.57%
Oxygen	3.60%	Oxygen	0.04%	Butane C_4H_{10}	0.29%
Nitrogen	1.40%	Nitrogen	0.01%	Nitrogen	1.19%
Water	8.00%	Water	0.00%	Water	0.00%
Ash	9.00%	Ash	0.01%	Carbon Dioxide	0.79%

Source: EPA, 1984. Industrial Waste Heat Recovery and the Potential for Emissions Reduction

The flue gas composition was determined from basic combustion equations. For example, the combustion of methane with 10% excess air is described by:

$$CH_4 + 1.1 * 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 0.2O_2 + 8.272N_2 \quad \text{(A6)}$$

Similar expressions were written for each species in the fuel (e.g. carbon, hydrogen, etc) to calculate the combustion products. Assuming complete combustion and 10% excess air, the approximate flue gas composition for main fuel types is listed in Table A1.2 below.

Table A1.2 - Assumed Exhaust Gas Compositions

Flue Gas Species	Volume %		
	Coal	Oil	Natural Gas
CO2	15.9%	12.9%	9.7%
H2O	7.0%	11.1%	18.7%
SO2	0.1%	0.0%	0.0%
N2	77.0%	76.1%	71.6%

(Based on fuel composition shown in Table A1.1 Calculated assuming complete combustion and 10% excess air)

Exhaust gas mass flow rate

The exhaust gas mass flow rate relative to fuel input is given by:

$$\frac{\dot{m}_{fuel}}{\dot{m}_{ex}} = \frac{\dot{m}_{fuel}}{\dot{m}_{fuel} + \dot{m}_{air}} \qquad \text{(A7)}$$

Where the mass of air is calculated from combustion reaction equations (e.g. equation A6).

3) Estimate exhaust gas temperature

Various processes are carried out at different temperatures; consequently the flue gas temperature varies for different processes. Estimates of typical temperatures were determined from a literature review and interviews with industry experts. Typical temperatures are reported in Table 4 (Section 2) of this report. Additionally, since this report estimates unrecovered waste heat, efforts were also made to estimate temperatures of heat streams exiting heat recovery devices (For example, exhaust temperatures from recuperators in glass furnaces are around 1800°F).

4) Estimate enthalpy, $h_i(t)$, of each species at the given temperature

For ideal gases, the enthalpy $h_i(t)$ of each species is a function of the temperature *(t),* and can be determined from

$$h_i(t) = \int_r^t C_{p,i}(t)dt \qquad \text{(A8)}$$

Where $h_i(t)$ is the enthalpy of the given species at the specified temperature t, r is the reference temperature (either 77°F and 300°F in this analysis), and $C_{p,I}$ is the specific heat capacity of the species as a function of temperature. Equations for the specific heat of different substances can be found in various tables, such as that shown in Table A1.3.

Table A1.3 - Ideal-gas Specific Heats of Various Gases as a Function of Temperature

Substance	Formula	$C_p=a+bt+Ct^2+dT^3$ (T in K, Cp in kJ/kmol, K)				Range (K)	% Error	
		a	b	c	d		Max	Avg.
Nitrogen	N_2	28.9	-1.57E-03	8.08E-06	-2.87E-09	273-1800	0.59	0.34
Oxygen	O_2	25.48	1.52E-02	-7.16E-06	1.31E-09	273-1800	1.19	0.28
Carbon Dioxide	CO_2	22.26	5.98E-02	-3.50E-05	7.47E-09	273-1800	0.67	0.22
Water Vapor	H_2O	32.24	1.92E-03	1.06E-05	-3.60E-09	273-1500	0.53	0.24
Sulfur Dioxide	SO_2	25.78	5.80E-02	-3.81E-05	8.61E-09	273-1800	0.45	0.24

Source: B.G. Kyle, 1984, *Chemical and Process Thermodynamics*

In the case of water vapor, which does not follow ideal gas behavior at lower temperatures, the enthalpy was determined from steam tables. The steam tables contain estimates of enthalpy at various temperatures and pressures. The partial pressure of water vapor was used, which was determined from the estimated molar fraction of water vapor in the flue gas and by assuming the flue gas is at atmospheric pressure.

A.2 *Calculation of Waste Heat Losses in Different Applications*

Glass Industry

Table A2.1 - Assumptions Used for Calculating Glass Melting Energy Consumption and Exhaust Gas Waste Heat Losses

		Production (tons/year)[a]	Natural Gas (10^6 Btu/ton)[a]	Net Electricity (10^6 Btu/ton)[b]	Fossil Fuel Consumption (TBtu)	Assumed Average Exhaust Temperature[c]	
						°F	°C
Glass							
Flat Glass		5,000,521					
	Regenerative	4,500,469	9	0	38	800	427
	Electric Boost	500,052	6	1	3	800	427
Container Glass		9,586,500					
	Regenerative	1,437,975	8	0	11	800	427
	Electric Boost	5,751,900	5	1	27	800	427
	Oxy-Fuel	1,917,300	4	1	8	2,600	1,427
	Electric Melter	479,325	-	3			
Pressed and Blown Glass		2,484,182					
	Regenerative	645,887	6	ND	4	800	427
	Direct Melter	844,622	12	ND	10	2,400	1,316
	Oxy-Fuel	869,464	4	ND	3	2,600	1,427
	Electric Melter	124,209	-	10			
Insulation Fiber		1,915,200					
	Electric Melter	1,436,400	-	8			
	Recuperative Melter	402,192	7	-	3	1,800	982
	Oxy-Fuel	76,608	6	-	0	2,600	1,427
Textile Fiber		1,124,800					
	Recuperative Melter	1,079,808	10	-	11	1,800	982
	Oxy-Fuel	44,992	6	-	0	2,600	1,427
Total		20,111,203			118		

a. Energetics 2002, Energy and Environmental Profile of the US Glass Industry. p. 56

b. Energetics 2002, p. 56. Based on conversion factor of 3412 Btu/kWh. Does not include electricity-related losses.

