Waste Heat Recovery in Industrial Facilities

Opportunities for Combined Heat and Power and Industrial Heat Pumps

1020134

Waste Heat Recovery in Industrial Facilities

Opportunities for Combined Heat and Power and Industrial Heat Pumps

1020134

Technical Update, December 2010

EPRI Project Manager

K R. Amarnath

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

ICF International

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

ICF International
12011 NE First Street
Bellevue, WA 98005

Principal Investigators
R. Tidball
K. Darrow

This report describes research sponsored by EPRI.

EPRI acknowledges Megan Douglas of ICF International for providing research assistance. Also acknowledged is Bruce Hedman at ICF for providing material on CHP bottoming cycle technologies and applications and for providing guidance on the calculation framework for estimating the waste heat to power potential. Jeff Smith at Recycled Energy Development provided information on target markets and market size estimates for waste heat to power projects.

EPRI appreciates the review comments provided by Stephanie Jumel and Eugenio Sapora of Electricité de France (EDF) and Gabriel Meric de Bellefon.

This publication is a corporate document that should be cited in the literature in the following manner:

Waste Heat Recovery in Industrial Facilities: Opportunities for Combined Heat and Power and Industrial Heat Pumps. EPRI, Palo Alto, CA: 2010. 1020134.

PRODUCT DESCRIPTION

Low-temperature waste heat streams account for the majority of the industrial waste heat inventory. With a reference temperature of 60°F (16°C), 65% of the waste heat is below 450°F (232°C) and 99% is below 1,200°F (649°C). With a reference temperature of 300°F (149°C), 14% of the waste heat is below 450°F, and 96% is below 1,200°F.

Waste heat is concentrated in a few industrial manufacturing sectors. Based on a review of 21 manufacturing sectors, the top two sectors that produce waste heat are petroleum and coal products (according to NAICS 324) and chemical manufacturing (NAICS 325). These two categories account for 53% of the waste heat inventory at a reference temperature of 60°F and 85% of the waste heat inventory at a reference temperature of 300°F.

Results and Findings

The waste heat inventory in the industrial sector in the United States was analyzed and is estimated to be on the order of 1.5–3 quads per year (quadrillion Btu/yr), or 1500–3000 TBtu/yr (trillion Btu/yr). This estimate is based on an ambient temperature reference point. With a higher temperature reference value of 300°F, the waste heat inventory is significantly smaller and is estimated to be 250–420 TBtu/yr.

Two waste heat recovery technologies—combined heat and power (CHP) bottoming cycles and industrial heat pumps—were reviewed. Although these technologies are used in the industrial sector, their market penetration is low. For CHP bottoming cycles, over 12,000 MW of identified power potential has been identified, but to date only 60 projects—totaling 753 MW of waste heat recovery—have been installed in the United States.

Compared to CHP bottoming cycles, a relatively large number of industrial heat pumps have been installed, but these industrial heat pumps generally have a smaller capacity. There are an estimated 3,000 industrial heat pumps operating in the United States, with the majority of these systems being used for lumber drying. Lumber drying heat pumps tend to have a relatively small heat output; the heating output capacity for all 3,000 heat pumps is estimated to be approximately 5,100 MMBtu/hr (based on an average heat output of 1.7 MMBtu/hr per heat pump).

Because CHP waste heat recovery systems and industrial heat pumps are frequently custom designed to meet site-specific conditions, there is a wide range of capital costs for these technologies. As a general guideline, capital costs for CHP systems that are driven with waste heat are estimated to be in the range of $2,000 to $2,500 per kW for large systems (>5 MW) and $3,500 to $4,500 per kW for small systems (<400 kW). For industrial heat pumps, capital costs are estimated to be in the range of $50,000 to $200,000 per MMBtu/hr of heat delivered to the process fluid stream.

Waste heat recovery yields lower CO_2 emissions. The upper bound on reducing CO_2 emissions is estimated to be approximately 88 million metric tons per year (MMT/yr)—almost 51 MMT/yr from CHP technologies and 37 MMT/yr from industrial heat pumps.

In addition to reducing CO_2 emissions, industrial heat pumps consume electricity and therefore provide beneficial electrification to society. The available waste heat under 300°F is estimated to be sufficient to power more than 23,000 industrial heat pumps based on an average heat output of 11.2 MMBtu/hr per heat pump (this is an average value; lumber drying heat pumps are generally smaller, while food processing and petrochemical heat pumps might be larger). These heat pumps represent an aggregate beneficial electric load of nearly 19 GW.

Challenges and Objectives

This report is intended to help utility personnel and other stakeholders seeking to identify industrial waste heat recovery opportunities and promote the adoption of energy recovery technologies—particularly waste heat–driven CHP systems and industrial heat pumps. By recovering waste heat, industrial customers can reduce the amount of energy they purchase, yielding lower energy costs and lower carbon emissions. Lower energy costs produce a tangible economic benefit, which can help industrial customers improve their competitive position. Reduced carbon emissions are important from the perspective of climate change and could have financial impacts depending on how state and federal agencies regulate greenhouse gases (GHGs).

Applications, Value, and Use

The industrial waste heat inventory is high, but recovering waste heat can be challenging, often requiring custom engineered solutions. CHP technologies and industrial heat pumps are currently used to recover waste heat, but the market penetration of these technologies is low. New technologies, such as industrial heat pumps operating with CO_2 as a refrigerant and CHP systems that incorporate small steam turbines, are being developed and should help expand opportunities for industrial waste heat recovery.

EPRI Perspective

The waste heat inventory information in this report can help utility personnel and other stakeholders target specific industrial sectors that offer the largest market opportunities for waste heat recovery. Information on CHP technologies and industrial heat pumps contained in this report can be used to match these technologies to site-specific waste heat opportunities.

Approach

This report was prepared by ICF International based on reviewing publicly available material, communicating with industry stakeholders (including equipment vendors, researchers, and consultants), and incorporating in-house information.

Keywords

Bottoming cycle
Combined heat and power
Industrial electrotechnologies
Industrial energy efficiency
Industrial heat pumps
Waste heat recovery

ACKNOWLEDGMENTS

This report was prepared by ICF International under contract with the Electric Power Research Institute (EPRI). The project team consisted of Rick Tidball, Ken Darrow, and Megan Douglas. Mr. Tidball and Mr. Darrow were the principal investigators and authors, and Ms. Douglas provided research assistance.

The authors thank Bruce Hedman at ICF for providing material on CHP bottoming cycle technologies and applications, and for providing guidance on the calculation framework for estimating the waste heat to power potential. The authors also thank Jeff Smith at Recycled Energy Development for information on target markets and market size estimates for waste heat to power projects.

The authors are grateful to EPRI for making this project possible, and wish to thank Ammi Amarnath, the EPRI project manager, for his guidance and insights. The authors appreciate the review comments provided by Stephanie Jumel and Eugenio Sapora of Electricite de France (EDF) and Gabriel Meric de Bellefon.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

This report is focused on waste heat recovery in the industrial market sector. By recovering waste heat, industrial customers can reduce the amount of energy they purchase, yielding lower energy costs and lower carbon emissions. Lower energy costs produce a tangible economic benefit, which can help industrial customers improve their competitive position. Reduced carbon emissions are important from the perspective of climate change, and could have financial impacts depending on how state and federal agencies regulate greenhouse gases (GHGs).

Objective and Scope

The objective of this report is to provide utility personnel with information that can be used to engage industrial customers that may be interested in implementing waste heat recovery technologies. This report includes estimates for the waste heat inventory in the industrial sector in the United States, and provides detailed information on two types of active heat recovery technologies:

- Combined heat and power (CHP) systems
- Industrial heat pumps (IHPs)

Heat exchangers are not covered in detail in this report, but are described briefly in **Appendix A**. Heat exchangers are passive devices that rely on heat flowing from a relatively high temperature fluid stream to a lower temperature fluid stream. In general, no energy is required to drive a heat exchanger (hence, the term passive). In contrast, active heat recovery technologies, such as CHP systems and IHPs, do require some type of energy input to recover the waste heat.

Approach

ICF prepared this report based on reviewing publicly available material, communicating with industry stakeholders (equipment vendors, researchers, and consultants), and incorporating in-house information. Original research was not conducted to create new or updated waste heat inventory data, and only limited information was examined to estimate market sales data for CHP and IHP technologies.

This report is intended to help utility personnel and other stakeholders that seek to identify industrial waste heat recovery opportunities and promote the adoption of waste heat recovery technologies – particularly CHP systems and industrial heat pumps. This report is not intended, however, to be an engineering design guide or economic analysis resource. Nor is this report intended to offer industrial heat recovery optimization guidelines, such as the information available from a pinch analysis (EPRI 1990).

Report Organization

This report is organized as follows:

- Chapter 1 -- Introduction
- Chapter 2 – Parameters that Influence Waste Heat Applications
- Chapter 3 – Energy Consumption and Carbon Dioxide Emissions
- Chapter 4 – Waste Heat Inventory
- Chapter 5 – CHP Bottoming Cycles
- Chapter 6 – Industrial Heat Pumps
- Chapter 7 – Summary
- References
- Appendix A – Overview of Heat Exchangers
- Appendix B – Conversion Factors

2
PARAMETERS THAT INFLUENCE WASTE HEAT APPLICATIONS

All waste heat recovery systems depend on three key elements (see **Figure 2-1**):

1. An available waste heat stream
2. A feasible recovery technology
3. A need for the recovered energy

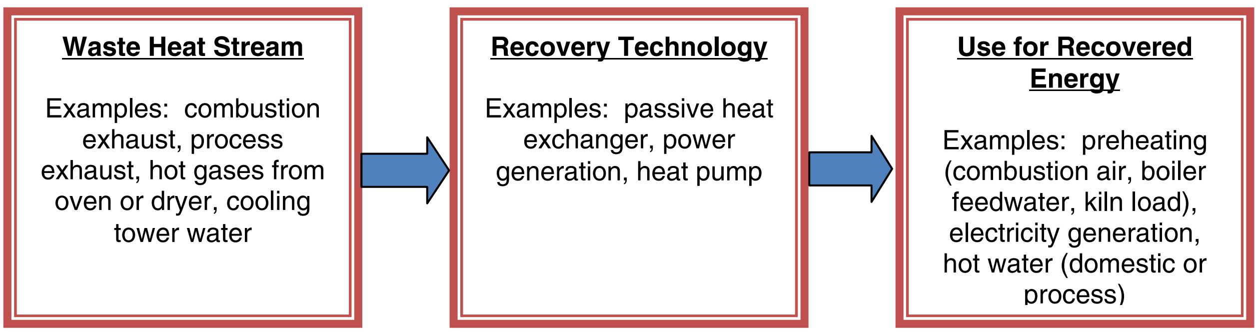


Figure 2-1
Three Requirements for a Waste Heat Recovery System

When evaluating a potential waste heat application, the first step is generally to conduct a quick screening study to determine if the three preceding elements exist. If the screening study is positive, then additional key factors need to be considered, which include:

- Heat quantity
- Temperature (or quality)
- Chemical composition
- Other factors (plant operating schedules, waste heat stream availability, etc.)

Heat Quantity

The amount of energy that can be extracted from a waste heat stream depends on the flow rate, specific heat, and temperature characteristics, and is given the by following formula (valid for single phase flow; does not account for phase change):

$$\dot{Q} = \dot{m} c \Delta T$$

where the variables are defined as (English units shown – metric unit conversions provided in **Appendix B**):

$\dot{Q}$ = rate of energy (power) extracted from the waste heat stream (Btu/hr)

$\dot{m}$ — mass flow rate of the waste heat stream (lb/hr)

c — specific heat of the waste heat stream (Btu/lb – °F)

ΔT — temperature change of the waste heat stream (°F)

Specific heat is defined to be the amount of energy required to raise the temperature of a unit of mass of that material by one degree. For example, the specific heat of water is 1 Btu/lb-°F, meaning that one Btu of energy is required to raise the temperature of one pound of water by one degree Fahrenheit. Specific heat values generally change with temperature and pressure and for gases are frequently reported in terms of the constant pressure heat capacity (c_p) or the constant volume heat capacity (c_v).

Heat Quality (Temperature)

The temperature, or quality, of the waste heat stream is perhaps the single most important parameter that determines how much energy can be recovered. As the temperature increases, the value, or quality of the waste heat stream increases. There are two reasons that the quality increases with temperature. First, high temperature waste heat streams can be used for a wide range of industrial plant needs, including the production of process steam, electric power production, combustion air preheating, and many low temperature applications (e.g., space heating or water heating). Second, the required surface area of a heat exchanger is inversely proportional to the temperature difference between the two streams, according to the following formula:

$$\dot{Q} = UA\Delta T$$

where the variables are defined as:

$\dot{Q}$ – rate of energy (power) extracted from the waste heat stream (Btu/hr)

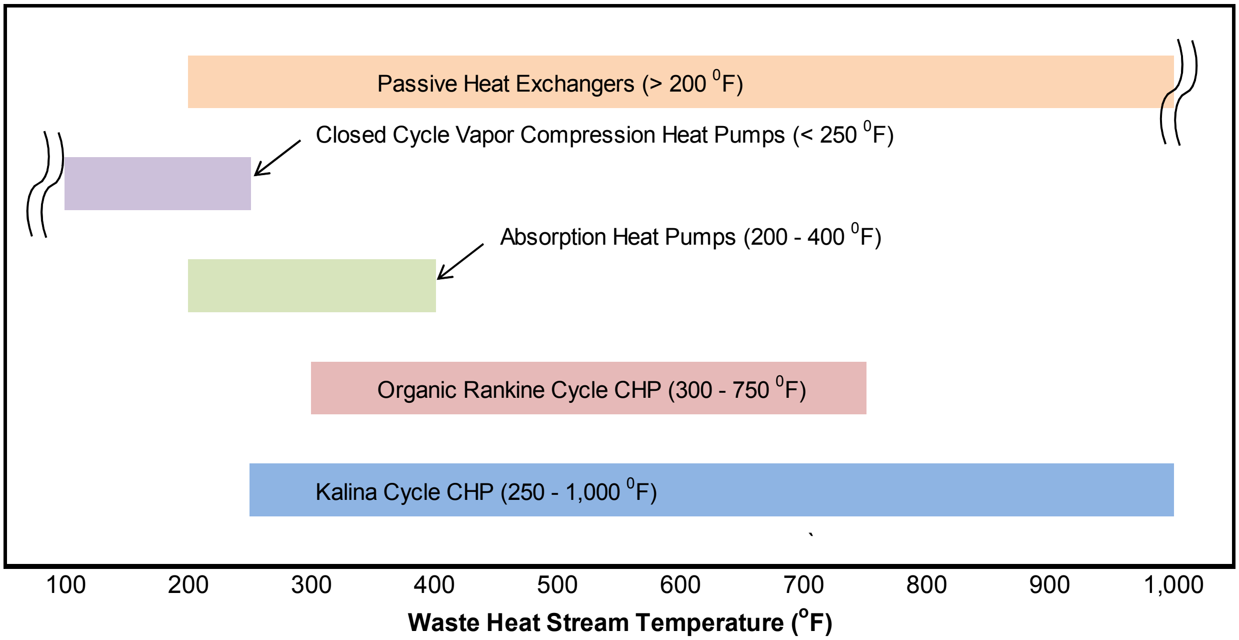
U heat transfer coefficient (Btu/hr ft^2 °F)

A – heat exchanger surface area (ft)^2

ΔT — temperature difference between the two streams (°F)

For low temperature waste heat streams, the size of the required heat exchanger often leads to prohibitive economics.

The temperature of a waste heat stream determines what type of energy recovery technology can be used. As indicated in **Figure 2-2**, passive heat exchangers work well for temperatures from about 200 °F to well above 1,000 °F. From about 250 to 750 °F, CHP systems can be used, and below 400 °F heat pumps can be applied.



Source: *Adapted from WSU, 2009b and Lewis 2009*

Figure 2-2
Technology Applications Based on Waste Heat Stream Temperature

Waste heat streams are often grouped into different temperature categories to distinguish how these streams might be used. **Table 2–1** shows waste heat streams that are categorized into three common temperature groups: low (< 450 ^{o}F), medium (450 – 1,200 ^{o}F), and high (> 1,200 ^{o}F). **Table 2–1** shows typical recovery opportunities and the technologies that can be used. As indicated, electric power production (i.e., CHP bottoming cycles) can be utilized with medium and high temperature waste heat streams, but generally not with low temperature waste heat sources. Industrial heat pumps are only utilized with low temperature waste heat streams.

Chemical Composition and Phase

The chemical composition and phase (e.g., liquid or gas) of waste heat streams are important factors that influence the selection and design of heat recovery equipment. Chemical composition and phase have a direct bearing on thermal properties, fouling and corrosion.

Thermal Properties

Heat transfer rates are dependent on fluid properties, flow rates, and heat exchanger geometries. An important consideration in selecting heat transfer equipment is the fluid phase (e.g., gas or liquid). In general, heat transfer coefficients tend to be higher for liquid phase waste heat streams compared to gas phase waste heat streams, which enables higher heat transfer rates per unit of heat exchanger surface area for a given temperature difference.

Table 2–1
Example Waste Heat Streams Classified by Temperature

Temperature Classification	Waste Heat Source	Use for Recovered Energy	Technologies
High (>1200 °F)	• Furnaces – Steel electric arc – Steel heating – Basic oxygen – Aluminum reverberatory – Copper reverberatory – Nickel refining – Copper refining – Glass melting • Iron cupolas • Coke ovens • Fume incinerators • Hydrogen plants	• Combustion air preheat • Process steam • Power generation • Furnace load preheating • Medium or low temperature process needs	• Passive heat exchangers – Recuperators – Regenerators – Air preheaters – Regenerative/recuperative burners – Finned tube heat exchangers and economizers – Waste heat boilers • CHP – steam driven
Medium (450 –1200 °F)	• Combustion exhaust streams – Steam boiler – Gas turbine – IC engine • Heat treating furnaces • Ovens – Drying – Baking – Curing • Cement kilns	• Combustion air preheat • Process steam • Power generation • Furnace load preheating • Feedwater preheating • Low temperature process needs	• Passive heat exchangers • CHP – Steam cycle – Organic Rankine cycle (ORC)
Low (< 450 °F)	• Combustion products from recovery systems – Gas fired boilers – Ethylene furnaces • Steam condensate • Cooling Water – Furnace doors – Annealing furnaces – Air compressors – IC engines – Refrigeration condensers • Ovens – Drying – Baking – Curing • Hot process liquids or solids	• Space heating • Domestic water heating • Low temperature process needs	• Heat pump (increase temperature to useful range) • ORC

Source: *Adapted from DOE, 2008, p8.*

Fouling

Fouling is a common problem in heat exchangers, and can substantially reduce heat exchanger effectiveness or cause system failure. 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.