c. Exhaust temperatures from regenerative, recuperative, and direct melters based on temperatures reported by Ross, 2004. *Glass Melting Technology: A Technical and Economic Assessment*, p. 185, Exhaust temperatures from oxyfuel furnaces based on temperatures reported by BCS 2006, *Engineering Scoping Study of Thermoelectric Generator Packages for Industrial Waste Heat Recovery, p. 28*

Table A2.2 - Estimated Exhaust Gas Waste Heat Losses from Glass Melting Furnaces

		% Fuel input lost as waste heat[a] 77°F Reference	% Fuel input lost as waste heat[a] 300°F Reference	Waste Heat Loss (TBtu/Year)[b] 77°F Reference	Waste Heat Loss (TBtu/Year)[b] 300°F Reference	Carnot Efficiency	Maximum Work Potential (TBtu/Year)[c] 77°F Reference
Glass							
Flat Glass							
	Regenerative	29%	12%	11.00	4.74	57%	6.31
	Electric Boost	29%	12%	0.82	0.35	57%	0.47
Container Glass							
	Regenerative	29%	12%	3.10	1.34	57%	1.78
	Electric Boost	29%	12%	7.77	3.35	57%	4.46
	Oxy-Fuel	36%	23%	2.78	1.79	82%	2.29
	Electric Melter						
Pressed and Blown Glass							
	Regenerative	29%	12%	1.02	0.44	57%	0.59
	Direct Melter	74%	57%	7.48	5.82	81%	6.08
	Oxy-Fuel	36%	23%	1.13	0.73	82%	0.93
	Electric Melter						
Insulation Fiber							
	Electric Melter						
	Recuperative Melter	56%	40%	1.58	1.12	76%	1.20
	Oxy-Fuel	36%	23%	0.16	0.10	82%	0.13
Textile Fiber							
	Recuperative Melter	56%	40%	6.05	4.28	76%	4.62
	Oxy-Fuel	36%	23%	0.09	0.06	82%	0.08
Total				42.99	24.11		28.94

a. Based on calculations described in section A.1. Percentage is reported as a percent of natural gas input, not total energy input.
b. Based on fuel consumption reported in Table A 1.
c. Maximum work obtainable from a heat engine operating between the combustion exhaust temperature and ambient temperature (77°F)

Cement Kilns

Table A2.3 - Assumptions Used for Calculating Cement Kiln Energy Consumption and Exhaust Gas Waste Heat Loss

	% US Production[a]	Clinker Production (tons/year)[b]	Fossil Fuel Consumption (10^6 Btu/ton)[a]	Fossil Fuel Consumption (TBtu/year)	CO_2 Emissions from Chemical Reaction (tons CO_2/ton Clinker)[c]	Assumed Average Exhaust Temperature[d] °F	Assumed Average Exhaust Temperature[d] °C
Cement							
Wet Kiln	20%		5.2	98.0		640	338
Dry Kiln	80%	18,804,158 77,575,552	3.8	291.5	0.589 0.589		
No Preheater	18%		4.6	80.2		840	449
Preheater	19%	17,362,947	3.7	67.8		640	338
Precalciner	43%	18,540,746	3.4	143.4		640	338
Total	100%	96,320,310		389.5			

a. Portland Cement Association, 2002., *US and Canadian Labor-Energy Input Survey*, 2000 Survey, p. 12-26

b. Determined by multiplying % US Production in 2000 by total production in 2005. 2005 data from Van Oss, 2007, *Cement US Geological Survey Minerals Yearbook 2005.*

c. BCS, 2003. *Energy and Emission Reduction Opportunities for the Cement Industry*, p.A4.. CO_2 gases from clinker reactions were included in estimates of exhaust gas composition and flow rate in order to calculate waste heat loss.

d. Exhaust temperatures for dry kiln with preheater and no preheater based on Peray, 1986. *The Rotary Cement Kiln*, p. 10.

e. Exhaust temperature for wet kiln and precalciner kiln were assumed to be the same as a preheater kiln.

Table A2.4 - Estimated Exhaust Gas Waste Heat Losses From Cement Kilns

	% Fuel input lost as waste heat[a]	% Fuel input lost as waste heat[a]	Waste Heat Enthalpy (TBtu/Year)[b]	Waste Heat Enthalpy (TBtu/Year)[b]	Carnot Efficiency	Maximum Work Potential (TBtu/Year)[c]
	77°F Reference	300°F Reference	77°F Reference	300°F Reference		
Cement						
Wet Kiln	19%	10%	18.8	9.4	51%	9.65
Dry Kiln						
No Preheater	26%	16%	20.6	12.8	59%	12.09
Preheater	20%	10%	13.9	7.0	51%	7.11
Precalciner	21%	11%	29.7	15.1	51%	15.23
Total			83.1	44.3		44.08

a. Based on calculations described in Section A.1. Since cement production also produces CO_2 via chemical reactions (about 0.6 Btu/ton), these additional emissions were included in calculations of exhaust gas enthalpy. The calculated percent waste heat lost by wet kilns, preheat kilns, and precalciner kilns varies slightly though these processes were assumed to have the same exhaust temperature. This is because each process has a different average energy consumption, and therefore the ratio of fuel-related emissions to reaction-related emissions varies. Varying exhaust gas chemical composition lead to varying estimates of gas enthalpy.

b. Based on energy consumption in Table A 3.

c. Maximum work obtainable from a heat engine operating between the combustion exhaust temperature and ambient temperature (77 F)

Iron and Steel Manufacturing

Assumptions and calculations for waste heat losses in iron and steel manufacturing are included below. For coke oven waste gas and hot blast stove exhaust gas, calculations of waste heat losses were performed using methods described in Appendix A.1. For coke oven gas, blast furnace gas, basic oxygen furnace gas, and electric arc furnace gas, the chemical composition of exhaust gases could not be calculated by simply assuming complete combustion of fuel sources. Therefore, estimates of exhaust gas composition, flow rate, and waste heat losses were based on data reported in published literature.