Corrosion

Waste heat streams that contain combustion products can present corrosion problems. Depending on the fuel used, combustion related flue gases contain varying concentrations of carbon dioxide, water vapor, NO_x, SO_x, and volatile organic compounds (VOCs). 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 not designed to tolerate these corrosive environments will fail prematurely. Therefore, heat exchangers used with combustion products are generally designed to maintain 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, while exhaust gases from coal or fuel oils with higher sulfur contents may be limited to 300 °F.

Chemical oxidation of carbon steel and stainless steel heat exchangers is another form of corrosion that can occur. Carbon steel at temperatures above 800 °F and stainless steel above 1,200 °F are subject to accelerated oxidation. At higher temperatures, it may be necessary to use high temperature alloys or composite materials.

Other Factors

Several other factors can influence the economic or technical viability of a waste heat recovery option, including:

- **Plant size** – Heat recovery on a small scale can be economically challenging (i.e., relative high capital costs and relatively low energy savings, leading to long payback periods).
- **Operating schedules** – If a waste heat source is only available for a limited time every day, the heat recovery equipment may be exposed to a high frequency of thermal cycling, which can reduce life. Also, it is important that the schedule for the heat source match the schedule for the heat load. If not, additional energy storage equipment may be needed, which increases capital costs.
- **Access to waste heat stream** – 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 inhibit the installation of bulky heat recovery equipment.
- **Ease of moving energy** – Constraints can be encountered based on transporting energy form of the waste heat stream. Hot liquid streams are frequently recovered, since they are easily transportable. Piping systems are easy to tap into, and the energy can be easily transported.

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. As a result, waste energy recovery is not widely practiced with hot solid materials.

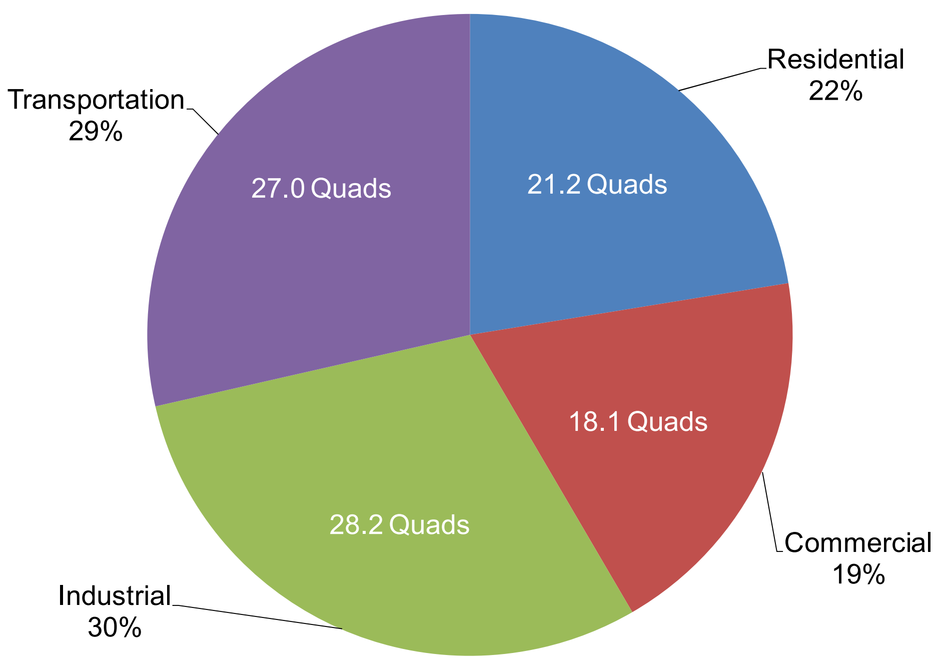
3

ENERGY CONSUMPTION AND CARBON DIOXIDE EMISSIONS

Energy consumption trends offer insights into waste heat recovery opportunities. While not directly correlated, the amount of energy consumed is one indicator of the potential waste heat that may be produced in a given market sector. In this chapter, both energy consumption and carbon dioxide emissions are presented.

Energy Consumption

The United States consumed nearly 95 quadrillion Btu (Quads) of total energy in 2009, which is equivalent to 100 exajoules (EJs)[1]. Of the four major economic sectors – residential, commercial, industrial, and transportation – the industrial sector used the largest share of total energy, accounting for over 28 Quads (29.5 EJ), or 30%, of all energy consumed (see **Figure 3-1**).



Source: *EIA, 2009*

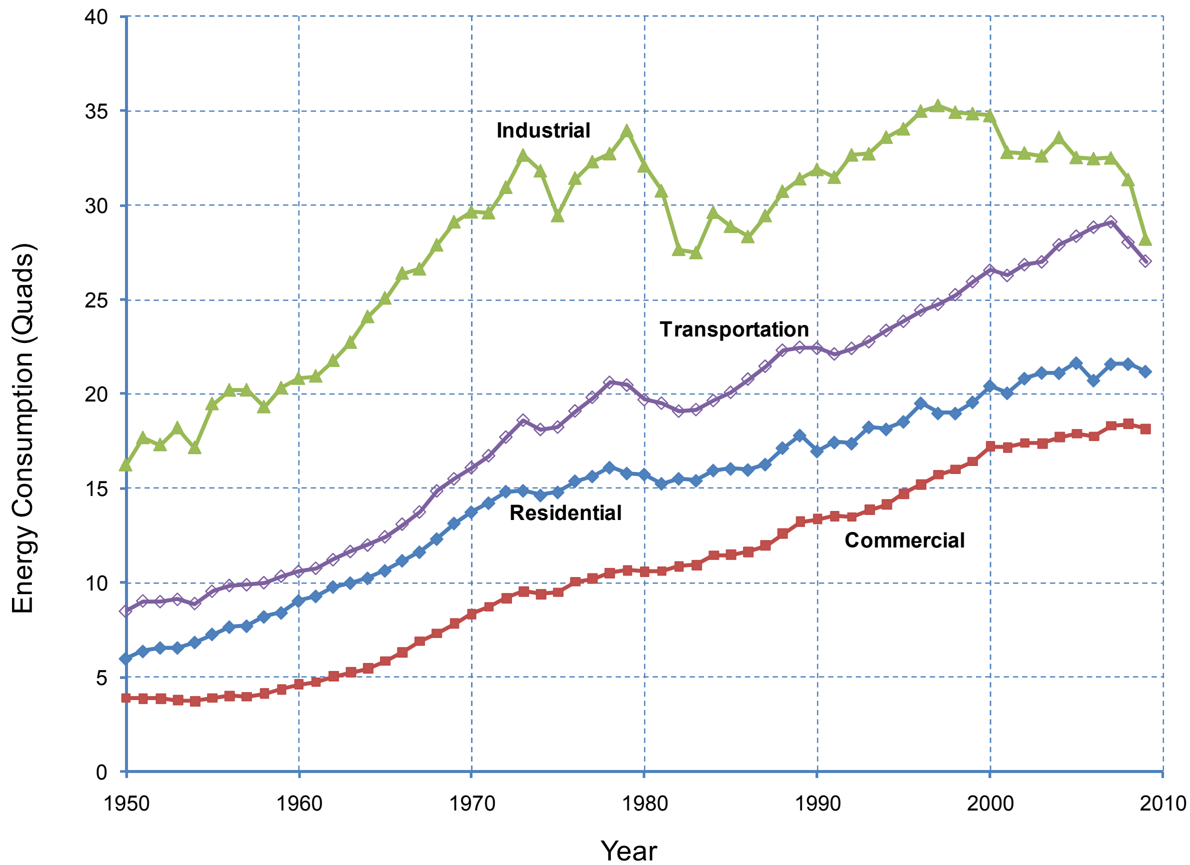
Note: *Includes energy associated with electric power generation*

Figure 3-1
Energy Use by End Use Sector, 2009

Energy consumption trends over the past six decades are shown in **Figure 3-2**. During this time period, all four economic sectors showed significant growth, with the industrial sector

[1] See **Appendix B** for conversion factors between English and metric units.

consistently accounting for the largest share of energy consumption. Relative to other sectors, the industrial sector has shown the highest volatility, and is particularly sensitive to changes in energy prices and economic conditions. The industrial sector showed sharp declines in the mid 1970s, early 1980s, 2001, 2005, and most recently in 2008 and 2009. These sharp declines can all be correlated with increased oil prices and/or weak economic conditions.



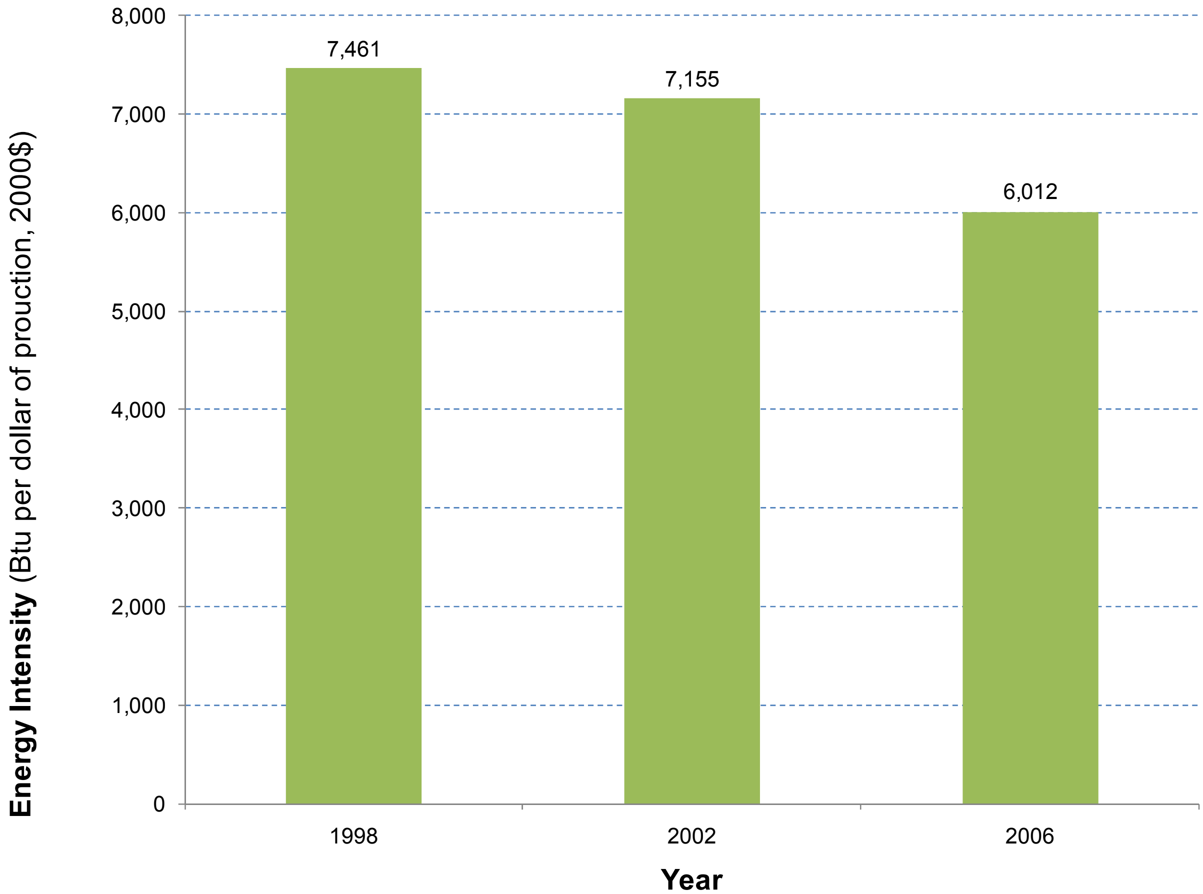
Source: *EIA, 2009*

Note: *Includes energy associated with electric power generation*

Figure 3-2
Energy Consumption Trends

Industrial energy consumption peaked in 1997 and has been declining since then. Other sectors have showed steady increases during this time, with the exception of the recession years in 2008 and 2009. If these trends continue, transportation, and not industry, will soon become the largest consumer of energy in the U.S.

More efficient use of energy has contributed to the reduction in industrial energy use. Based on data from the Energy Information Administration's Manufacturing Energy Consumption Survey (MECS), the energy intensity, as measured in Btu per dollar of production, has declined by approximately 19% between 1998 and 2006 (see **Figure 3-3**). Some of this reduced energy consumption may be due to the shifting of basic industrial production offshore or other factors, but the trend points to the success of increasing energy efficiency in the industrial sector.

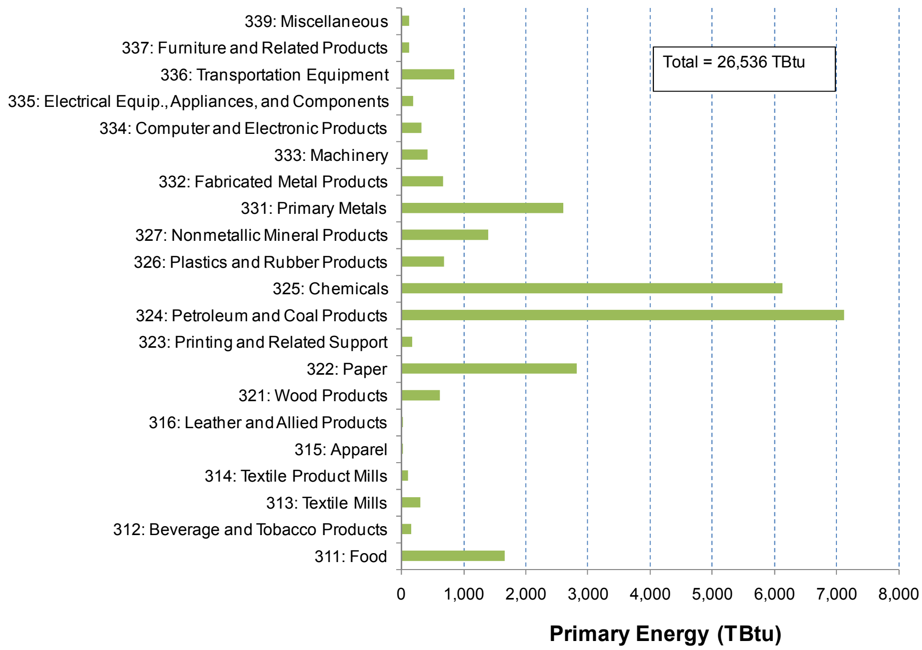


Source: EIA, 2010a.

Figure 3-3
Energy Intensity Factors

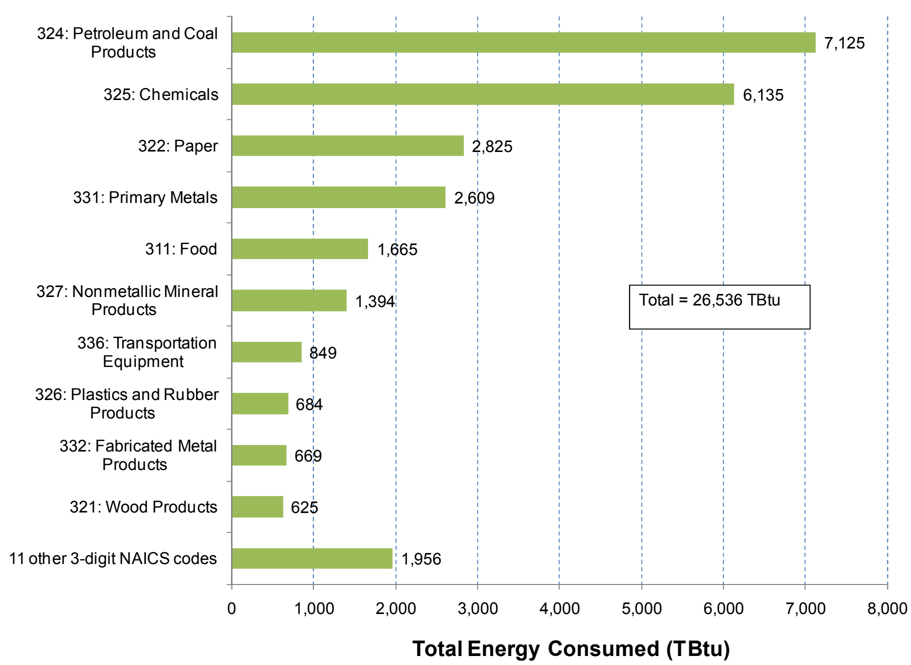
The EIA MECS data provide a snapshot of where energy is used in the industrial sector. **Figure 3-4** shows energy consumption for 21 industrial market sectors (three digit NAICS codes for categories 31-33). These 21 manufacturing sectors acount for 26.5 Quads of energy consumptions, which is about 94% of the total industrial sector energy consumption (total = 28.2 Quads). These consumption figures include the amount of energy used to produce electricity.

Figure 3-5 shows the data arranged by consumption for the top 10 industrial sectors. The top five sectors –petroleum and coal, chemicals, paper, primary metals, and food – account for 77% of the energy consumption. The top 10 sectors account for 93% of the consumption.