Table A2.5 - Assumptions for Calculating Energy Consumption and Waste Heat Losses in Iron and Steel Manufacturing

	Production (tons steel/year)[a]	Net Energy Consumption (10^6 Btu/ton)[b]	Net Energy Consumption (TBtu/year)	Assumed Average Exhaust Temperature[i]	
				°F	°C
Steel	104,579,800				
Integrated Steel Mills	56,473,092				
Coke Ovens	56,473,092	1.16[c]	66		
Coke Oven Gas	56,473,092			1,800	980
Waste Gas	56,473,092			392	200
Blast Furnace	56,473,092	11.31[d]	642		
Blast Furnace Gas	56,473,092			200	430
Blast Stove	56,473,092	1.24[e]	70		
Blast Stove Exhaust -No Recovery	28,236,546			482	250
Blast Stove Exhaust - With Recovery	28,236,546			266	130
Basic Oxygen Furnace	56,473,092	0.82[f]	50	3,100	1,700
Mini Mills	38,485,366				
Electric Arc Furnace	48,106,708				
No Scrap Preheat	38,485,366	1.50[g]	58	2,200	1,200
With Scrap Preheat	9,621,342	1.39[h]	13	400	204

a. Total steel production from USGS *2005 Minerals Yearbook: Iron and Steel*. p. 38.5 2007. It was assumed that integrated steel mills are responsible for 54% of steel production, based on Energetics, 2000, *Energy and Environmental Profile of the US Iron and Steel Industry. p. 3.* Also assumed 50% of blast stoves include heat recovery.

b. Values do not include electricity-related losses. Values include credit for recovered fuel.

c. Freuhan, p. 16

d. Energetics, p. 6. Value initially reported per ton of pig iron. Converted to tons of steel assuming 1000 kg steel produced for every 940 kg pig iron. Based on data reported by PCC, B*est Available Techniques Reference Document on the Production of Iron and Steel*. p. 176. 2001.

e. Energetics, p. 45. 10-12% of blast furnace energy consumption is in the hot blast stove.

f. Energetics, p. 12.

g. Energetics, p. 62.

h. Energetics, p. 64. Scrap preheat saves from 5-10% of power input.

i. See temperatures listed in Table A 8.

Table A2.6 - Estimated Exhaust Gas Waste Heat Losses from Selected Processes in Iron and Steel Manufacturing

	Waste Heat (TBtu/yr)	Waste Heat (10^12 Btu/Year)	Carnot Efficiency	Maximum Work Potential (10^12 Btu/Year)c
Integrated Steel Mills				
Coke Ovens				
Coke Oven Gas[a]	15.8	13.9	76%	12.1
Waste Gas[b]	11.2	10.0	37%	4.1
Blast Furnace				
Blast Furnace Gas[c]	5.3	-	19%	1.0
Blast Stove Exhaust[a]				
No Recovery	10.6	1.9	43%	4.6
With Recovery	3.2	-	26%	0.8
Basic Oxygen Furnace[d]	27.1	26.0	85%	23.0
Electric Arc Furnace[e]				
No Recovery	5.3	4.9	80%	4.2
With Recovery	0.1	0.1	38%	0.1
Mini Mills				
Electric Arc Furnace				
No Scrap Preheat	5.8	5.4	80%	4.6
With Scrap Preheat	0.2	0.1	38%	0.1
Total	85	62		57

a. Based on estimates shown in Table A2.9.
b. Based on calculations described in Section A.1
c. Based on estimates shown in Table A2.10
d. Based on estimates shown in Table A2.11
e. Based on estimates shown in Table A2.12

Table A2.7 - Assumed Composition of Exhaust Gases in Iron and Steel Manufacturing

	Hydrogen (H_2)	Carbon Monoxide (CO)	Carbon Dioxide (CO_2)	Nitrogen (N_2)	Methane (CH_4)	Ethane (C_2H_6)	H_2O
Coke Oven							
Coke Oven Gas[a]	52%	4%	2%	-	37%	5%	-
Coke Oven Waste Gas[b]			8%	70%			22%
Blast Furnace Offgas[c]			8%				
Blast Furnace Gas[c]	3%	26%	21%	50%	-	-	-
Hot Blast Stove Offgas[d]			26%	68%			5%
Basic Oxygen Furnace Gas[e]		73%	16%	8%	-	-	-
Electric Arc Furnace OffGas[f]	11%	18%	14%	57%	-	-	-

a. Based on COG composition reported in IPCC, Best Available Techniques Reference Document on the Production of Iron and Steel. p. 116. 2001.
b. Calculated, based on complete combustion of coke oven gas.
c. IPCC, p. 176.
d. Calculated, based on complete combustion of blast furnace gas enriched with coke oven gas.
d. IPCC, p. 233
e. CO_2, CO and H_2 concentrations 3% based on Allendorf et. al., 2003, Final Report: Optical Sensors for Post Combustion Control in Electric Arc Furnace Steelmaking. Assumed remaining exhaust gas composition consists of N_2

Table A2.8 - Assumed Average Exhaust Temperature of Exhaust Gases in Iron And Steel Manufacturing

Source	Assumed Average Exhaust Temperature °F	Assumed Average Exhaust Temperature °C
Coke Oven		
Coke Oven Gas[a]	1,800	980
Coke Oven Waste Gas[b]	392	200
Blast Furnace		
Blast Furnace Gas[c]	200	430
Hot Blast Stove Off-gas		
No Heat Recovery[d]	482	250
With Heat Recovery[e]	266	130
Basic Oxygen Furnace[f]	3,100	1,700
Electric Arc Furnace		
With Scrap Preheat[g]	2,200	1,200
No Scrap Preheat[h]	400	204

a. Rorick, F. 2007. personal communication.
b. Bisio, G and Rubatto, G. 1998, "Energy Saving and some Environment Improvements in Coke-Oven Plants," Energy Volume 25. p. 249.
c. Obenchain, W, 2007, personal communication.
d. Canada Centre for Mineral and Energy Technology (CANMET) Present and Future Use of Energy in the Canadian Steel Industry. p. 65. 1997
e. Lin, P. and Wang, P. *Efficiency Improvement of the Hot Blast Generating System by Waste Heat Recovery*. p. 116
f. Energetics, 2000, *Energy and Environmental Profile of the U.S. Iron and Steel Industry*. p. 55.
g. CANMET, p. 134.
h. Electric Power Research Institute (EPRI), 1997, Center for Materials Production, "Electric Arc Furnace Scrap Preheating." p. 1.