Source: *EIA, 2010a.*

Figure 3-4
Energy Consumption for 21 Industrial Sectors (NAICS 31-33, 2006 data)

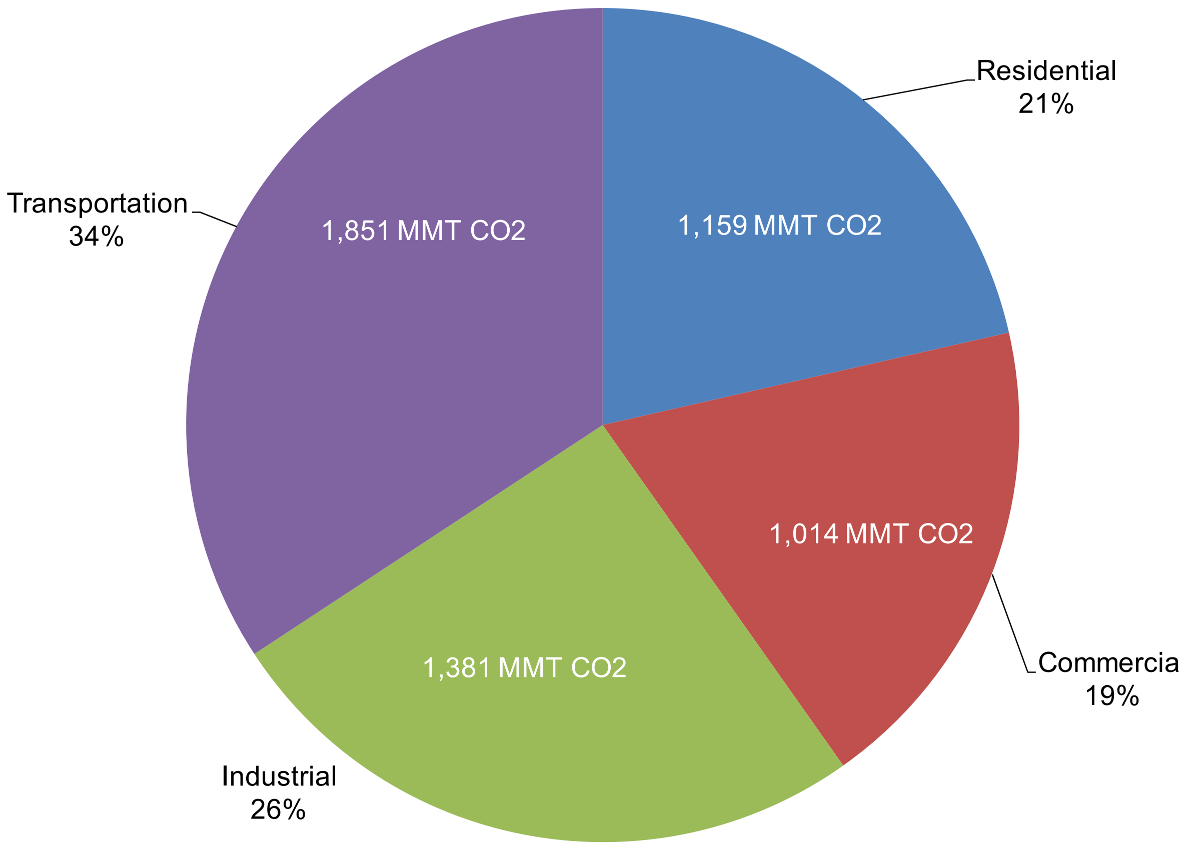


Source: *EIA, 2010a.*

Figure 3-5
Energy Consumption for Top 10 Industrial Sectors (2006 data)

Carbon Dioxide Emissions

In 2009, the industrial sector emitted nearly 1,400 million metric tons of carbon dioxide (MMT CO_2), representing 26% of total CO_2 emissions produced by the four major economic sectors (see **Figure 3-6**). The transportation sector contributed the largest share of CO_2 emissions, producing over 1,800 MMT CO_2 of (34% of total).

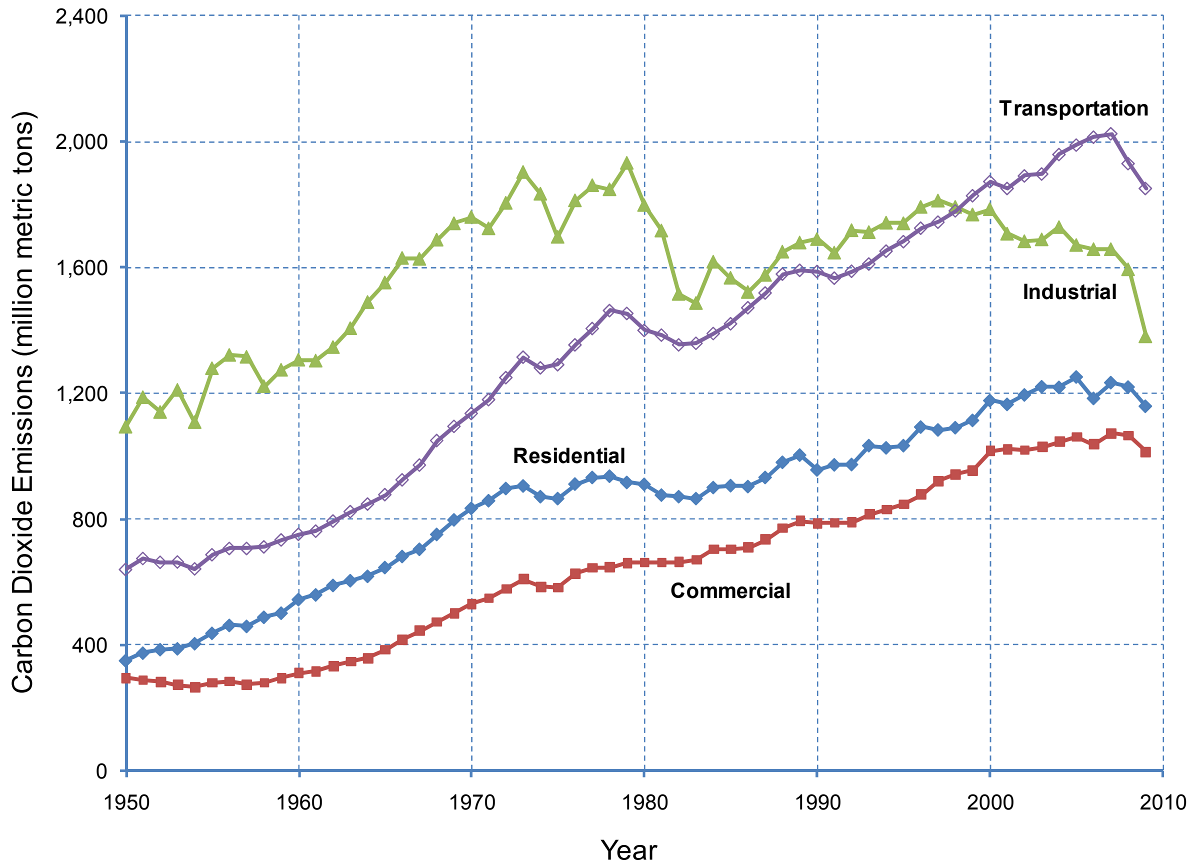


Source: *EIA, 2009*

Note: *Includes energy associated with electric power generation*

Figure 3-6
Carbon Dioxide Emissions by End Use Sector, 2009

Carbon dioxide emission trends over the past six decades are shown in **Figure 3-7**. The industrial sector had the largest share of CO_2 emissions through the late 1990s. In 1998, the transportation and industrial sectors crossed over, and since 1998 the transportation sector has had the largest share of CO_2 emissions. Relative to other sectors, CO_2 emissions in the industrial sector have shown the highest volatility. As discussed previously, the industrial sector is particularly sensitive to changes in energy prices and economic conditions. Sharp declines in industrial CO_2 emissions can all be correlated with reductions in energy consumption that resulted from increased oil prices and/or weak economic conditions.



Source: *EIA, 2009*

Note: *Includes energy associated with electric power generation*

Figure 3-7
Carbon Dioxide Emissions by End Use Sector, 2009

4

WASTE HEAT INVENTORY

Several studies have been conducted to characterize waste heat emitted from industrial processes. Two recent studies include one prepared by United Technologies Research Center (UTRC) for Oak Ridge National Laboratory (ORNL, 2004), and another prepared by BCS, Incorporated for DOE (DOE, 2008)

Both studies analyzed a large number of industrial processes to determine both the quantity of waste heat that is emitted and the quality of that heat. The BCS study evaluated industrial processes that collectively consumed 8.6 Quads of energy in 2006. The UTRC study analyzed the 2001 EPA National Emissions Inventory (NEI) (formerly known as the National Emission Data System, or NEDS)[2]. This database is heavily weighted toward major emissions sources in refinery, petrochemical, and other large facilities that exceed certain threshold emissions levels. Neither source looked at all industries or all processes. However, most concentrated energy consuming processes in the most energy intensive industries are covered.

Table 4–1 shows the industrial waste heat inventory estimated by BCS and UTRC. Both studies provide two temperature reference points for their estimates.

Table 4–1
Estimated Waste Heat Inventory

Temperature Range for Waste Heat Streams (°F)		Waste Heat Inventory (TBtu/yr / % of total)			
		BCS Study		UTRC Study	
		77 °F Basis	300 °F Basis	60 °F Basis	300 °F Basis
Low	< 450	903 / *61%*	37 / *14%*	1,985 / *65%*	57 / *14%*
Medium	450-1,200	466 / *32%*	130 / *51%*	1,053 / *34%*	349 / *82%*
High	>1,200	108 / *7%*	89 / *35%*	46 / *1%*	17 / *4%*
Total		**1,477**	**256**	**3,083**	**424**

Note: *Totals and percentages may differ due to rounding.*

The lower temperature basis in **Table 4–1** –77 °F for BCS and 60 °F for UTRC – is intended to represent ambient conditions. The ambient temperature reference point provides an upper bound on the maximum amount of waste heat that is available, based on reducing the waste heat temperature to ambient conditions. The 300 °F reference temperature is based on two practical limitations that often exist in industrial plants. First, industrial process fluid temperatures frequently need to be above 300 °F, and waste heat streams with a temperature below this temperature have limited value. Second, many industrial waste heat streams consist of combustion products, and cooling combustion products below 250 to 300 °F frequently creates corrosive condensates that shorten the life of metal components. In general, combustion exhaust waste heat streams are not cooled below 250 to 300 °F to avoid the formation of corrosive condensates.

---

[2] UTRC also estimated waste heat from 108 industrial processes. Only the UTRC NEI analysis is discussed in this report.

The BCS and UTRC studies show that there is a significant amount of waste heat available in the industrial sector, estimated at approximately 1,500 to 3,000 trillion Btu per year (TBtu/year). This upper bound estimate is referenced to ambient temperature conditions. As indicated, the amount of waste heat available at a reference temperature of 300 °F is significantly lower, and is in the range of approximately 250 to 420 TBtu/yr.

Additional data from the UTRC study is shown in **Table 4–2**, which provides a breakdown of the waste heat inventory grouped into 100 °F temperature bins (chart shown in **Figure 4-1**). **Table 4–3** shows the same data grouped into four temperature bins: <300 °F, 300-450 °F, 450-1,200 °F, and > 1,200 °F. Based on a reference temperature of 60 °F, 45% of the waste heat inventory is below 300 °F, 65% is below 450 °F, and 99% is below 1,200 °F. With a reference temperature of 300 °F, 14% of the waste heat inventory is below 450 °F and 96% is below 1,200 °F. At a 300 °F reference temperature, there is no usable waste heat below 300 °F.

Table 4–2
Waste Heat Inventory by Temperature Range (NAICS Codes 31-33)

Temperature Range (°F)	**Waste Heat (TBtu)**	
	Temperature Baseline (°F)	
	60	300
<100	200	0.0
100-200	680	0.0
200-300	505	0.0
300-400	480	32.6
400-500	240	49.8
500-600	448	113.5
600-700	54	16.1
700-800	16	5.3
800-900	62	21.8
900-1000	352	167.5
1000-1100	0	0.1
1100-1200	0	0.0
1200-1300	8	2.0
1300-1400	4	2.0
1400-1500	4	1.9
1500-1600	6	2.0
1600-1700	4	0.3
1700-1800	19	9.0
1800-1900	0	0.0
TOTAL	**3,083**	**424**

Source: *UTRC study, NEI methodology (ORNL, 2004)*

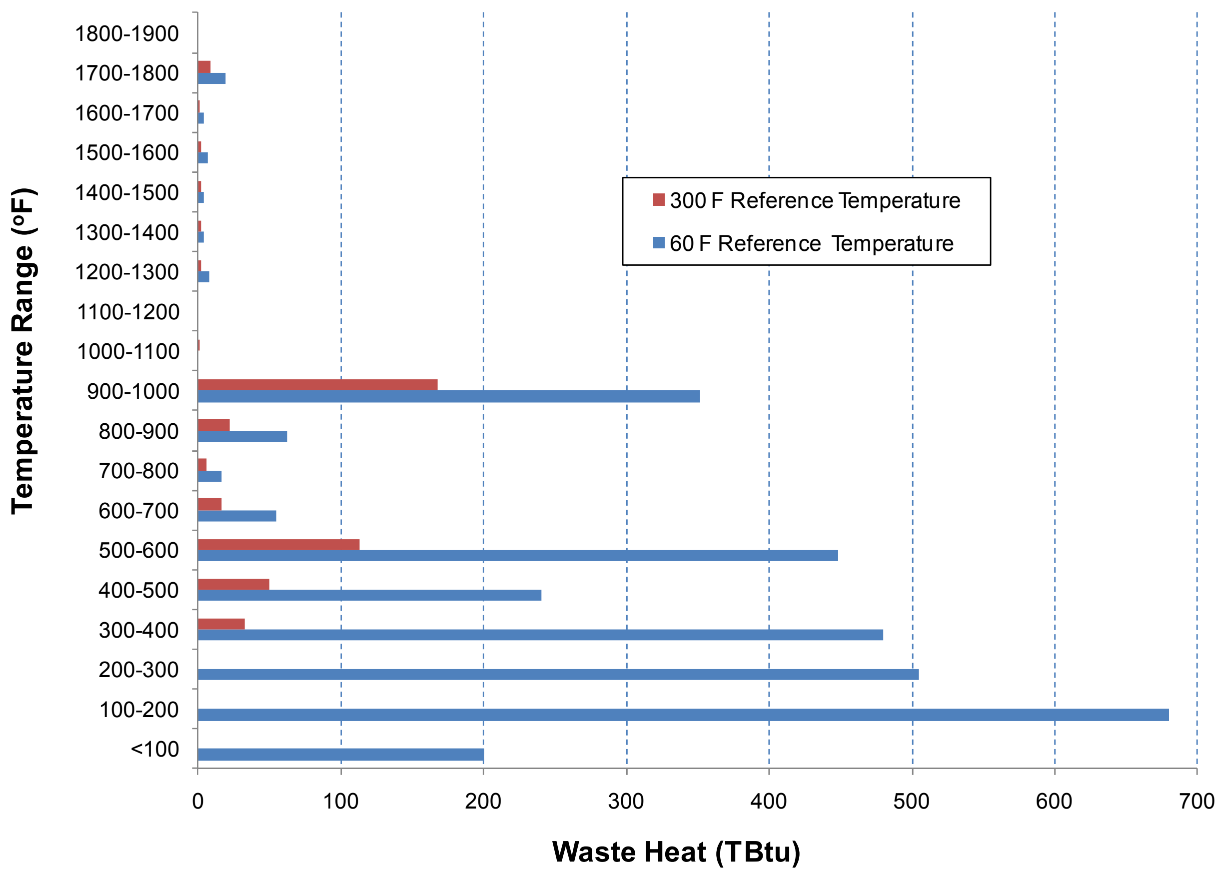
Notes: *1) Numerical values estimated from graphical data in UTRC study. Differences may exist between values in this table and actual data used by UTRC.*

2) Totals and percentages may differ due to rounding.

Table 4–3
Waste Heat Inventory Grouped into Four Temperature Bins

Temperature Range (°F)	Waste Heat (TBtu)	
	Temperature Baseline (°F)	
	60	300
<300	1,385 / 45%	0 / 0%
300-450	600 / 20%	57 / 14%
450-1,200	1,053 / 34%	349 / 82%
>1,200	46 / 1%	17 / 4%
Total	**3,083**	**424**

Note: *Totals and percentages may differ slightly due to rounding.*



Source: *UTRC study, NEI methodology (ORNL, 2004)*

Figure 4-1
Waste Heat Inventory by Temperature Range (NAICS Codes 31-33)

The UTRC study categorized the industrial waste heat emissions for 21 industrial manufacturing segments (based on 3-digit NAICS codes). The results for all 21 sectors are shown in **Table 4–4** and **Figure 4-2**. Results for the top eight segments (based on a 60 °F baseline temperature) are shown in **Figure 4-3**. These results show that waste heat is concentrated in just a few manufacturing sectors. The top two waste heat sectors are petroleum and coal products (NAICS 324) and chemical manufacturing (NAICS 325). At a 60 °F reference temperature, these two categories account for 53% of all waste heat. The results are even more concentrated when using a reference temperature of 300 °F. At this higher reference temperature, the top two categories account for 85% of all waste heat.

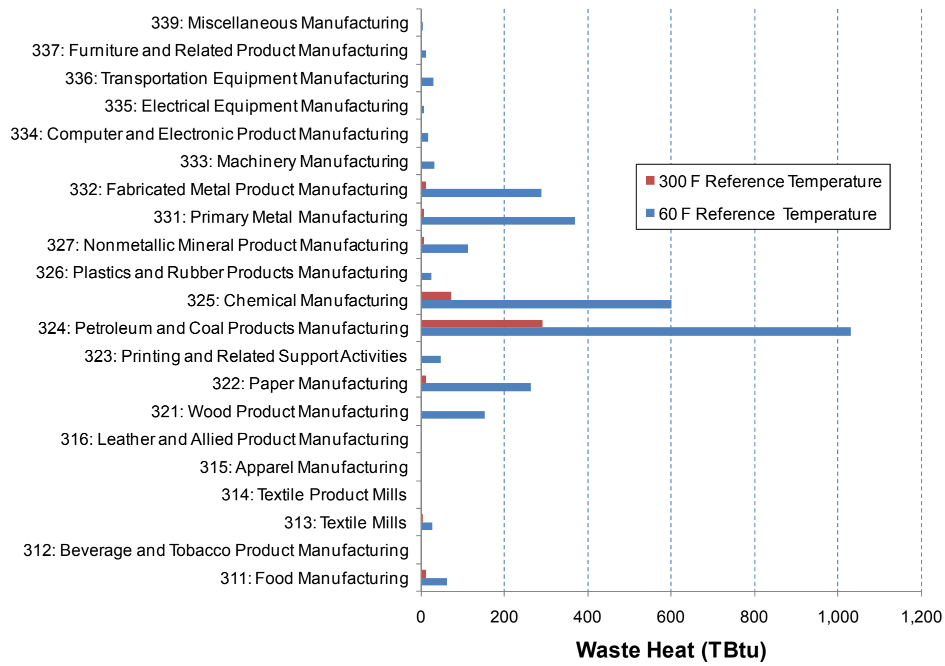
Table 4–4
Waste Heat Inventory by Manufacturing Sector

Manufacturing Sector (arranged by 3-digit NAICS code)	Waste Heat (TBtu)	
	Temperature Baseline (°F)	
	60	300
311: Food Manufacturing	62	12.8
312: Beverage and Tobacco Product Manufacturing	2	0.1
313: Textile Mills	26	3.5
314: Textile Product Mills	0	0.1
315: Apparel Manufacturing	2	0.0
316: Leather and Allied Product Manufacturing	0	0.0
321: Wood Product Manufacturing	152	2.4
322: Paper Manufacturing	263	11.0
323: Printing and Related Support Activities	48	1.3
324: Petroleum and Coal Products Manufacturing	1,032	290.0
325: Chemical Manufacturing	600	71.9
326: Plastics and Rubber Products Manufacturing	24	0.4
327: Nonmetallic Mineral Product Manufacturing	112	7.6
331: Primary Metal Manufacturing	368	8.0
332: Fabricated Metal Product Manufacturing	288	12.6
333: Machinery Manufacturing	32	0.7
334: Computer and Electronic Product Manufacturing	18	0.2
335: Electrical Equipment Manufacturing	7	0.2
336: Transportation Equipment Manufacturing	30	0.8
337: Furniture and Related Product Manufacturing	11	0.3
339: Miscellaneous Manufacturing	5	0.0
TOTAL	**3,083**	**424**

Source: *UTRC study, NEI methodology (ORNL, 2004)*

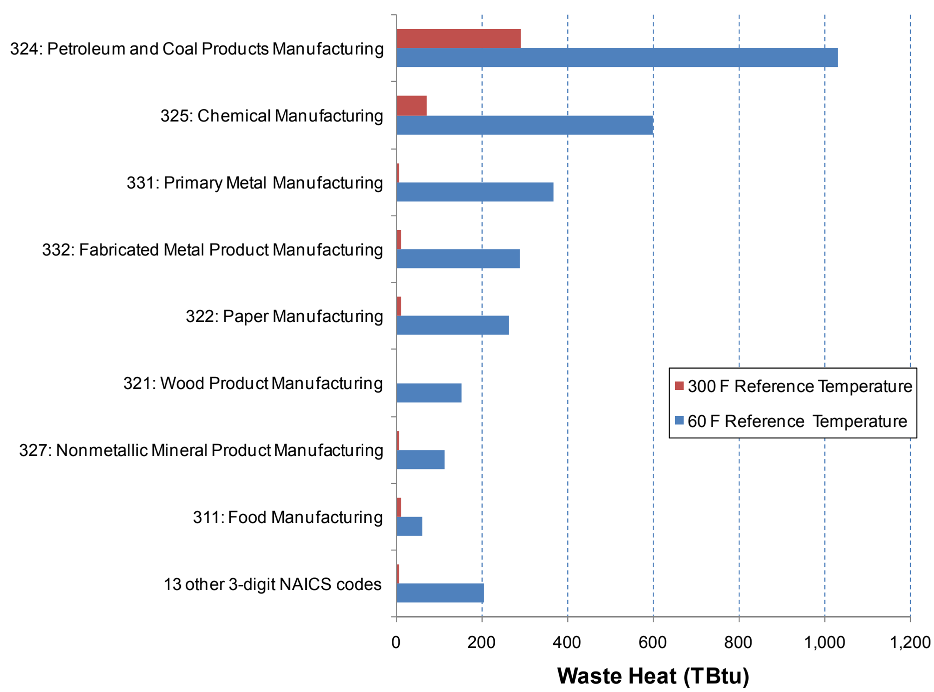
Notes: *1) Numerical values estimated from graphical data in UTRC study. Differences may exist between values in this table and actual data used by UTRC.*

2) Totals and percentages may differ due to rounding.



Source: UTRC study, NEI methodology (ORNL, 2004)

Figure 4-2
Waste Heat Inventory for 21 Industrial Manufacturing Sectors



Source: UTRC study, NEI methodology (ORNL, 2004)

Figure 4-3
Waste Heat Inventory for Top 8 Industrial Manufacturing Sectors

Table 4–5 shows the temperature breakdown for the eight sectors with the largest energy consumption at a reference temperature of 60 °F (chart shown in **Figure 4-4**). As indicated, the petroleum and coal products sector produces a relatively large amount of high quality waste heat. This sector (NAICS 324) produces 766 TBtu of waste heat above 450 °F.

Table 4–5
Temperature Allocation for Top 8 Sectors, 60 °F Reference Temperature

Manufacturing Sector (arranged by 3-digit NAICS code)	Waste Heat (TBtu) by Temperature Range				TOTAL (TBtu)
	<300	300-450	450-1,200	>1,200	
311: Food Manufacturing	7	21	34	0	**62**
321: Wood Product Manufacturing	94	50	9	0	**152**
322: Paper Manufacturing	137	103	23	0	**263**
324: Petroleum and Coal Products	156	110	760	6	**1,032**
325: Chemical Manufacturing	358	90	128	24	**600**
327: Nonmetallic Mineral Product	43	47	22	0	**112**
331: Primary Metal Manufacturing	289	58	20	2	**368**
332: Fabricated Metal Product	135	121	32	0	**288**
Other 13 3-digit NAICS codes	165	1	25	14	**206**
TOTAL	**1,385**	**600**	**1,053**	**46**	**3,083**

Source: *UTRC study, NEI methodology (ORNL, 2004)*

Notes: *1) Numerical values estimated from graphical data in UTRC study.*
2) Totals may differ due to rounding.

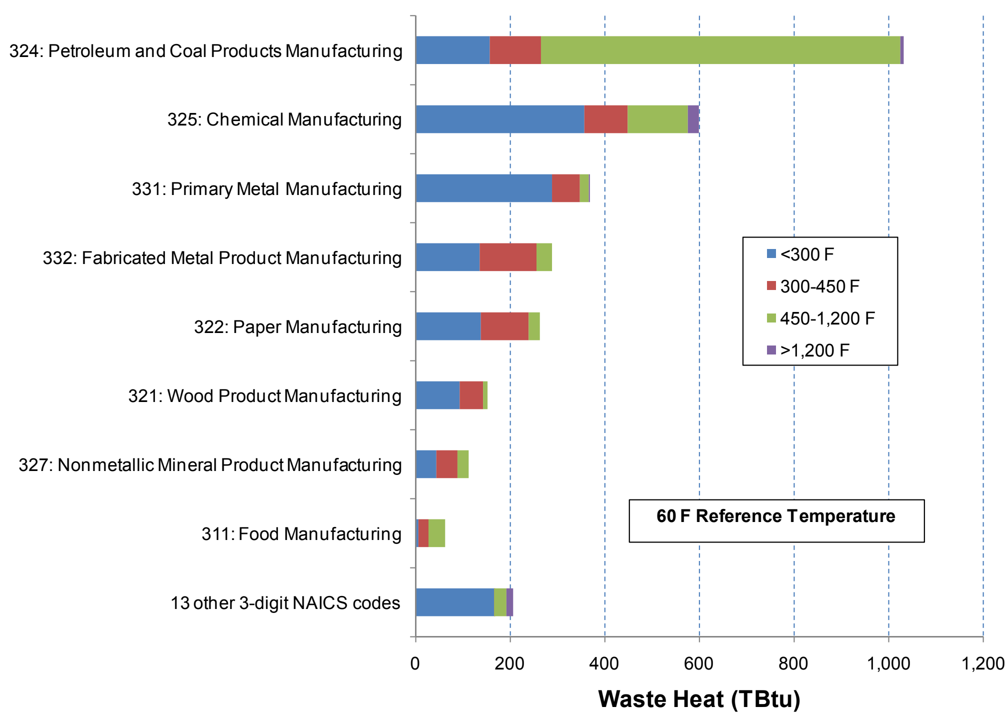


Figure 4-4
Temperature Allocation for Top 8 Sectors, 60 °F Reference Temperature

Table 4–6 and **Figure 4-5** show the temperature breakdown at a reference temperature of 300 °F for the same eight sectors shown in **Table 4–5**. The quantity of high quality (> 450 °F) waste heat in the petroleum and coal products sector (NAICS 324) is clearly pronounced in **Figure 4-5.**

Table 4–6
Waste Heat Inventory, Top 8 Sectors, 300 °F Reference Temperature

Manufacturing Sector (arranged by 3-digit NAICS code)	Waste Heat (TBtu) by Temperature Range				TOTAL (TBtu)
	<300	300-450	450-1,200	>1,200	
311: Food Manufacturing	---	3	10	0	**13**
321: Wood Product Manufacturing	---	2	0	0	**2**
322: Paper Manufacturing	---	8	3	0	**11**
324: Petroleum and Coal Products	---	18	272	0	**290**
325: Chemical Manufacturing	---	9	50	13	**72**
327: Nonmetallic Mineral Product	---	3	4	0	**8**
331: Primary Metal Manufacturing	---	4	3	1	**8**
332: Fabricated Metal Product	---	9	3	0	**13**
Other 13 3-digit NAICS codes	---	1	4	3	**8**
TOTAL	**---**	**57**	**349**	**17**	**424**

Source: *UTRC study, NEI methodology (ORNL, 2004)*

Notes: *1) Numerical values estimated from graphical data in UTRC study.*
2) Totals may differ due to rounding.

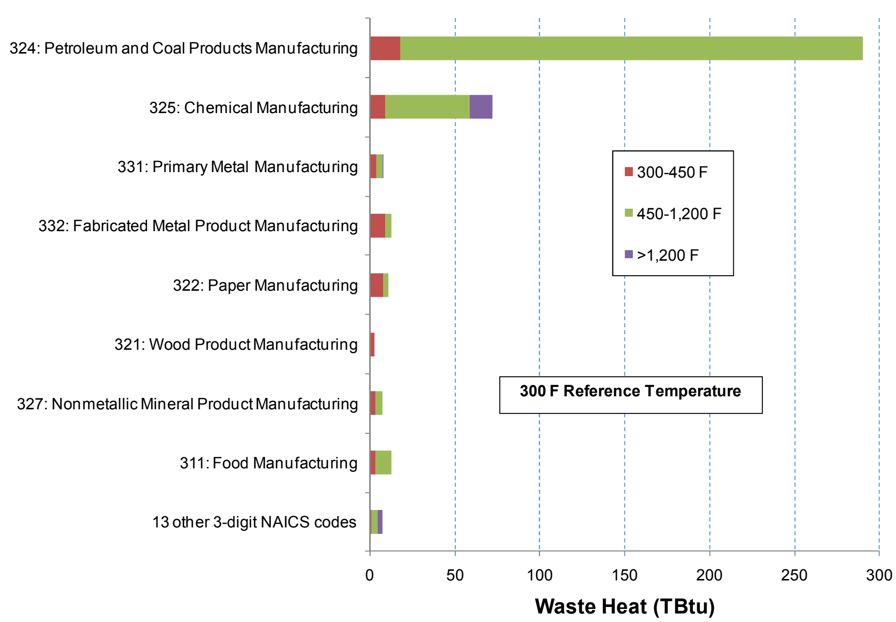


Figure 4-5
Temperature Allocation for Top 8 Sectors, 300 °F Reference Temperature

5
COMBINED HEAT AND POWER BOTTOMING CYCLES

The most common form of combined heat and power (CHP) is configured as a *topping cycle*, where fuel is combusted in a heat engine to generate power, and the waste heat from the power generation equipment is then used for an industrial process, usually in the form of steam generation for on-site process use. Waste heat streams can also be used to generate power in what is called a *bottoming cycle*. In a bottoming cycle, fuel is combusted for an industrial process or in a power topping cycle, and the waste heat from that process or topping cycle is then used in a heat engine to generate power. In a topping cycle, the fuel combustion process provides for very high heat source temperatures for the heat engine with high power generation efficiency. To be effective, a bottoming cycle must have a source of waste heat that is of sufficiently high temperature for a heat engine to both thermodynamically and economically feasible. In addition, the best sources of waste heat for bottoming cycles are high volume and high load factor so that the power generation equipment can operate with both economies of scale and the capital cost can be offset by nearly constant output.

There are emerging technologies that convert heat into power without using a heat engine. These technologies include thermoelectric, piezoelectric, thermionic, and thermophotovoltaic approaches. These approaches will be described in a later section. However, none of them are close to commercial practicality for converting large industrial waste heat streams to power.

This section describes the basic requirements of a heat engine to produce power in the context of utilizing available industrial waste heat streams. Commercially available and emerging technologies are described along with examples of their use, and a categorization of suitable industrial applications is presented.

Technology Description

The physical laws of converting heat into work fall under the study of thermodynamics. The limits of efficiency for these conversion devices are defined by the temperature difference between the heat source and the heat sink.

A heat engine acts by transferring energy from a warm region to a cool region of space and, in the process, converting some of that energy to mechanical work – as illustrated in **Figure 5-1**. The cycle may also be reversed. The system may be worked upon by an external force, and in the process, it can transfer thermal energy from a cooler system to a warmer one, thereby acting as a refrigerator or heat pump rather than a heat engine.

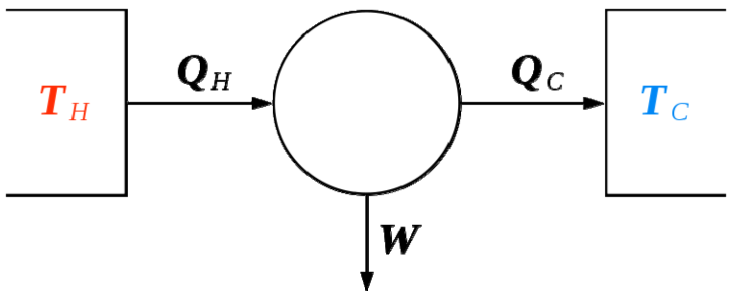


Figure 5-1
Ideal Heat Engine Conceptual Diagram

This maximum, or *Carnot*, efficiency   is defined to be:

$$= W/ Q_H = 1 - (T_C / T_H)$$

where

- W – work done by the system (energy exiting the system as work)
- Q_H – heat put into the system (heat energy entering the system)
- T_C – absolute temperature of the cold reservoir
- T_H – absolute temperature of the hot reservoir

The theoretical maximum efficiencies for a heat engine producing work (mechanical energy or power) based on this function are shown in **Figure 5-2**. The efficiency is calculated from the high temperature on the X-axis down to 85 ^{o}F, a heat sink temperature that could be produced by a cooling tower. As the temperature of the heat source (heat quality) declines, the theoretical efficiency also declines. A heat source at 1200 ^{o}F has twice the efficiency potential as a heat source at 400 ^{o}F. The efficiencies of actual heat engines described in this section are, in fact, much lower due to irreversible losses in their operation.

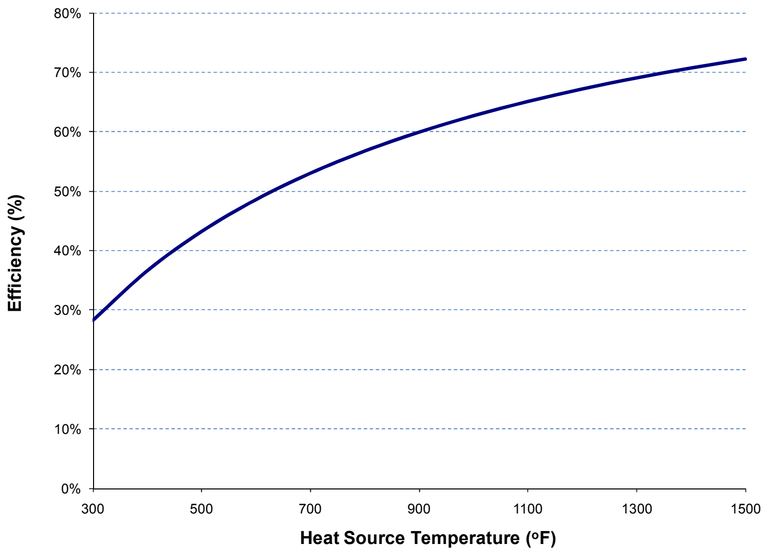


Figure 5-2
Maximum Theoretical Efficiencies as a Function of Heat Source Temperature

Rankine Cycle

Most commercial waste heat recovery (WHR) bottoming cycles can be described thermodynamically as *Rankine Cycles*. In a Rankine cycle, heat is supplied externally to a fluid in a closed loop. Water is the most commonly used fluid; steam turbines produce most of the power in the world, including power from coal, biomass, solar thermal, and nuclear energy. Systems using other fluids or combinations of fluids, as will be described later, have been developed that have certain advantages over water in WHR applications.