Table A2.9 - Estimate of Coke Oven Gas Waste Heat

Coke Oven Gas Waste Heat Calculations		
Coke Oven Gas Enthalpy[a]		
(77°F Reference)	1,501	Btu/lb COG
(300°F Reference)	1,319	Btu/lb COG
Production rates:		
Coke Oven Gas Production (per ton coke)[b]	0.24	ton COG/ton coke
Pig Iron Production[c]	2.43	ton pig iron/ton coke
Steel Production[d]	1.06	ton steel/ton pig iron
Coke Oven Gas Production (per ton steel)	0.09	ton COG/ton steel
Waste Heat Loss		
(77°F Reference)	0.28	10^6 Btu/ton steel
(300°F Reference)	0.25	10^6 Btu/ton steel

a. Based on assumed chemical composition and temperature listed in Tables A 7 and A 8.
b. IPCC *Best Available Techniques Reference Document on the Production of Iron and Steel*, p. 114. 2001.
c. Energetics, 2000, *Energy and Environmental Profile of the U.S. Iron and Steel Industry*, p. 41
d. IPCC, p.122

Table A2.10 - Estimate of Blast Furnace Gas Waste Heat

Blast Furnace Gas Waste Heat Calculations		
Flue Gas Enthalpy[a]		
(77°F Reference)	23	Btu/lb gas
(300°F Reference)	-	Btu/lb gas
Production rates:		
Blast Furnace Gas Production (per ton pig iron)[b]	4,369	lb gas/ton pig iron
Liquid Steel Production[c]	1.06	ton steel /ton pig iron
Blast Furnace Gas Production (per ton steel)	4,107	lb gas/ ton steel
Waste Heat Loss		
(77°F Reference)	0.09	10^6 Btu/ton steel
(300°F Reference)	-	10^6 Btu/ton l steel

a. Based on assumed chemical composition and temperature listed in Tables A 7 an d A 8.
b. IPCC, *Best Available Techniques Reference Document on the Production of Iron and Steel*, p. 176. 2001 .Based on gas production rate 1600 Nm^3/metric ton of pig iron, and on chemical composition in Table A 5.
c. IPCC, p.122

Table A2.11 - Estimate of Basic Oxygen Furnace Off-gas Waste Heat

Basic Oxygen Furnace Off-gas Waste Heat Estimate		
Flue Gas Enthalpy[a]		
(77°F Reference)	2409	Btu/lb gas
(300°F Reference)	93	Btu/lb gas
Production Rate		
BOF Gas Production[b]	199.15	lb gas/ ton liquid steel
Waste Heat Loss		
(77°F Reference)	0.48	10^6 Btu/ton liquid steel
(300°F Reference)	0.46	10^6 Btu/ton liquid steel

a. Based on assumed chemical composition and temperature listed in Tables A 7 and A 8.

b. IPCC *Best Available Techniques Reference Document on the Production of Iron and Steel*, p. 1233. 2001.

Table A2.12 - Estimate of Electric Arc Furnace Off-gas Waste Heat

Electric Arc Furnace Off-gas Waste Heat Estimate[a]		
Without Scrap Preheat		
Average Power Input to Furnace[b]	1.5	10^6 Btu/ton steel
Percent of Power Input Lost in Off-gas[c]	20%	
Percent of Offgas Losses Consisting of Sensible Heat[c]	50%	
Average Waste Heat Loss		
77°F Reference[e]	0.15	10^6 Btu/ton steel
300°F Reference[f]	0.14	10^6 Btu/ton steel
With Scrap Preheat		
Average Energy Input to Furnace[g]	1.388	10^6 Btu/ton steel
Average Waste Heat Loss		
77°F Reference f	0.02	10^6 Btu/ton steel
300°F Reference f	0.01	10^6 Btu/ton steel

a. Due to the high variation electric arc furnace off-gas composition, temperature, and off-gas flow rate, waste heat estimates were not calculated using the same methods listed previously. Instead, estimates are simply based on common industry estimates that 20% of furnace inputs are lost as waste heat. The fraction of sensible heat loss, and the ratio of losses for different exhaust temperatures and different reference states were estimated based on an assumed average chemical composition shown in table letter.

b. Based on energy input reported by Energetics, 2000, *Energy and Environmental Profile of the US Iron and Steel Industry*, p. 63. Value includes electricity consumption, but not the primary fuels used for generating electricity..

c. Freuhan 1998, The Making, Shaping, and Treating of Steel, AISE Steel Foundation, p. 605

e. Based on average energy input and typical percent energy losses.

f. The assumed off-gas chemical composition was used to estimate the ratio between calculated gas enthalpy at different temperatures. Estimated heat loss at 2,200°F with a 77°F reference was used to calculate heat loss at other exhaust temperatures.

g. Energetics, p. 64. Scrap preheating reduces energy consumption about 10%.