In a heat recovery Rankine cycle a working fluid in the liquid state is first pumped to elevated pressure before entering a heat recovery boiler (as illustrated in **Figure 5-3**). The pressurized fluid is vaporized by the hot exhaust, and then expanded to lower temperature and pressure in a turbine, generating mechanical power that can drive an electric generator. The low pressure working fluid is then exhausted to a condenser at vacuum conditions where heat is removed by condensing the vapor (could include some condensed liquid phase) back into a liquid. The condensate from the condenser is then returned to the pump for continuation of the cycle.

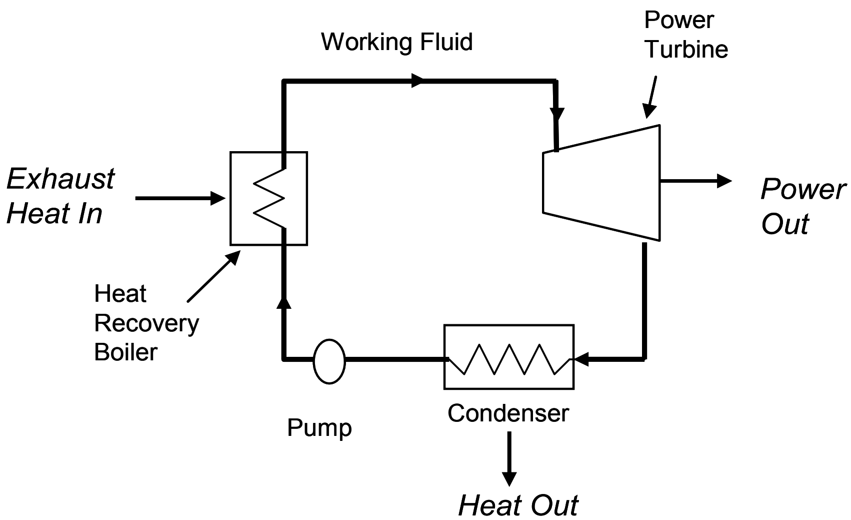


Figure 5-3
Rankine Cycle Heat Engine

One of the principal advantages the Rankine cycle compared to other thermodynamic cycles is that during the compression stage relatively little work is required to drive the pump, since the working fluid is in the liquid (nearly incompressible) phase. The energy required for raising the pressure of the fluid is a function of the change in volume; therefore, raising the pressure of a compressible gas requires much more energy than raising the pressure of an incompressible liquid. By condensing the fluid to a liquid, the work required by the pump consumes only 1% to 3% of the turbine power and contributes to a much higher efficiency. However, the range between the heat source and heat sink temperatures is typically much lower than for a combustion turbine, limiting both theoretical and practical efficiencies. For WHR applications, the Rankine cycle efficiency typically ranges from 30-50% of the Carnot efficiency.

Steam Turbine Power Systems

The most common example of the Rankine cycle is the steam turbine. Steam turbines are one of the oldest and most versatile prime mover technologies still in general production. Power generation using steam turbines has been in use for about 100 years. Most of the electricity produced in the United States today is generated by conventional steam turbine power plants. The capacity of steam turbines can range from 50 kW to several hundred megawatts for large utility power plants. Steam turbines are widely used for CHP applications in the U.S. and Europe.

Unlike gas turbine and reciprocating engine CHP systems where heat is a byproduct of power generation, steam turbines normally generate electricity as a byproduct of heat (steam) generation. A steam turbine is captive to a separate heat source and does not directly convert fuel to electric energy. The energy is transferred from the boiler to the turbine through high pressure steam that in turn powers the turbine and generator. This separation of functions enables steam turbines to operate with a wide variety of fuels and waste heat streams.

Steam turbines offer a wide array of designs and complexity to match the desired application and/or performance specifications. Steam turbines for utility service may have several pressure casings and elaborate design features, all designed to maximize the efficiency of the power plant.

For industrial applications, steam turbines are generally of simpler single casing design and less complicated for reliability and cost reasons. CHP can be adapted to both utility and industrial steam turbine designs.

Steam turbine-based CHP systems are primarily used in industrial processes where solid waste fuels, or waste heat are readily available for boiler use. In fuel fired CHP applications, steam is extracted from the steam turbine and used directly in a process or for district heating, or it can be converted to other forms of thermal energy including hot water or chilled water. In systems driven by waste heat from a process, the systems are more likely to use condensing turbines. For non-condensing applications, steam is exhausted from the turbine at a pressure and temperature sufficient for the CHP heating application.

Steam turbine systems are very commonly found in paper mills as there is usually a variety of waste fuels from hog fuel to black liquor recovery. Chemical plants are the next most common industrial user of steam turbines followed by primary metals. There are a variety of other industrial applications including the food industry, particularly sugar mills. There are commercial applications as well. Many universities have coal powered CHP generating power with steam turbines. Some of these facilities are blending biomass to reduce their environmental impact.

Organic Rankine Cycle

A Rankine cycle that uses a hydrocarbon as the working fluid is referred to as an *organic Rankine cycle* (ORC). ORCs are based on the Rankine cycle shown previously in **Figure 5-3** and include similar but slightly different components including a vaporizer, preheater, condenser and recuperator. The ORC uses an organic working fluid that typically has a lower boiling point and higher vapor pressure than water, making it more efficient than a steam turbine for lower temperature heat sources — sometimes as low as 150ºF (66ºC). Options for working fluids include silicon oil, propane, isopentane, isobutane, xylene, haloalkanes, and toluene. The working fluid is chosen based on the best thermodynamic match to the heat available. **Figure 5-4** shows one configuration of an ORC with regenerator. These systems are used with a “dry” fluid that exits the turboexpander at a higher temperature than the condenser.

The ideal working fluid should have a high latent heat and density to absorb more energy from the source in the evaporator and thus reduce the required flow rate, the size of the facility, and the pump consumption. The fluid’s critical point (the combination of pressure and temperature where the fluid transitions from a liquid state to a gaseous state) should be above the engine’s operating temperature in order to allow it to absorb all the heat available up to that temperature. The required operating pressure should not pose a danger of explosion or rupture. The fluid’s pressure inside the condenser should be above ambient air pressure in order to prevent air inflow into the system. The required volume of fluid in its gaseous state should be small enough to avoid the need for costly, over-sized turbines, boilers, and condensers (Duffy, 2005).

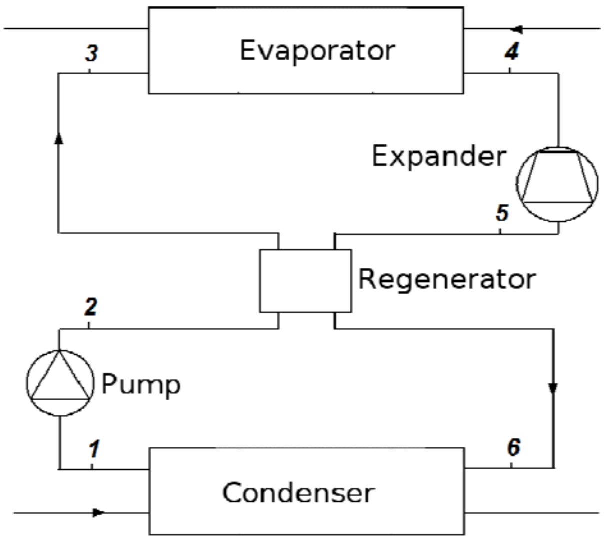


Figure 5-4
Organic Rankine Cycle Heat Engine with Regenerator

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%). Systems can be utilized for waste heat sources as low as 300 F.

While both cycles are classified as Rankine cycle heat engines, there are a few differences between a steam cycle and an ORC (Duffy, 2005):

- Heating and expansion occurs with the application of heat to an evaporator, not a boiler. While nearly identical in function, an evaporator does not require an on-site boiler operator.
- The condenser is not operated at a vacuum or at sub atmospheric pressure in order to avoid introducing air into the system.
- For those applications where higher temperatures are available to heat the organic working fluid, a regenerator is often added to increase the efficiency of the system. Regenerators are typically constructed of a wire metal mesh or a series of closely spaced thin metal plates. The void spaces between the metal wires and plates allow for easy flow of the working fluid through the regenerator. The relatively large surface area of the metal permits conduction of heat. As the heated organic fluid leaves the expander, it passes through the regenerator, and some of its heat remains. When the cooled organic fluid leaves the condenser, it passes through the regenerator in the opposite direction, acquiring some of the previously deposited heat, and preheating the fluid before it enters the evaporator. Less heat is thus needed to evaporate the liquid, which increases the efficiency of the engine, since it is doing the same amount of work.
- High molecular weights of the organic fluids permit operation of the expansion turbine at low speeds and high efficiencies (as high as 80-85%). Lower turbine speeds obviate the need for a reduction gear to drive an electrical generator.
- Overall electric generation efficiency is only around 8-15%, for low (300 ºF) to medium (800ºF) temperature range for waste heat. These efficiencies are typically lower than higher

temperature steam turbine systems due to the limits of Carnot efficiency as a function of evaporator and condenser temperatures. A Carnot engine operating with a heat source at 300 ºF [150 ºC] and rejecting it at 77 °F [25 ºC] is only about 30% efficient. In this light, an efficiency of 10-20% is a substantial percentage of theoretical efficiency.

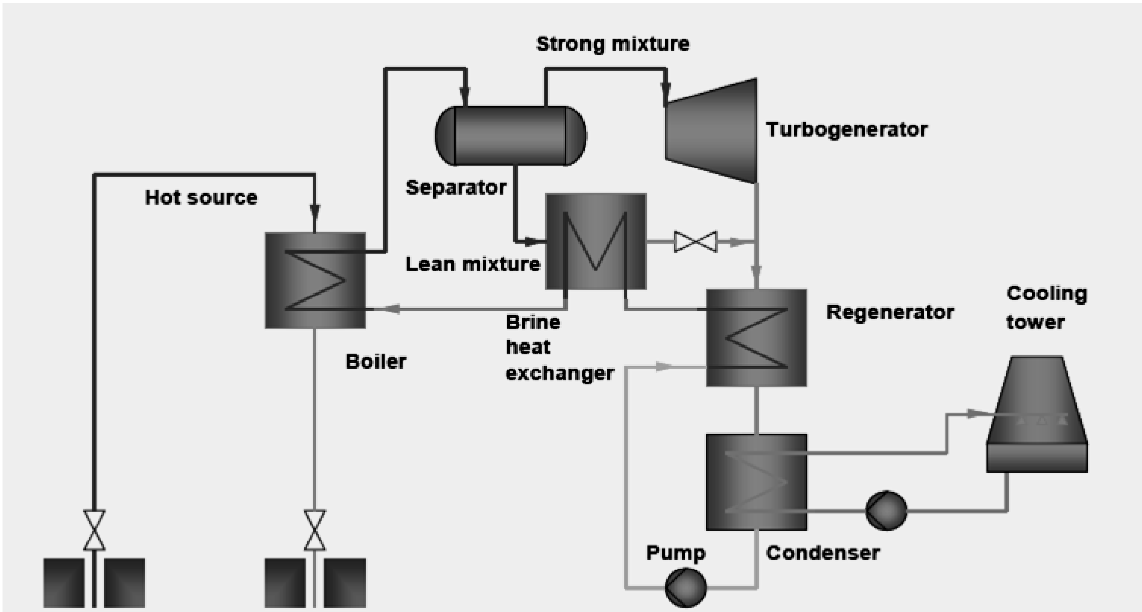
ORCs are commonly used to generate power in geothermal power plants, and more recently, in pipeline compressor heat recovery applications. Waste heat to power projects are more difficult to justify for low (~500 ^{o}F or lower) temperature waste heat, especially if the waste heat supply is not continuous and auxiliary energy is required. 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 930 ºF. The ORC provided 12% of the plant's electricity requirements and reduced CO_2 emissions by approximately 7,000 tons per year (DOE, 2008).

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.

Kalina Cycle

The Kalina cycle is a variation of the Rankine cycle, using a binary fluid pair as the working fluid (typically water and ammonia). **Figure 5-5** shows a schematic view of a Kalina cycle power plant from waste heat. In addition to the classic 4-stage Rankine cycle components (evaporator, turbine, condenser, compressor) there is a distillation-condensation subsystem consisting of a series of separators, heat exchangers, and pumps.

Like ORC, the Kalina cycle is specifically designed for converting thermal energy to mechanical power, optimized for use with thermal sources which are at a relatively low temperature compared to the heat sink (or ambient) temperature. The primary difference between a single fluid Rankine cycle and the Kalina cycle is the temperature profile during boiling and condensation. In the steam turbine and ORC cycles, the temperature remains constant during boiling. As heat is transferred to the working fluid, its temperature slowly increases to boiling temperature, at which point the temperature remains constant until all the fluid 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 in counterflow heat exchangers. Consequently, these systems achieve significantly greater energy efficiency (DOE, 2008). Since the phase change from liquid to steam is not at a constant temperature, the temperature profiles of the hot and cold fluids in a heat exchanger can be made closer, thus making the global efficiency of the heat transfer bigger. For this reason, this cycle is increasingly popular in geothermal power plants, where the hot fluid is very often below 212 ºF (100 ºC).



Source: *Thekdi, 2007.*

Figure 5-5
Kalina Cycle Heat Engine

The Kalina cycle has an operating temperature range that can accept waste heat at temperatures of 250-1,000 °F. Operating efficiencies are around 15% with waste heat temperature of 300 °F. The Kalina cycle is 15-25% more efficient than ORC at the same temperature level. The systems have a relatively high cost ($2,000 to $3,000 per kW capacity) with a large percentage of total cost (capital and maintenance) in heat exchangers (Thekdi, 2007).

Ammonia/water absorption cycle is commercially used for heat-activated refrigeration. Ammonia absorption power system was first patented as the Kalina cycle in 1982, followed by publication in 1984. 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. Waste heat recovery plants using the Kalina Cycle technology are in operation at a Sumitomo Metal steelworks and Fuji Oil's refinery in Tokyo Bay. Geothermal plants exist in Husavik, Iceland, and Unterhaching, Germany, recently built by Siemens. The Kalina cycle trademark and patents are owned by Global Geothermal Ltd, (GGL) the parent of Recurrent Engineering, Inc.

In 1999, GGL installed a 3.5 MW system at the Sumitomo Metal Industries in Japan. This energy recovery power plant utilizes 208°F hot water as a source of heat and is cooled with seawater. The project has an annual energy savings equivalent of over 40,000 barrels of oil per year (Global Geothermal, 2010).

Comparison of Rankine Power Cycles

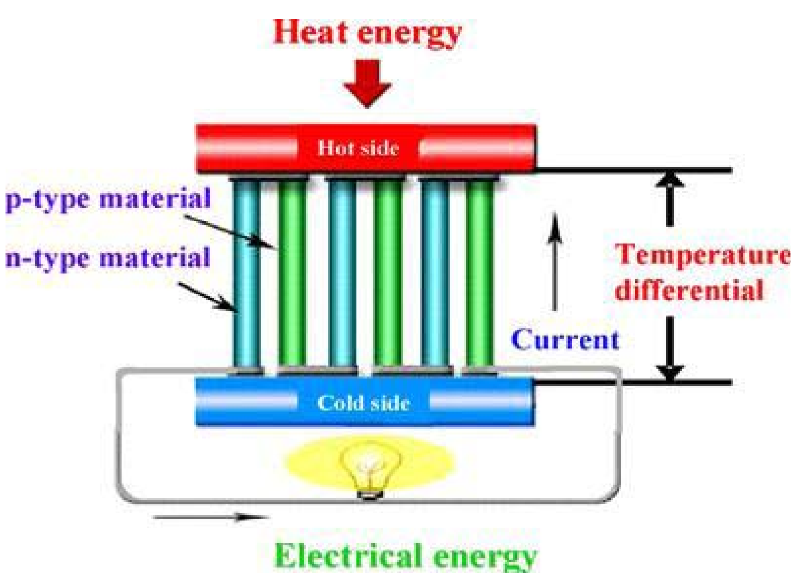
The three types of Rankine cycle power cycles discussed here overlap to a certain degree. However, there are advantages to each. The steam Rankine cycle is the most familiar to industry and is generally economically preferable where the source heat temperature exceeds 800 °F. For lower temperatures, ORC or Kalina cycle systems are used. They can be applied at temperatures lower than steam turbines, below around 500 °F, and they are more efficient in moderate temperature ranges. Kalina systems have the highest theoretical efficiencies. Their complexity makes them generally suitable for large power systems of several megawatts or greater. ORC systems can be economically sized in small, sub-megawatt packages, and they are also well suited to the use of air-cooled condensers, making them appropriate for applications such as pipeline compressor stations that do not have access to water and have no existing water conditioning systems.

Emerging Technologies for Direct Power Conversion

There are a number of advanced technologies in the R&D stage that could, in the future, provide additional options for direct power generation from waste heat sources. These include thermoelectric, piezoelectric, thermionic, and thermo-photovoltaic (thermo-PV) 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.

Thermoelectric Generation

Thermoelectric generation (TEG) converts a heat differential directly into electricity. In a phenomenon known as the Seebeck effect, when two different semiconductor materials are subjected to a heat source and heat sink, a voltage is created between the two semiconductors (**Figure 5-6**). In the reverse of this process, 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.



Source: *Thekdi, 2007*

Figure 5-6
Thermoelectric Generation System

A recent study by PNNL and BCS examines the opportunity for TEG in various industrial waste heat streams and identifies performance requirement and RD&D needs (BCS 2006). The study concluded that advanced TEG 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 (DOE, 2008).

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. Several universities are conducting research on identifying and developing low cost materials that would improve thermoelectric efficiency and reduce cost. While work is mainly in the research phase, there is a start-up company, Alphabet Energy, which has attracted venture capital to develop and commercialize concepts that were researched by the University of California at Berkeley and Lawrence Berkeley National Laboratory. The near term interest for the technology is for military applications, while commercial applications are envisioned within 2-5 years.

Piezoelectric Power Generation

Piezoelectric Power Generation (PEPG) is an option for converting low temperature waste heat (200-300 ºF) to electrical energy. 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 (DOE, 2008) 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
- 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% (DOE, 2008). 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.

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.

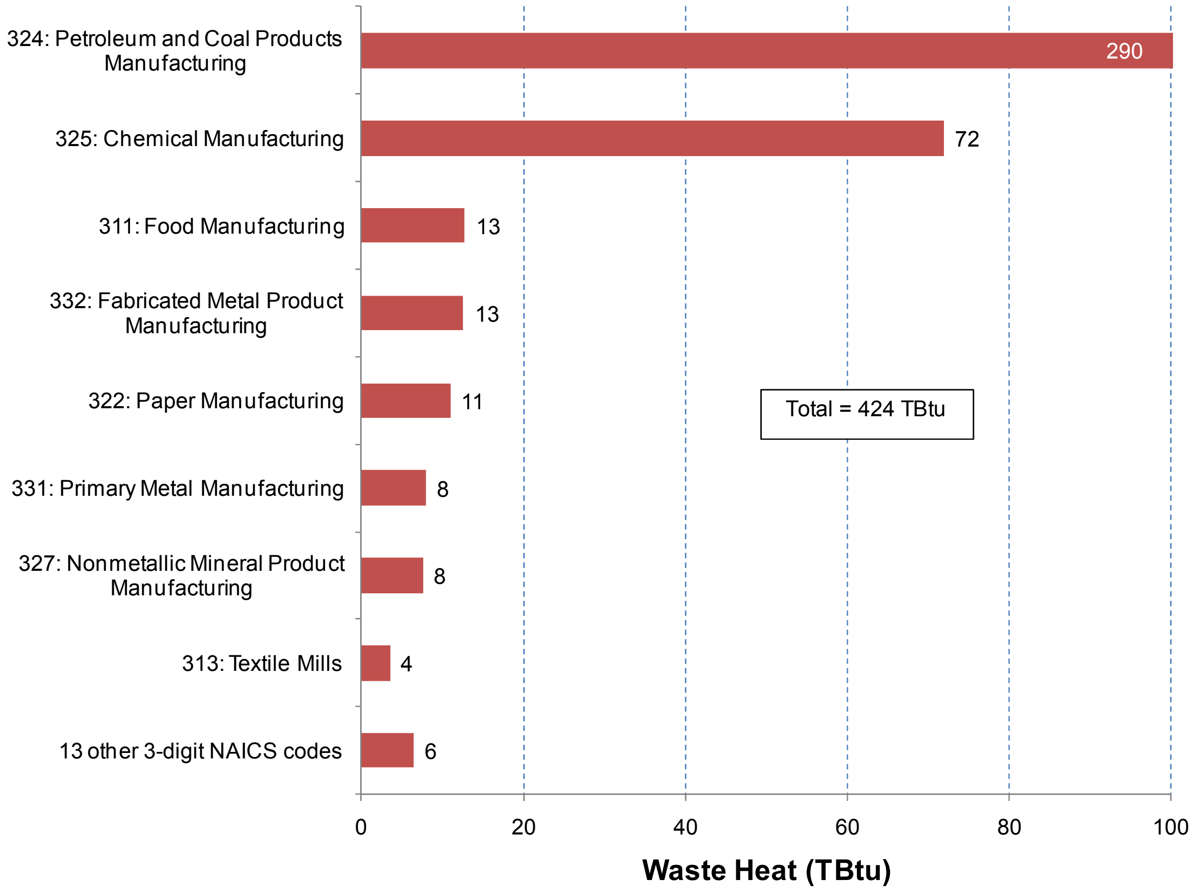
MIT, with the Salt Lake City-based company ENECO, has developed a semiconductor technology that converts heat into electricity using solid state thermionics, a combination of thermoelectrics and thermionics. ENECO produced a single, solid state device that exhibited up to 35% of Carnot efficiency at much lower temperatures (200-600 °F) making it suitable for waste heat applications. The device is a sandwich of three layers of semiconductor. One of the outer layers is heated and the other is kept at ambient temperature. The middle layer is an insulator that maintains the temperature difference. The heat causes electrons to eject, generating an electrical current. (PNNL, 2006) The concept received research support from the Department of Defense and the National Institute of Standards and Technology. In 2008, ENECO filed for Chapter 11 Bankruptcy. Further development of this concept is on hold for lack of financial support.

Thermo Photovoltaic Generator

Thermo-photovoltaic (TPV) generators convert radiant energy into electricity. These systems involve a heat source, an emitter, a radiation filter, and a PV cell. 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. A number of materials are considered for use as an emitter. These materials must have a high melting point, high thermal conductivity, high emissivity, high corrosion resistance, resistance to thermal shock, and be capable of being formed and machined into the required configurations. Materials that have been screened as good candidate emitters include boron nitride, niobium based metal alloys, INCOLOY MA956, silicon carbide and related composites, zirconium oxide/yttrium oxide, and aluminum oxide (Saxton, 1997).. TPV 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 (DOE, 2008).

Applications

As discussed in **Chapter 4**, high quality waste heat is concentrated in a small number of large industries. The eight industries shown in **Figure 5-7** account for 98% of the total estimated waste heat (300 °F basis) from the EPA NEI database (ORNL, 2004). This section describes the waste heat to power opportunities in these industries as well as identified opportunities in other areas.



Source: *UTRC study, NEI methodology (ORNL, 2004)*

Figure 5-7
Waste Heat for Top 8 Industrial Sectors (300 °F reference temperature)

NAICS 324: Petroleum and Coal Product Manufacturing

Petroleum and coal product manufacturing, the largest energy consuming industrial group, includes the production of refined end-use products, such as gasoline, kerosene, and LPG, as well as the production of feedstocks used in other industries, such as chemical manufacturing and rubber and plastics manufacturing. Basic processes used in petroleum refineries include distillation processes (fractionation), thermal cracking processes, catalytic processes, and treatment processes. Although these processes use large amounts of energy, modern refineries use heat produced in exothermic reactions for heating other processes, resulting in integrated heat recovery systems for process use. Many exhaust streams still contain high-quality waste heat that could be recovered for power production. An example is the exhaust from petroleum coke calciners. In the process, petroleum coke is heated to 2400 F; the exhaust is typically 900 to 1,000 F leaving the calciner.

Petroleum refineries operate a large number of topping cycle combined heat and power systems to produce steam and power. Some of these facilities operate combined cycle power plants, producing additional power from a portion of the steam produced by the CHP plants. The use of WHR from process heat streams is not widely practiced. A Kalina cycle WHR power plant is operating in Japan. Commissioned in 2005, the Fuji Oil 4 MW waste heat plant uses heat from two sources, a lightweight hydrocarbon vapor and low pressure steam as part of a waste heat-to-electricity project within the Fuji Oil refinery in Chiba, Japan. According to the builder of this system, Global Geothermal, the project is the first successful integration of a waste heat generation technology with the Eureka process for hydrocarbon processing (Global Geothermal, 2010).

NAICS 325: Chemical Manufacturing

The chemical industry is the second largest consumer of energy in the U.S. according to the 2006 Manufacturing Energy Consumption Survey, accounting for 3.2 quads of energy usage. It has numerous processes with the potential to emit significant amounts of waste heat. The U.S. chemical industry is also extremely diverse, producing on the order of 70,000 products (Energetics, 2000). There are several major sectors of the industry, including petrochemicals, industrial gases, alkalies and chlorine, cyclic crudes and intermediates (e.g., ethylene, propylene, and benzene/toluene/xylene), plastics materials, synthetic rubber, synthetic organic fibers, and agricultural chemicals (fertilizers and pesticides) in which high temperature exhaust is released that could be recovered for power generations.

There are 5 CHP systems in U.S. ethanol plants operating on waste heat produced by thermal oxidizers that are operated for volatile organic compound (VOC) destruction. These five plants have a combined capacity of 17 MW.

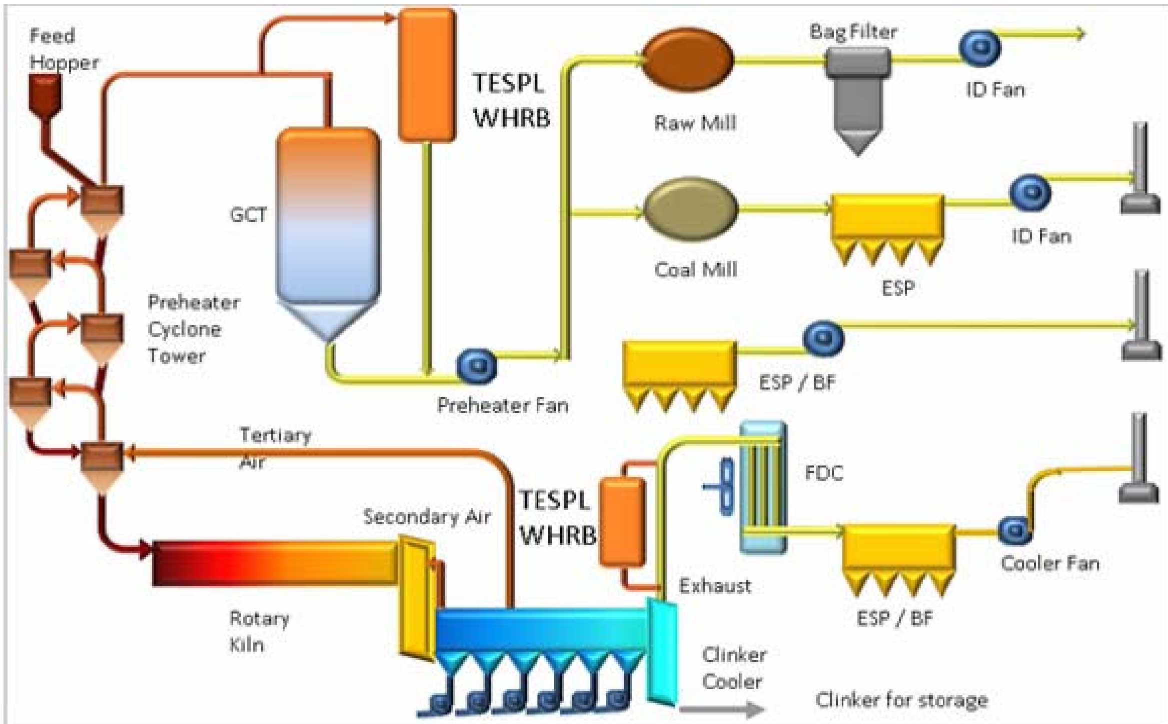
In Yichang City, China, the Yihua Dajiang Compound Fertilizer Co., Ltd, a 600,000 ton/year sulfuric acid plant has installed a heat recovery steam generator system to power a 12 MW steam turbine. The electricity is supplied to Sodium Hydroxide plants in Yihua Chemical Industry Stock Company and the heat is fed to Phosphoric Acid plants in Yihua Dajiang Compound Fertilizer Co. Ltd.

NAICS 327: Non-metallic Mineral Product Manufacturing

The non-metallic mineral products industries, which include cement manufacturing, glass and glass products manufacturing, clay tile and brick material manufacturing, are large consumers of energy with a strong potential for use of WHR for power production. The glass industry uses raw material melting furnaces, annealing ovens, and tempering furnaces, all operated at high temperatures. Modern glass factories use regenerative furnaces to maintain high energy efficiency. In addition, electric boosting is used increasingly on furnaces to improve efficiency and yield, and oxy-fuel firing reduces energy usage and increases efficiency. Clay building products are fired in high-temperature kilns. Clay firing employs tunnel kilns and periodic kilns, depending on the product being produced. Periodic kilns do not represent a good opportunity for heat recovery for power due to their intermittent operation, but tunnel kilns are steadier in output and could provide an economic application.

NAICS 327310: Cement

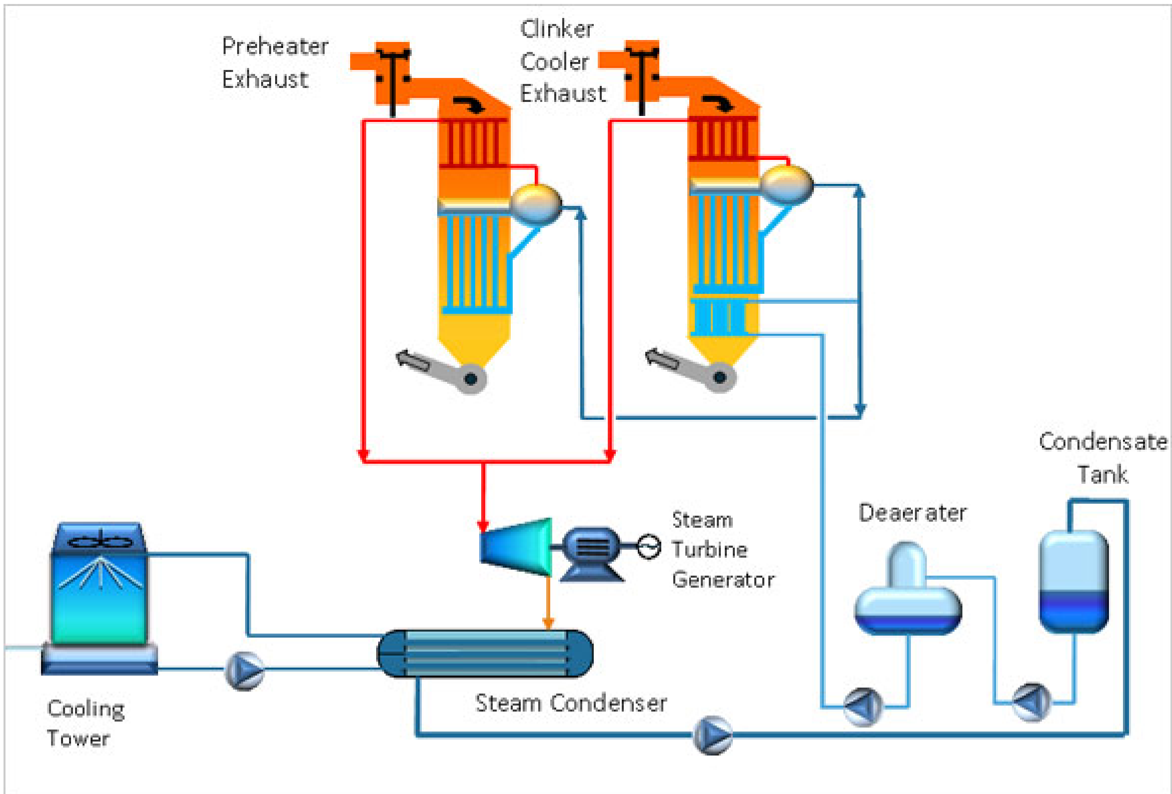
The cement industry uses large rotary kilns operated at temperatures close to 2,000 ^{o}F to produce clinker. More generically, this is a calcining process, also used to produce gypsum, alumina, soda ash, lime, and kaolin clay. There processes produce a high temperature exhaust that can be utilized for WHR to power systems. **Figure 5-8** shows a schematic representation of a 1,700 MT/day cement plant in KCP Ltd, Mancherla, India with WHR to power installation. The system is designed by Transparent Energy Systems Private Ltd (TESPL) with waste heat recovery boilers (WHRB) installed on the cyclone preheater and clinker cooler.



Source: *TESPL, 2010*

Figure 5-8
Cement Process for WHR to Power

Figure 5-9 shows the detail of the cement plant WHR power plant. The boiler is a patented design vertical co-flow boiler suitable to handle highly dust laden gases. Heat is recovered from the flue gas in the form of superheated steam that powers a 2.3 MW condensing steam turbine power generator. The WHRB inlet temperatures are 710 °F from the preheater and 575 °F from the clinker cooler.



Source: *TESPL, 2010*

Figure 5-9
Detail of TESPL WHR Power Plant

Based on the process heat flows analyzed for the U.S. cement industry (DOE, 2008), the total WHR to power potential for cement is estimated at 391 MW as shown in **Table 5–1** . The estimate is based on the waste heat available down to 300 °F. The power capacity was estimated assuming 40% of Carnot efficiency could be achieved by a Rankine cycle power system at a facility operating 7,000 hours per year.

Table 5–1
Waste Heat to Power for Cement Industry (estimated potential)

Source	Total Energy Use (TBtu/yr)	Exhaust Temp (°F)	Waste Heat 300 °F Basis (TBtu/year)	Carnot Efficiency (%)	Power Potential (40% of Carnot) (MW)
Wet Kiln	98	640	9.4	50%	79
Dry Kiln					
No Preheater or Precalciner	80.2	840	12.8	58%	124
With Preheater	67.8	640	7	50%	59
With Precalciner	143.4	640	15.1	50%	128
Total	**389.4**		**44.3**		**391**

Source: *Adapted from BCS (DOE, 2008)*

NAICS 327410: Lime

Lime production is based on another calcining process that occurs in large rotary kilns similar to the cement industry. Graymont, Ltd. has installed a WHR power plant on a new (2008) 1,050 ton/day rotary lime kiln in Pleasant Gap, PA (see **Figure 5-10**). The newest lime kiln incorporates a highly efficient emissions scrubbing system along with 5 MW of power generation from a waste heat recovery system. The waste heat recovery and power generation system is the only one of its kind installed on a lime kiln in North America.