Aluminum Melting

Table A2.13 - Assumptions Used for Calculating Aluminum Melting Energy Consumption and Exhaust Gas Waste Heat Loss

	Production (tons/year)[a]	Energy Consumption (10^6 Btu/ton)[b]	Energy Consumption adjusted for yield, (10^6 Btu/ton)[c]	Energy Consumption (TBtu/Year)	Assumed Average Exhaust Temperature[d]	
					°F	°C
Primary Aluminum Melting	2,734,062	48.2	49.2	134.6	1292	700
Secondary Al Refining Furnaces	3,294,980					
No Heat Recovery	2,471,235	3.6	3.8	9.3	2100	1150
With Recovery	823,745	2.6	2.7	2.2	1000	538
Total	6,029,042	54.4	55.7	146.1		

a. Total primary and secondary aluminum production from Patricia A Plunkert, 2007. USGS Mineral Commodity Summaries 2007. Year 2006 estimate. Percent of secondary furnaces using waste heat recovery based on personal communication with Rooy, E., indicating 1/3 of furnaces with capacities over 40,000 lbs use waste heat recovery. In order to account for less waste heat recovery in smaller furnaces, assumed only 25% of all secondary furnaces use waste heat recovery.

b. Energy consumption in primary aluminum refining from BCS, 2003, *US Requirements for Aluminum Production: Historical Perspective, Theoretical Limit sand New Opportunities.* Tables F-1 and F-2.. Value does not include electricity-related losses. Secondary aluminum specific energy for systems with and without heat recovery from Li, T. "Performance of secondary aluminum melting: Thermodynamic analysis and plant-site experiments." *Energy* 31. p. 1770. 2006.

c. BCS 2003, Table F2. Yield for primary ingot casting is about 98%, secondary casting is about 96%. (Note, yield for shape casting is significantly lower, but accounted for in metal casting calculations (Table A 16).

d. Primary aluminum melting temperature from BCS 2003, p.27. Secondary aluminum temperature from Wechsler, T. and Gitman, G. "Use of the Pyretron Variable Ratio Air/Oxygen Fuel/Burner System for Aluminum Melting," *Aluminum Industry Energy Conservation Workshop XI Papers.* The Aluminum Association. p. 273. 1990.

Table A2.14 - Estimated Off-gas Waste Heat Loss from Primary and Secondary Aluminum Melting

	% Fuel input lost as waste heat[a]	% Fuel input lost as waste heat[a]	Waste Heat Enthalpy (TBtu/Year)[b]	Waste Heat Enthalpy (TBtu/Year)[b]	Carnot Efficiency	Maximum Work Potential (TBtu/Year)[c]
	77°F Reference	300°F Reference	77°F Reference	300°F Reference		77°F Reference
Primary Aluminum Melting	2%	2%	2.6	2.2	69%	1.80
Secondary Al Refining Furnaces						
No Heat Recovery	66%	45%	6.1	4.2	79%	4.8
With Recovery	34%	16%	0.8	0.4	0.6	0.5
Total			9.5	6.7		7.1

a. Waste heat losses from secondary melting furnaces were calculated using methods described in A 1.. For primary aluminum, see Table A2.15.
b. Based on energy consumption in Table A 13.
c. Maximum work obtainable from a heat engine operating between the combustion exhaust temperature and ambient temperature (77°F)

Table A2.15 - Estimate of Primary Aluminum Cell Waste Heat

Primary Aluminum Melting Off-gas and Sidewall Waste Heat Estimate		
Primary Aluminum Production[a]	2,734,062	tons/year
Offgas Waste Heat Estimate:		
CO_2 emissions per unit aluminum[b]	1.22	tons CO_2/ton aluminum
CO_2 Enthalpy at 1,292ºF		
77ºF Reference	312	Btu/lb CO_2
300ºF Reference	264	Btu/lb CO_2
Off-gas waste heat loss[c]		
77ºF Reference	2.6	TBtu/year
300ºF Reference	2.2	TBtu/year
Sidewall Waste Heat Estimate:		
Energy Consumption[d]	134.6	TBtu/year
Percent Sidewall Losses[e]	45%	
Sidewall Losses	61	TBtu/year
Carnot	69%	
Work Potential	42	TBtu/year

a. Patricia A Plunkert, 2007. USGS Mineral Commodity Summaries 2007. Year 2006 estimate
b. BCS, 2003., US Requirements for Aluminum Production: Historical Perspective, Theoretical Limits and New Opportunities, Table E-4
c. Calculated from aluminum production, CO_2 emissions rate, and CO_2 enthalpy
d. Based on estimates in Table A 13
e. Burkin, A.R. 1987, *Production of Alumina and Aluminum* Chichester: John Wiley & Sons. p. 63.

Metal Casting Melting Furnaces

Table A2.16 - Assumptions for Calculating Energy Consumption and Off-gas Waste Heat Losses in Selected Metal Casting Furnaces

	Production (tons/year)[b]	Estimated Percentage of Production (%)[c]	Production (tons/year)	Energy Consumption (10^6 Btu/ton)[b]	Energy Consumption adjusted for yield (10^6 Btu/ton)[d]	Energy Consumption (TBtu/Year)	Assumed Average Exhaust Temperature[e]	
							F	C
Aluminum	2,633,613							
Reverberatory Furnace		90%	2,370,252	3.61	8.03	19.0	2100	1150
Stack Melter		10%	263,361	1.95	4.33	1.1	325	160
Iron Cupola[a]	6,076,119							
Low efficiency cupola		80%	4,860,895	5.76	9.6	46.7	1650	900
High efficiency cupola		20%	1,215,224	3.84	6.4	7.8	400	204

a. Schifo, J., 2004. Theoretical/Best Practice Energy Use in Metalcasting Operations, p. 28. Paper describes two types of cupolas: high efficiency and low-efficiency cupolas. Approximately 20% of cupolas can be approximated as "high efficiency". It is assumed that all high efficiency cupolas include a recuperative air preheat system.

b. Secondary aluminum production based on ratio of shape casting to total production reported by BCS, 2003. *US Requirements for Aluminum Production: Historical Perspective, Theoretical Limits and New Opportunities.* Tables A2. 2003. Current aluminum production data from Plunkert, P., 2007.USGS Mineral Commodity Summaries: Aluminum. Year 2006 estimate. Iron cupola production data from Schifo, p. 30.

c. Schifo, pp. 30-39.

d. Assumes 45% yield for aluminum casting, based on BCS 2003, Table F2, and 60% in iron casting, based on Schifo, p. 30.

3. Secondary aluminum temperature without heat recovery from Wechsler, T. and Gitman, G. 1990, "Use of the Pyretron Variable Ratio Air/Oxygen Fuel/Burner System for Aluminum Melting." *Paper presented at the Aluminum Industry Energy Conservation Workshop XI*. Jacksonville Florida November 1990. Stack melter exhaust temperature from Schifo, p. 40. Iron cupola exhaust temperatures from personal communication with Eppich, B. Eppich Technologies.

Table A2.17 - Estimated Off-gas Waste Heat Losses in Selected Metal Casting Furnaces

	% Fuel input lost as waste heat[a]	% Fuel input lost as waste heat[a]	Waste Heat Loss (TBtu/Year)[b]	Waste Heat Loss (TBtu/Year)[b]	Carnot Efficiency	Maximum Work Potential (TBtu/Year)[c]
	77°F Reference	300°F Reference	77°F Reference	300°F Reference		77°F Reference
Aluminum						
Reverberatory Furnace	66%		12.5	8.5	79%	988%
Stack Melter	15%	0%	0.2	-	24%	4%
Iron Cupola[a]						
Low efficiency cupola	41%	33%	19.3	15.3	75%	14.4
High efficiency cupola	11%45%	2%	0.8	0.2	38%	0.3

a. Based on calculations described in Section A.1.
b. Based on fuel consumption reported in Table A 16.
c. Maximum work obtainable from a heat engine operating between the combustion exhaust temperature and ambient temperature (77 F)

Table A2.18 - Assumptions Used for Calculating Industrial Boiler Exhaust Gas Waste Heat Loss

	Assumed Fraction of Total Capacity	Energy Consumption (TBtu/year)	Assumed Average Exhaust Temperature	
	%		°F	°C
Industrial Boilers		6,500		
No Heat Recovery[a]	25%	1,625	500	260
With Heat Recovery[a]	75%	4,875		
Conventional Fuels[b]	38%	2,438	300	150
Byproduct Fuels	38%	2,438	350	177

a. Assumes 75% of boiler capacity includes economizers. Based on conversations with boiler manufacturers, economizers are more common for large capacity units (e.g. greater than 25 MM Btu/hr), while less common for smaller capacity units. An ORNL study indicates that U.S. boiler capacity is heavily dominated by large units greater than 50 MM Btu/hr, as shown in Table A 19. (ORNL, 2005, *Characterization of the U.S. Industrial/Commercial Boiler Population* p. 2-2.). Therefore, 75% was chosen as a reasonable representation of waste heat recovery practice.

b. Approximately 1/2 of boilers use byproduct fuels, according to ORNL, p. 2-5. It was assumed that byproduct fuels will require higher final exhaust temperatures compared to conventional fuels. Final temperature estimates for economizers with conventional and byproduct fuels based on BCS, 2006. *Engineering Scoping Study of Thermoelectric Generator Packages for Industrial Waste Heat Recovery*, p. 28 and Stultz, S, and Kitto, J.B. ed., 1992. *Steam: its Generation and Use*. Barberton, Ohio: The Babcock & Wilcox Company. p. 26-5.

Table A2.19 - Boiler Capacity Estimates

Boiler Size (Million Btu/hr)	Total Capacity (Million Btu/hr)	Percent of Total Capacity
<10	102,305	7%
10-50	277,810	19%
50-100	243,125	16%
100-250	249,135	17%
>250	616,210	41%
	1,488,585	100%

Source: ORNL, 2005, *Characterization of the U.S. Industrial/Commercial Boiler Population* p. 2-20

Table A2.20 - Estimated Exhaust Gas Waste Heat Losses in Industrial Boilers

	% Fuel input lost as waste heat[a]	% Fuel input lost as waste heat[a]	Waste Heat Loss (TBtu/Year)[b]	Waste Heat Loss (TBtu/Year)[b]	Carnot Efficiency	Maximum Work Potential (TBtu/Year)[c]
	77°F Reference	300°F Reference	77°F Reference	300°F Reference		77°F Reference
Boilers						
No Heat Recovery	21%	4%	347.7	73.0	44%	153.2
With Heat Recovery						
Conventional Fuels	16%	0%	394.3		30%	116.5
Byproduct Fuels	18%	1%	427.8	27.0	34%	144.4

a. Based on calculations described in section A.1.
b. Based on fuel consumption reported in Table A 18
c. Maximum work obtainable from a heat engine operating between the combustion exhaust temperature and ambient temperature (77°F)

Appendix B: Status of Conventional and Emerging Waste Heat Technologies

Table 10 from Section 3 is shown below and describes the status of different waste heat recovery technologies in selected applications. The commercialization status, technical feasibility, and economic feasibility of different recovery technologies in different applications are represented via different symbols. A "+" for commercial, technical, and economic status indicates that the technology is frequently used, has no technical barriers, and is cost-effective. Meanwhile, a "-" under commercial, technical, and economic status indicates that the system is not deployed, not technically feasibly, or cost prohibitive. The tables on subsequent pages provide notes explaining the rationale for the "score" assigned each technology.