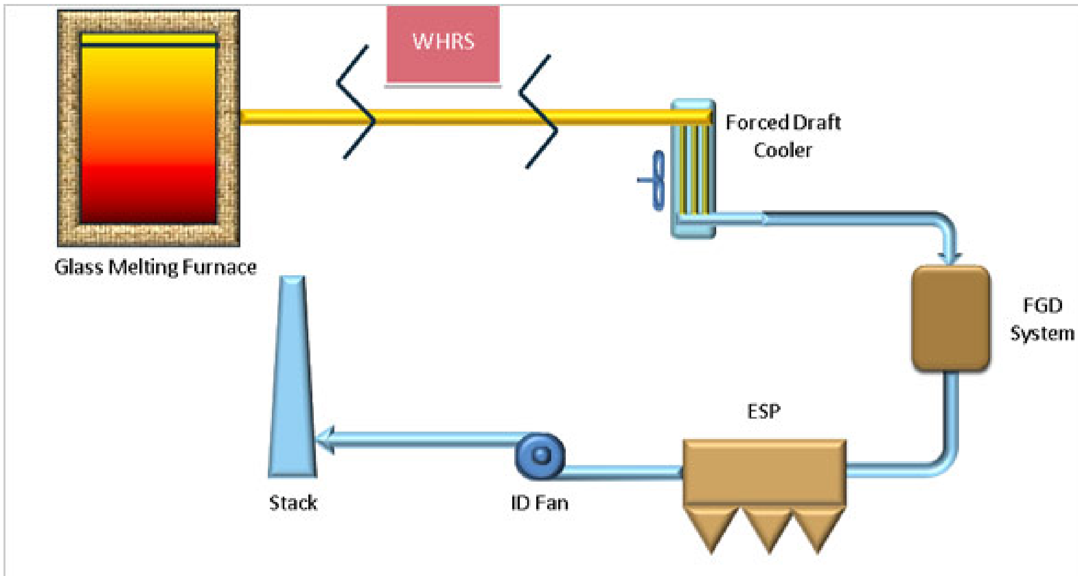
Source: *Graymont, 2009*

Figure 5-10
Graymont, Ltd WHR to Power from Lime Production

Based on the power output (5 MW) and capacity of the Pleasant Gap plant (1,050 tons/day), it is estimated that 4.8 kW per MT per day of lime production is possible. If total U.S. lime production of 19.8 million MT per year installed WHR to power, the total output (350 day/year continuous production) the total WHR power capacity from lime production would be 269 MW (RED, 2010).

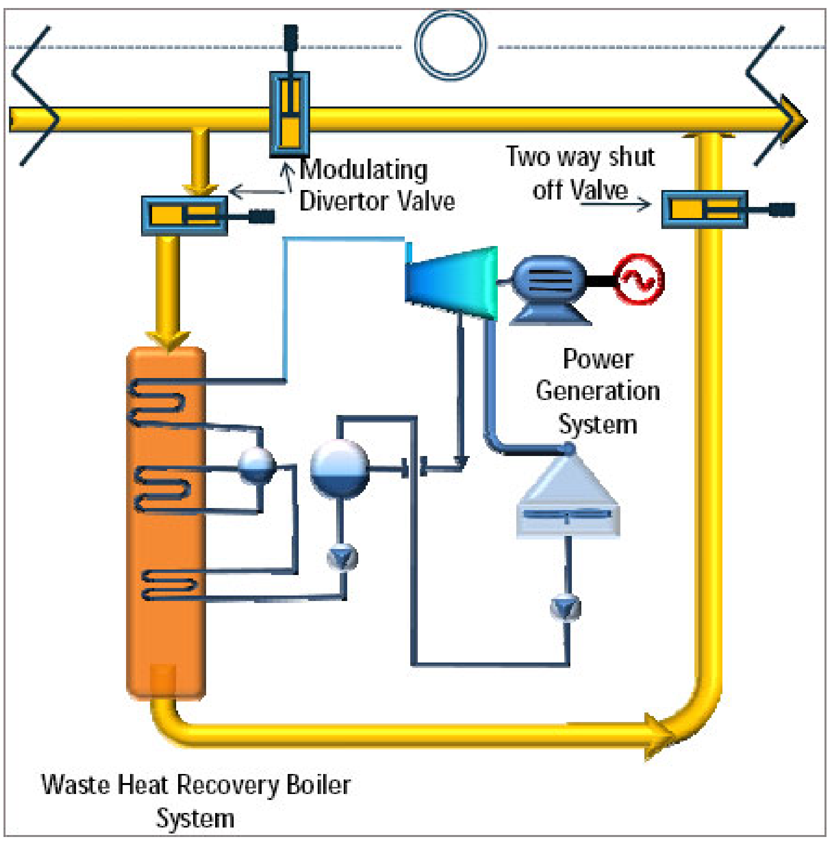
NAICS 327211, 327212: Flat Glass and Container Glass

The glass industry uses raw material melting furnaces, annealing ovens, and tempering furnaces, all operated at high temperatures. Modern glass factories use regenerative furnaces to maintain high energy efficiency. In addition, electric boosting is used increasingly on furnaces to improve efficiency and yield, and oxy-fuel firing reduces energy usage and increases efficiency. TESPL has installed a WHR power plant at a flat glass plant in India. The basic process is shown schematically in **Figure 5-11** and the WHR to power installation detail is shown in **Figure 5-12**.



Source: *TESPL, 2010*

Figure 5-11
Float Glass Production Schematic



Source: *TESPL, 2010*

Figure 5-12
WHR to Power System for Glass Plant

The 1,230 kW WHR to power plant was installed on a 700 MT/day float glass furnace at the Saint Gobain Glass Indian production facility. Exhaust gas from the furnace goes to the stack at high temperature, through a series of gas cleaning steps. There were a number of challenges to WHR in this application. The system needed to maintain negative pressure in the furnace for safe operation. This was accomplished by the use of a control system tied to diverter valves that diverted excess gas as needed to maintain the proper system pressure. There was also dust in the exhaust and the need to maintain heat in the exhaust for the flue gas desulfurization step downstream of the WHR. The condensing steam turbine uses an air cooled condenser (TESPL, 2010).

Based on the process heat flows analyzed for the U.S. glass industry (DOE, 2008), the total WHR to power potential for glass is estimated at 281 MW as shown in **Table 5–2** . The estimate is based on the waste heat available down to 300 °F. The power capacity was estimated assuming 40% of Carnot efficiency could be achieved by a Rankine cycle power system at a facility operating 7,000 hours per year.

Table 5–2
Waste Heat to Power for Glass Industry (estimated potential)

Source	Total Energy Use TBtu/yr	Exhaust Temp °F	Waste Heat 300 °F Basis TBtu/year	Carnot Efficiency %	Power Potential 40% of Carnot MW
Regenerative	54.4	800	6.5	57%	62
Recuperative	13.6	1800	5.4	76%	69
Oxy-fuel	12.8	2600	2.7	82%	37
Electric Boost	34.9	800	3.7	57%	35
Direct Melter	10.1	2400	5.8	81%	79
Total	**125.8**	**---**	**24.1**	**---**	**281**

Source: *Adapted from BCS (DOE, 2008)*

NAICS 33: Primary Metal Manufacturing

Primary metals manufacturing contains a large number of high temperature processes from which waste heat can be recovered. This section describes opportunities in primary iron and steel production, primary aluminum production, metal casting, and silicon/ferro-silicon production.

NAICS 331111: Iron and Steel Mills

Steel mills have a number of high temperature heat recovery opportunities. In integrated mills, waste heat can be recovered from coke ovens, blast furnaces for iron production, and basic oxygen furnaces for steel production. There are also opportunities to recover waste heat from the electric arc furnace in steel "mini-mills" that produce steel largely from recycled scrap. About 46% of steel production in the U.S. now comes from these mini-mills.

This section examines WHR opportunities from coke ovens, blast furnaces, basic oxygen furnaces that are major energy consuming parts of integrated steel production, and at electric arc furnaces that are the major energy consuming process at steel mini-mills.

Coke ovens

Producing coke is an essential part of blast furnace operations. The most commonly used process is the byproduct process. In the byproduct process chemical byproducts (tar, ammonia, and light oils) in the coke oven gas are recovered, while the remaining combustible coke oven gas is cleaned and recycled within the steel plant. Waste heat could be recovered from the hot gas exiting the coke ovens at 1200-1800 °F; however, these gases are full of tars and contaminants that would make heat recovery difficult. Some steel mills in Japan recover about a third of the energy contained in the hot coke oven gas keeping the exit temperature above the condensation point for the tars – about 840 °F.

Another source of waste heat in coke ovens is the waste gases exiting the flue at 400 °F from combustion of the recycled and cleaned coke oven gas. (DOE, 2008)

Blast Furnace

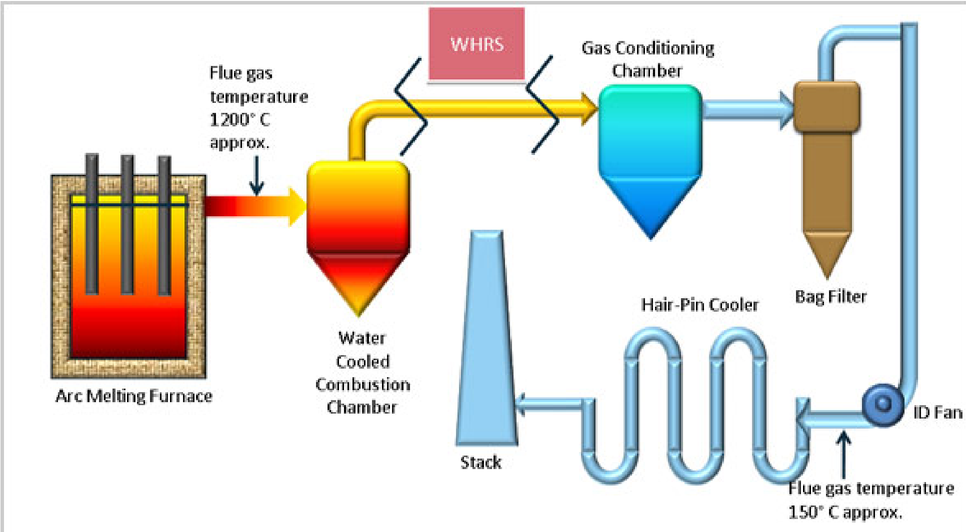
The blast furnace converts iron ore into pig iron. Older blast furnaces had high exhaust temperatures around 900°F New furnaces have been designed for more efficient heat transfer; consequently, exhaust gases are in the low temperature range. Sensible heat loss is estimated at 5 TBtu/year. Blast furnace gas is itself a low Btu fuel that is recovered and used within the mill, often blended with other fuels to increase its heating value. There are 910 MW of existing CHP capacity using blast furnace gas as the input fuel. These systems are not included in the waste heat recovery potential, which is based solely on the physical specific heat contained in the exhaust gas and not the value of the gas as an internally produced fuel.

Basic Oxygen Furnace

The basic oxygen furnace (BOF) uses oxygen to refine pig iron into steel. The heat required for the refining and melting process is provided by the exothermic reaction within the furnace. For U.S. production, the very high temperature off-gases from the BOF equal 27 TBtu/yr of waste heat. 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. Heat recovery is more costly and maintenance intensive due to contaminants in the exhaust stream.

Electric Arc Furnace

About 46% of total U.S. steel production comes from scrap-based “mini-mills” that use an electric arc furnace to melt and refine scrap into new steel. Waste heat recovery opportunities are shown in **Figure 5-13**. Waste heat exits the EAF at about 2,200 °F. The heat can be captured in a waste heat recovery steam boiler for conversion to power, use in district heating operations, or in other on-site needs. The most common form of heat recovery in EAF operation is scrap preheating.



Source: *TESPL, 2010*

Figure 5-13
Waste Heat Recovery from Electric Arc Furnaces

Iron and Steel Industry Summary

Table 5–3 summarizes the energy use, waste heat recovery potential and potential WHR power capacity for exhaust heat streams in primary iron and steel production in the U.S. WHR potential is 57 TBtu/year which could support 692 MW of WHR power capacity. Processes with low temperature exhaust streams or low temperature cooling water (induction heaters/melters) are not considered commercially viable because of the low heat source temperature.

Table 5–3
Waste Heat to Power for Iron and Steel Mills (estimated potential)

Source	Total Energy Use TBtu/yr	Exhaust Temp °F	Waste Heat 300 °F Basis TBtu/year	Carnot Efficiency %	Power Potential 40% of Carnot MW
Coke Oven	65.5	---	---	---	---
Coke Oven Gas	---	1800	13.9	76%	177
Coke Oven Waste Gas	---	392	10	36%	60
Blast Furnace	642.3	---	---	---	0
Blast Furnace Gas	---	200	---	---	0
Blast Stove Exhaust	---	---	---	---	0
No Recovery	36.2	482	1.9	42%	13
with Recovery	34.1	266	---	---	0
Basic Oxygen Furnace	49.7	3100	26	85%	369
Electric Arc Furnace	---	---	---	---	---
no recovery	57.7	2200	5.4	80%	72
with recovery	13.3	400	0.1	37%	1
Total	**828.6**	**---**	**57.3**	**---**	**692**

NAICS 331312: Primary Aluminum Production

The U.S. has 300 aluminum production plants consuming about 770 TBtu/year. There is energy recovery potential from the exhaust from the Hall Heroult cells and secondary melting as shown in **Table 5–4** (DOE, 2008). These waste exhaust streams have a potential for 85 MW of power production.

In addition to the small exhaust losses from primary aluminum production in Hall Heroult cells, there are also an estimated 55 TBtu/year of sidewall losses through, conduction, convection, and radiation. Presently, there is no commercial way to reduce or recover these sidewall losses as they are necessary to maintain a frozen crust along the walls to minimize corrosion of the refractory. In the future, it may be possible to design thermoelectric power production into the sidewalls that can produce power and control sidewall heat transfer (DOE, 2008).

Table 5–4
Waste Heat to Power for Primary Aluminum Production (estimated potential)

Source	Total Energy Use TBtu/yr	Exhaust Temp °F	Waste Heat 300 °F Basis TBtu/year	Carnot Efficiency %	Power Potential 40% of Carnot MW
Hall Heroult Cells	134.6	1,292	2.2	69%	25
Secondary Melting	---	---	---	---	---
no recovery	9.3	2,100	4.2	79%	55
with recovery	2.2	1,000	0.4	63%	4
Total	**146.1**	**---**	**6.8**	**---**	**85**

NAICS 331112: Silicon/Ferrosilicon Production

Silicon and ferrosilicon alloys are produced in electric arc melters. Batch melters have exhaust gas temperatures that range from 625 to 2,550 °F during the cycle. This temperature swing makes heat recovery difficult. Continuous charge furnaces have much lower temperature swings with an average exhaust temperature of about 1,400 °F.

Recycled Energy Development is building a 65 MW waste heat recovery power plant at a silicon plant in West Virginia. The proposed plant will produce power from the arc furnace exhaust at a rate of 0.54 MW/MW. This rate of production is possible because, in addition to the electricity, a large quantity of coal and other combustible materials are charged into the furnace to achieve the necessary reduction of silicon dioxide to silicon metal (RED, 2010).

Silicon manufacture requires about 1.20 kWh of electricity per MT of silicon (Hjartarson, 2009). Based on the U.S. production of silicon and ferrosilicon alloys of 300,000 MT per year, the total U.S. potential for power generation from silicon manufacture is 196 MW. This estimate is based on the assumption of continuous charging, a practice that may not be widely practical for a low volume product like silicon.

NAICS 3315: Ferrous and Nonferrous Foundries

Metal foundries contain a variety of waste heat sources, such as melting furnace exhaust, ladle pre-heating, core baking, pouring, shot-blasting, castings cooling, heat treating, and quenching.

The highest temperature waste heat sources are the off gases from melting and heat-treating furnaces. The exhaust from the heat-treating furnaces is the cleanest steady temperature source, free of particulates and corrosives. Pouring and core baking are also high-temperature waste heat sources, but economic utilization is difficult because of the intermittent nature of waste heat generation or the relatively small streams.

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. Aluminum reverberatory furnaces are only 30-35% efficient and have exhaust temperatures of about 2,000-2,400 °F. Stack melters, while more efficient (40-45%), are less commonly used due to higher maintenance costs and more restrictive requirements on charging. Stack melters have exhaust temperatures of about 250-400 ºF.

Melting furnaces for iron casting include Induction furnaces, electric arc furnaces, and cupola furnaces. Cupolas make up about 60% of the total melting capacity in the industry (DOE, 2008). The efficiency of cupola furnaces has improved substantially in recent years ranging from 5 MMBtu/ton for older models to 3.4 MMBtu/ton for newer designs. Older cupolas are about 50% efficient with exhaust gas temperatures ranging from 1,500-1,800 °F. Newer furnaces employing recuperators have exhaust temperatures of 400 °F (DOE, 2008). Induction heating and melting furnaces have water cooling circuits that produce low temperature waste heat. These low temperatures, below 150 °F, are not attractive for power generation using commercial technology; however, advanced systems might be applied in the future.

Table 5–5 shows the energy consumption, waste heat produced, and WHR power potential for aluminum and iron foundries. Theoretically, 303 MW of power could be produced from this waste heat; however, the current practice and focus within the industry is to achieve greater heat recover through the use of recuperators for air preheating, thereby reducing the energy requirements for the melting process.

Table 5–5
Waste Heat to Power for Foundries (estimated potential)

Source	Total Energy Use TBtu/yr	Exhaust Temp °F	Waste Heat 300 °F Basis TBtu/year	Carnot Efficiency %	Power Potential 40% of Carnot MW
Aluminum					
Reverb Furnace	19.0	2,100	8.5	79%	112
Stack Melter	1.1	250	---	---	---
Iron Cupola					
no recovery	46.7	1,650	15.3	74%	190
with recovery	7.8	400	0.2	37%	1.0
Total	**74.6**	**---**	**24.0**	**---**	**303**

NAICS 332: Fabricated Metals

Processes generating waste heat include metal pre-heating, heat treatment, cleaning, drying, and furnace heating.

Based on the UTRC waste heat analysis (ORNL, 2004), the energy emissions by temperature range for fabricated metals processing total 12.6 TBtu/year and range from 300-700 °F. The estimated WHR power production potential for this quantity and quality of waste heat is estimated to be 79 MW.

All other Manufacturing

Based on the UTRC waste heat analysis (ORNL, 2004), the energy emissions by temperature range for all other manufacturing industries total 10 TBtu/year. Over 70% of this energy is available at less than 500 °F, but there is some energy available at higher temperatures. The estimated WHR power production potential for this quantity and quality of waste heat is estimated to be 74 MW.