	Iron/Steel																	
	Coke Oven						Blast Furnace						BOF			EAF		
	Coke Oven Gas			Waste Gas			Blast Furnace Gas			Hot Blast Stove Exhaust			Basic Oxygen Furnace Gas			Electric Arc Furnace Offgas		
	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic
Regenerator	-	-	-	+	+	+	-	-	-	n	n	-	x	x	x	x	x	x
Recuperator	-	-	-	n	-	-	-	-	-	n	n	-	x	x	x	x	x	x
Heat Wheel	-	-	-	n	m	-	n	n	n	+	+	+	x	x	x	x	x	x
Passive Air Preheater	-	-	-	-	o	o	n	n	n	+	+	+	x	x	x	x	x	x
Thermal Medium System	o	o	-	n	m	-	n	n	n	+	+	+	n	n	n	n	n	n
Waste Heat Boiler	-	-	-	-	-	-	n	-	n	n	-	-	o	+	o	n	-	n
Low T Power Cycle	-	-	-	n	m	-	-	n	n	-	m	n	x	x	x	x	x	x
Solid State Generation	-	-	-	-	m	-	-	-	-	-	m	-	-	-	-	-	-	-
Load preheat																+	+	o
Process Specific/Other2	o	o	-	o	o	-	o	+	-									

	Glass Industry						Cement			Aluminum						Metal Casting			Cross-cutting		
	Glass Melting																				
	Gas-fired Melting Furnace			Oxyfuel Melting Furnace			Cement Kiln			Hall-Heroult Cells			Melting Furnaces			Iron Cupola			Steam Boiler		
	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic	Commercial	Technical	Economic
Regenerator	+	+	o	-	o	-	n	n	n	-	-	-	+	+	o	n	n	n	-	+	-
Recuperator	+	+	+	-	o	-	n	n	n	-	-	-	+	+	o	+	+	+	+	+	+
Heat Wheel	o	o	-	n	o	-	n	n	n	-	-	-	o	+	o	n	n	n	+	+	+
Passive Air Preheater	n	n	n	-	o	-	n	n	n	-	-	-	n	n	n	n	n	n	+	+	+
Thermal Medium System	n	n	n	n	n	n	n	n	n	-	-	-	n	n	n	n	n	n	+	+	+
Waste Heat Boiler	o	+	-	o	+	-	+	+	+	-	-	-	n	n	n	n	n	n	x	x	x
Low T Power Cycle	x	x	x	x	x	x	o	+	o	-	-	-	x	x	x	n	n	n	-	m	n
Solid State Generation	-	m	-	-	m	-	-	m	-	-	m	-	-	m	-	-	m	-	-	m	-
Load preheat	n	m	n	o	o	o	+	+	+	n	n	n	+	+	o				+	+	+
Process Specific/Other2							+	+	+												

1. This table is reproduced in Appendix B with detailed notes

2. "Process-specific" includes coal moisture control for coke making, dry-type top pressure recovery turbines for blast furnaces, and recovery from cement clinker cooler.

Key:	Commercialization Status	Technical Feasibility	Economic Feasibility
	+ Frequently used in US	+ No technical barriers	+ Cost-effective
	o Limited commercialization	o Proven in limited applications	o Application-specific
	- Not deployed	m May be feasible, but not demonstrated	- Cost-prohibitive
		- Not technically feasible	
	n Not addressed in available literature		
	x Not applicable		

Table B1 - Status of Waste Heat Recovery Technologies in the Iron and Steel Industries

	Iron/Steel																							
	Coke Oven								Blast Furnace								BOF				EAF			
	Coke Oven Gas				Waste Gas				Blast Furnace Gas				Hot Blast Stove Exhaust				Basic Oxygen Furnace Gas				Electric Arc Furnace Offgas			
	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes
Regenerator	-	-	-	1	+	+	+	6	-	-	-	10	n	n	-	13	x	x	x	16	x	x	x	16
Recuperator	-	-	-	1	n	-	-	7	-	-	-	10	n	n	-	13	x	x	x	16	x	x	x	16
Heat Wheel	-	-	-	1	n	m	-	7	n	n	n	11	+	+	+	14	x	x	x	16	x	x	x	16
Passive Air Preheater	-	-	-	1	-	o	o	8	n	n	n	11	+	+	+	14	x	x	x	16	x	x	x	16
Thermal Medium System	o	o	-	2	n	m	-	7	n	n	n	11	+	+	+	14	n	n	n		n	n	n	
Waste Heat Boiler	-	-	-	3	-	-	-	9	n	-	n	10	n	-	-	13	o	+	o	17	n	-	n	
Low T Power Cycle	-	-	-	1	n	m	-	7	-	n	n	11	-	m	n	15	x	x	x	18	x	x	x	18
Solid State Generation	-	-	-	4	-	m	-	4	-	-	-	4	-	m	-	4	-	-	-	4	-	-	-	4
Load Preheat													x	x	x		n	n	n		+	+	o	19
Process Specific/Other	o	o	-	5	o	o	-	5	o	+	-	12												

Cell key defined on Page B-1

1. Use of heat exchangers with coke oven gases is almost never done. There have been a few efforts for heat recovery, but these generally stall due to significant contaminants in the gas stream. (Beer, p. 189)
2. Bisio p. 258, a heat transfer medium has been successfully used to recover heat from coke oven gas in the ascension pipe in at least one case.
3. Plants in Japan have attempted using a waste heat boiler, but ceased operation due to problems with tar condensation. (Bisio, p. 258)
4. Solid state generation has not yet been used for any industrial exhaust gas heat recovery. It may have potential for use in clean exhaust streams.
5. Waste heat from either coke oven gas or waste gas can sometimes be used to remove coal moisture (CANMET, p. 10)
6. The use of regenerators is a common practice in coke ovens. The regenerator recovers heat from waste gas and heats the incoming combustion air or blast furnace gas. It is not used to recover coke oven gas. (IPCC p, 113. Perry, p. 9-62).
7. A variety of recovery devices may be technically feasible, since waste gases are relatively clean. However, since waste gases leaving the regenerator are at average temperatures of about 200°C, most systems for further recovery would probably not be economical.
8. Heat pipes can be used to further recover waste heat in waste gases after the regenerator. This has been done in a few cases using a heat pipe (Bisio p.264)
9. Unreasonable, given low gas temperatures leaving the regenerator.
10. Typical blast furnace exhaust temperatures are likely too low for these high temperature recovery devices to be feasible.
11. Beyond the use of dry-type pressure recovery turbines, no discussion of sensible heat recovery from blast furnace gases was discovered in published literature.
12. Some systems use top pressure recovery turbines to recover pressure energy. These are usually in conjunction with wet cleaning systems. Dry-type turbines are commercial abroad, but not common in the US. This type enables recovery of both kinetic energy and sensible heat. (CANMET, p. 64.Beer p. 188)
13. The exhaust temperature from this application is too low to make this recovery option practical.
14. Various systems have been used for recovery from hot blast stoves, both for preheating air and fuel (Pei Hsun and CANMET, p. 65).
15. Exhaust gases are relatively clean and in the low-medium temperature range. Therefore, low temperature power generation may be an option.
16. Combustion air preheat is irrelevant.
17. A variety of waste heat boiler designs have been used to recover sensible heat and/or chemical energy contained in BOF offgases. (CANMET, p. 117-119).
18. Exhaust temperatures from this application are too high for low temperature Rankin cycles to be a reasonable option. Additionally, discontinuous furnace operation would be a challenge.
19. Scrap preheating is a common practice with electric arc furnaces.

Table B2 - Status of Waste Heat Recovery Technologies in the Glass and Cement Industries

	Glass Melting Furnaces								Cement			
	Gas-fired Melting Furnaces				Oxyfuel Melting Furnaces				Cement Kiln			
	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes
Regenerator	+	+	o	1	-	o	-	7	n	n	n	8
Recuperator	+	+	+	1	-	o	-	7	n	n	n	8
Heat Wheel	o	o	-	2	n	o	-	7	n	n	n	8
Passive Air Preheater	n	n	n		-	o	-	7	n	n	n	8
Heat Transfer Medium	n	n	n		n	n	n		n	n	n	8
Waste Heat Boiler	o	+	-	3	o	+	-	3	+	+	+	9
Low T Power Cycle	x	x	x	4	x	x	x	4	o	+	o	10
Solid State Generation	-	m	-	5	-	m	-	5	-	m	-	5
Load Preheat	n	m	n	6	o	o	o	6	+	+	+	11
Process Specific/Other									+	+	+	12

Cell key defined on Page B-1

1. Regenerators are frequently used in large glass furnaces favored by economies of scale. Smaller furnaces use less efficient recuperators or do not use heat recovery (US DOE *Glass Melting Technology* , pp. 52-54).
2. Though heat wheels have been used in some cases, the gas seals required often cannot endure the harsh temperature conditions associated with glass furnaces. (Wilmott, p. 80)
3. Used unsuccessfully in the US 40 years ago, frequently abandoned due to high levels of sulfate deposition. Currently used in Europe. Technical feasibility is increasing due to automated cleaning methods. (Wishnick)
4. Exhaust temperatures are too high
5. Solid state generation has not yet been used for any industrial exhaust gas heat recovery.
6. Batch and cullet preheat systems are currently commercialized in Europe, but are only used in one location in the US (Greenman). Batch preheat systems are generally considered as options for oxyfuel furnaces. Gas-fired furnaces rely on regenerators and
7. Preheating the oxidant is technically possible, but inefficient due to the small volumetric flow rate of the oxidant (Glusing, p. 6).
8. Combustion air preheat with gas-gas heat exchangers is possible, but typical use for cement kiln combustion exhaust is preheating meal or power generation.
9. Combustion exhausts are used for steam/power generation in some US plants, but plants typically prefer to use waste heat to preheat meal rather than for power generation.
10. Low temperature power cycles are considered a good option for recovering heat from clinker cooler exhaust. Commercialization status is unclear, though it has been used in at least 1 location in Germany (Heidelberg).
11. It is a common practice to use preheaters to preheat the raw meal. (Portland Cement Association, p. 12-26).
12. Recovery from the clinker cooler is a common practice (Worrell, p. 23)

Table B3 - Status of Waste Heat Recovery Technologies in the Aluminum, Metal Casting and Steam Boilers

	Aluminum								Metal Casting Iron				Steam Boiler			
	Hall-Heroult Cells				Melting Furnaces				Iron Cupola				Boiler			
	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes	Commercial	Technical	Economic	Notes
Regenerator	-	-	-	1	+	+	o	3	n	n	n		-	+	-	
Recuperator	-	-	-	1	+	+	o	3	+	+	+	7	+	+	+	8
Heat Wheel	-	-	-	1	o	+	o	4	n	n	n		+	+	+	8
Passive Air Preheater	-	-	-	1	n	n	n		n	n	n		+	+	+	8
Heat Transfer Medium	-	-	-	1	n	n	n		n	n	n		+	+	+	8
Waste Heat Boiler	-	-	-	1	n	n	n		n	n	n		x	x	x	
Low T Power Generation	-	-	-	1	x	x	x	5	n	n	n		-	m	n	9
Solid state Generation	-	m	-	2	-	m	-	2	-	m	-	2	-	m	-	2
Load Preheat	n	n	n	1	+	+	o	6					+	+	+	10
Process Specific/Other																

Cell key defined on Page B-1

1. No efforts have been made to recover exhaust gas waste heat from primary aluminum cells (Hayden). There is also little physical space available for heat transfer equipment.

2. Solid state generation has not yet been used for any industrial exhaust gas heat recovery.

3. Several secondary melting furnaces have installed regenerators and recuperators. However, there are many cases where recovery equipment is removed due to complications in operation and maintenance (Hayden).

4. Heat wheels have been developed for use in aluminum furnaces, but they have not been successfully commercialized in the United States (Hauck).

5. Exhaust temperatures are too high

6. Charge preheating is used in some aluminum melting operations, including secondary aluminum refining furnaces and aluminum metal casting furnaces (Eppich).

7. Combustion exhaust gases are used to preheat the hot blast (Schifo, p. 28-30).

8. A variety of gas-gas heat exchangers have been used with steam boilers (Babcock and Wilcox, pp. 19-3 - 19-13)

9. Low temperature power generation may be an option for exhaust gases from boilers fired with clean fuels (e.g. natural gas). However, there is no indication that this has been attempted.

10. Use of economizers to preheat boiler feedwater is a very common practice (Matallah)