Other Markets

There are other markets with WHR to power potential in addition to industrial applications. These markets include:

- Engine and gas turbine exhaust heat recovery
  - Natural gas pipeline compressor stations
  - Landfills with power generation using landfill gas
- Flare gas
  - Landfills without power generation
  - Oil and gas production operations
- Steam pressure reduction
  - District heating customers
  - Industrial customers (not included in WHR estimate from previous section)

Natural Gas Compressor Stations

There are 15 ORC power generation systems installed at natural gas compressor stations in North America. These systems have a total electric capacity of 75 MW using the exhaust heat from 247,000 hp of gas turbine driven compressors. As shown in **Table 5–6,** if all of the 16.9 million hp of U.S. gas pipeline compressor capacity employed WHR to power systems, the total capacity would be over 2,500 MW. Based on an industry evaluation of the opportunity, the economic market today is limited to gas turbines over 15,000 hp with annual load factors exceeding 5,250 hours. With these parameters, the economic market for WHR to power is 900 MW (Hedman, 2008).

Table 5–6
Waste Heat to Power for Natural Gas Compressor Stations (estimated potential)

Waste Heat Recovery (WHR) to Power Production Rate		
Installed WHR to Power Capacity	75,500	kW
Compressor HP for Installed Systems	504,000	HP

Output Potential	0.15	kW/HP
Technical Potential		
Total U.S. Compressor Capacity	16.9	million HP
WHR to Power Potential	2,532	MW
Projected Economic Market		
Gas turbine drive > 15,000 HP and greater than 5,250 hours/year operation	900	MW

Source: *Hedman, 2008*

Landfill Gas

There are two opportunities for WHR at landfills. At those facilities that use engines or turbines to produce power, there is an opportunity for additional power generation using ORC systems to generate power from the exhaust gases. Those facilities that do not have energy recovery could install ORC to generate power from the WHR from the gas flaring.

The potential for WHR to power at sites that already generate power using engines or turbines is 268 MW, based on the quantity of electric only power systems from these technologies and the waste heat available from the engine exhaust (EPA, 2010). **Table 5–7** shows the number of existing electric only projects at landfills and the potential power that could generated by adding Rankine bottoming cycles.

Table 5–7
Waste Heat to Power for Landfills (estimated potential)

Generation Type	Sites	Power Capacity	Recoverable Exhaust Heat		Exhaust Temp	Electric Gen. Eff.	WHR Power Potential
		MW	Btu/kWh	TBtu/yr	°F	%	MW
Reciprocating Engine	417	1,206	2,063	21.2	939	24.7%	180.1
Gas Turbine	38	232	5,179	10.2	961	24.9%	87.9
Combined Cycle	8	98	No or Low Potential				
Microturbine	15	5					
Organic Rankine Cycle	1	0					
Steam Turbine	21	171					
Stirling Cycle Engine	2	0					
Total	**502**	**1,712**	**---**	**31.4**	**---**	**---**	**268.0**

According to EPA, there are 520 candidate landfills that do not currently recover energy from landfill gas flaring. EPA estimated that 1,156 MW of power could be generated at these sites, assuming reciprocating engines were used. Based on the differential efficiencies of engine generation and Rankine cycle generation, the power potential if steam or Organic Rankine cycle systems were added is 857 MW.

The total WHR to power potential in landfills is the sum of bottoming cycles that could be added to existing power projects plus the potential from sites that currently do not recover energy, or a total of 1,125 MW of Rankine cycle power generation.

Flare Gas in Oil and Gas Production and Processing

In oil and gas production, methane-containing gases are vented and flared throughout the production cycle. Flares are used for both background and upset (emergency) use. This methane can be recovered and used for local power production. A 2005 LBNL study estimated the total potential of power production from this source at 260 MW (LBNL, 2005).

Steam Pressure Reduction

A market niche is developing for small back pressure steam turbine power systems to be installed in parallel with steam pressure reducing valves (PRV) for applications where steam is produced or delivered at a higher pressure than needed. This situation typically exists for commercial or industrial facilities that are connected to a steam district heating system or for industrial sites that have a centralized high pressure steam production and distribution system with multiple steam using applications, many of them at low pressure.

A customer of a district heating system may receive steam at 200 psig and require only 15 psig for an absorption chiller. A PRV typically is used to reduce pressure in this case. The PRV does not recover energy or work from the pressure reduction. A back pressure steam turbine, on the other hand, can be used to generate power. This power generation is not "free" energy, because the work performed by the turbine removes energy from the steam flow. The efficiency of this power generation, however, is very high – approaching the original boiler efficiency. With an 80% efficient boiler, power can be generated in this manner at a heat rate of under 4,500 Btu/kWh (HHV). Technically, this is not WHR because the heat removed for power generation must be resupplied to meet the end-use steam need. However, this process is included in many discussions of WHR to power.

This opportunity also exists within industrial facilities where steam generation is often at a higher pressure. This application was not included in the previous sections discussing industrial WHR to power potential.

LBNL estimated the power potential from steam pressure reduction at 290 MW for customers connected to district heating systems and 2,100 MW for industrial applications. The industrial estimate was based on a rather generous assumption that 40% of industrial steam use is or could be generated at a higher pressure than is needed (LBNL, 2005).

The total 2,390 MW of power would require an additional 75 TBtu/year of fuel consumption but would avoid 175 TBtu/year of fuel that would be required to generate the equivalent amount of power in central power stations. Therefore, this application could potentially save 100 TBtu/year in fuel use.

Summary of Waste Heat Recovery to Power Potential

Industrial Waste Heat Recovery

Table 5–8 provides a synthesis of the total WHR to power market potential by industry sector based on the analyses of UTRC and BCS with two additional sectors analyzed by Recycled Energy Development (RED). Total technical potential for WHR to power for the industrial sector is estimated at 5,852 MW.

Table 5–8

Waste Heat to Power by Industrial Market Sector (estimated potential)

NAICS	Industry	Source	Power Generation Potential (MW)
311	Food	UTRC	98
322	Paper	UTRC	66
324	Petroleum and Coal Products	UTRC	2,594
325	Chemicals	UTRC	724
327	Nonmetallic Minerals	---	---
327211, 327212	Glass	BCS	281
327310	Cement	BCS	391
327410	Lime	RED	269
331	Primary Metals	---	---
331111	Primary Iron and Steel	BCS	692
331312	Primary Aluminum	BCS	85
331112	Silicon, Ferrosilicon	RED	196
3313, 3315	Metal Casting	BCS	303
332	Fabricated Metals	UTRC	79
	All other Industry	UTRC	74
Total			**5,852**

Sources: *UTRC (DOE, 2004), BCS (ORNL, 2008), and RED (RED, 2010)*

WHR from Other Markets

The total estimate potential from other markets is 6,307 MW as shown in **Table 5–9**. The total combined estimate of WHR to power production in all markets is over 12,000 MW.

Table 5–9
Waste Heat to Power for Other Markets (estimated potential)

Industry	Source	Power Generation Potential (MW)
Natural Gas Compressor Stations	ICF	2,532
Landfill Gas	EPA LMOP	1,125
Flare Gas Heat Recovery	LBNL	260
District Heating Steam Pressure Recovery	LBNL	290
Industrial Steam Pressure Recovery	LBNL	2,100
Total	**---**	**6,307**

Sources: *Adapted from Hedman (Hedman, 2008), EPA, (EPA, 2010), and LBNL (LBNL, 2005)*

Economic and Environmental Considerations

WHR to power systems include the power generation system (steam, ORC, or Kalina cycle), the waste heat recovery equipment (boiler or evaporator), power conditioning and interconnection, and soft costs associated with getting the project in place. The costs of the different Rankine cycle power systems are fairly similar, differing more as a function of size than type. A detailed cost comparison for each type and size of system was beyond the scope of the project. However, a simple comparison is presented in **Table 5–10**. Costs are shown for a representative large system (>5 MW) and a small system (<400 kW). The capital costs shown are representative costs quoted by developers and vendors (DOE, 2010). Capital costs are amortized over a 20 year life at 8% interest. O&M costs estimates vary widely. A range of $0.002 -$0.010/kWh was chosen for this comparison. Rankine cycle power systems have low maintenance costs; however, the heat recovery and boiler maintenance must also be considered. For WHR to power projects, there are no fuel costs. The waste heat is free. For steam pressure reduction projects, there is an incremental fuel cost. WHR to power costs range from 3.1 to 7.5 cents/kWh. With the added fuel costs ranging from $6.50-7.00/MMBtu, steam pressure reduction power costs range from 6 to 10.7 cents/kWh.

Table 5–10
Waste Heat to Power Cost Comparison

Cost Component	Large System	Small System
Capital Costs, $/kW	$2,000-2,500	$3,500-$4,500
WHR to Power Generating Costs		
Amortized Capital, $/kWh	$0.029-0.036	$0.051-0.065
O&M Costs, $/kWh	$0.002-0.005	$0.005-0.010
Power Cost, $/kWh	**$0.031-0.041**	**$0.056-0.075**
Steam Pressure Reduction Power Costs		
Amortized Capital, $/kWh	$0.029-0.036	$0.0510-0.065
O&M Costs, $/kWh	$0.002-0.005	$0.005-0.010
Added Fuel Costs	$0.029-0.032	$0.029-0.032
Power Cost, $/kWh	**$0.060-0.070**	**$0.085-0.107**

The potential carbon dioxide emissions savings from deploying all of the 12,000 MW of WHR to power potential are shown in **Table 5–11**. The savings are based on the average utility grid CO_2 emissions rate of 1,329 lb/MWh (EPA, 2008) with 6.55% line losses (U.S. grid average 2008.) The power systems are assumed to operate an average of 7,000 hours/year. The waste heat projects have no added CO_2 emissions. The pressure reduction projects do have added emissions – calculated on the basis of natural gas combustion at a 4,500 Btu/kWh heat rate. The total emissions savings equal 50.7 million MT of CO_2 per year.

Table 5–11
Potential Carbon Dioxide Emissions Savings from WHR to Power Projects

Market	Technical Potential (MW)	CO_2 Emissions (million MT/year)		
		Avoided	Added	Net Savings
Industrial WHR	5,852	26.3	--	26.3
Other WHR	3,917	17.6	--	17.6
Industrial Pressure Reduction	2,100	9.4	3.5	5.9
District Heating Pressure Reduction	290	1.3	0.5	0.8
Total	**12,159**	**54.7**	**4.0**	**50.7**

Commercialization Status

This section describes the available products and vendors, the status of market penetration of systems to date, barriers to further implementation, and areas of research and development needed.

Products and Vendors

This section lists products and manufacturers for heat cycle power generation using steam, ORC, or Kalina cycle systems.

Small Steam Power Equipment Suppliers and Developers

Steam Power LLC, Milford OH – Steam Power is a system supplier of steam turbine generator sets. The company provides packaged systems that operate at back pressure and condensing modes. Steam Power also supplies steam boiler heat recovery systems to improve steam plant efficiency which improves CHP system payback. Additionally, Steam Power refers consulting engineers and CHP project developers to clients who can benefit from steam turbine generator installations. For me information, see http://www.stmpwr.com/Steam_Power/Home.html.

Anguil Environmental Systems Inc – Anguil produces waste heat recovery boilers. They installed an air to steam; waste heat recovery boiler to recover exhaust waste heat from a natural gas fired regenerative thermal oxidizer and produce 25 psig steam. For more information, see http://www.anguil.com/company.aspx.

Alternative Energy Solutions (AES), a subsidiary of Wichita Burner, Inc. is an integrator of renewable energy technologies having to do with biomass gasification and conservation through CHP. AES focuses on the delivery of modular, proven technologies that either provide energy from biomass or reduce consumption of petroleum products through CHP systems. The company is also a provider of solid fuel-fired (biomass-fired) energy producing equipment, steam powered electrical generators, and CHP units. They provide biomass-fueled generators and heat exchangers to make steam, hot water, hot oil, or hot air when electricity is desired. AES also delivers heat and electricity modules in the PowerTherm CHP unit. For more information, see http://www.wichitaburner.com/.

Primary Energy Ventures LLC, Oak Brook IL – Primary Energy builds, owns, and operates innovative Recycling Energy facilities in the United States serving its customers' needs for reliable, low-cost, and environmentally sustainable electric and thermal energy. The company's core competency is capturing and using waste energy and fuels with proven technologies and otherwise utilizing traditional fuel more efficiently, thus lowering costs. Primary Energy's

Recycling Energy projects generate thermal and electric energy on site with less reliance on the external power grid, minimizing costs and exposure to system vulnerabilities. Partnering with Primary Energy allows a customer's team to focus on its own core business. Recycling Energy is the efficient conversion of traditional fuels, waste fuels, and waste heat into useful heat and power. Recycling Energy includes:

- Recovering the heat or fuel value of exhaust streams normally vented or flared.
- CHP projects that efficiently use traditional and nontraditional fuels.
- And the use of solid and liquid byproduct fuels that extract electricity from pressure drop across thermal and gas distribution systems (more information at http://www.primaryenergy.com/projects.htm).

TurboSteam Corporation, Turners Falls, MA – Manufacturer – Designs, manufactures, commissions, and finances packaged "heat-first" CHP projects that extract zero-cost, zero-emission electricity from existing waste heat and/or pressure flows. Founded in 1986, the company has installed 166 systems in 38 states and 18 countries as of February, 2004. For more information, see http://www.turbosteam.com/what_ts_offers.html.

Skinner Power Systems, LLC - Erie, PA – Manufacturer, Service Company – Custom manufacturer of single stage steam turbines available with capacities from 0.5 hp to 3,000 hp. Specifications of turbines include 900 psi maximum inlet gauge pressure, 900 psig inlet pressure, 900 degrees F maximum inlet temperature, 175 psig backpressure, 150 psi maximum exhaust gauge pressure, 18-28 in. wheel pitch diameter and 800-7,000 rpm speed. Features of turbines include mechanical drive and electric generating packages, oil relay governor, trip units, ball and sleeve bearing, ball thrust, carbon ring gland seal, stainless steel blades, nozzles, valves, shafts and strainers. For more information, see http://www.skinnerpowersystems.net/content/.

Siemens Corporation, Multiple Locations – Manufacturer, Custom Manufacturer, Manufacturers' Rep, Service Company – Worldwide manufacturer of steam turbines. Industrial steam turbines are available in power ratings up to 250 MW with either single casing direct drive/geared drive or dual casing geared drive. Large scale steam turbines are available in power ratings up to 1200 MW. For more information, see http://www.powergeneration.siemens.com/prod.

A B Industrial - West Chester, PA – Distributor, Manufacturer, Custom Manufacturer, Service Company – Manufacturer and distributor of steam turbines under the brand names Coppus, Elliot, Prime, Prime-Air, Terry, and Tuthill. For more information, see http://www.abpump.com.

Elliott Company, Multiple Locations – Manufacturer, Custom Manufacturer, Service Company – Manufacturer of geared and steam turbines. Specifications of turbines include 650 psig to 1,500 psig initial pressure, 750 degrees F to 900 degrees F initial temperature, 100-375 psig exhaust pressure, 5,000-8,500 rpm speed, 12-28 in. wheel pitch dia., 3 in. ... to 10 in. inlet sizes, 6 in. to 42 in. exhaust size and 200 hp to 10,000 hp power. Features of turbines include split casings, casing joints, balanced rotors, journal and thrust bearings, steam seal covers, steam chests, bearing case seals, inner and outer slingers, water jacketed bearing housings, carbon ring steam seals and oil, nozzle and carbon rings. For more information, see http://www.elliott-turbo.com/turbines.asp.

Dresser-Rand, Multiple Locations – Manufacturer – Manufacturer of COPPUS brand steam turbines, 45-3000 kW capacity, Coppus, MA; Murray Turbines, up to 20,000 kW, Burlington, IQ; and Tuthill Nadrowski turbines, up to 4,500 kW, Germany. For more information, see www.dresser-rand.com.

Carrier Corporation, multiple locations – MicroSteam Power System – Carrier is offering a small steam turbine generator, up to 275 kW, that allow facilities to generate power instead of using pressure reducing valves for reducing steam pressures. Since the system is designed to deliver steam to the facility after power generation, it is not a bottoming cycle, nor does it reduce the quantity of waste heat at a facility. For more information, see http://www.commercial.carrier.com/commercial/hvac/product_description/1,3059,CLI1_DIV12_ETI434_PRD1638,00.html.

ORC Equipment Suppliers and Developers

Ormat Technologies, *Reno, NV*. Ormat has over 1,000 MW of ORC generation deployed worldwide, the vast majority of this capacity in geothermal power applications, though they have developed a market for power generation from heat recovered at natural gas pipeline compressor stations. Ormat recovered energy generation systems are based on a pre-packaged Ormat Energy Converter (OEC) that consists of a vaporizer/preheater, turbine generator, air-cooled condenser and feed pump. Ormat participates in the compressor heat recovery market as an equipment supplier, turn-key EPC, and third party build/own/operate developer. Ormat serves as a third-party build, own, and operate developer. Ormat currently owns and operates seven systems on compressor stations. They also operate an eighth system for a third-party developer, MDU.

GE Oil and Gas, Houston, TX. GE Oil and Gas announced the introduction of the ORegen waste heat recovery system in January 2009. The ORegen system appears to be designed specifically to match with GE gas turbines including PGT25, PGT25+, PGT25+G4, MS5001, MS50002C, MS5002D and MS6001B models. Expected power generation output ranges from 6.9 MW to 15.6 MW across the gas turbine models. The ORegen ORC system was developed by Nuovo Pignone SpA business unit, mostly likely using Rotoflow (another GE business unit) expanders. There is no evidence of GE actively marketing the ORegen system in the United States at this time. The U.S. Department of Energy announced a research project with GE in December 2008 to optimize the ORC system by eliminating the secondary heat exchanger loop (i.e., incorporating a direct evaporator design). DOE's justification of the project indicated that "current waste heat recovery technologies, including organic Rankine cycles … are technically feasible but economically unattractive. This limits their current use to a small number of niche applications." It is unknown if GE has installed any ORegen units in commercial duty.

Turbine Air Systems, Houston, TX. TAS is a designer and manufacturer of pre-engineered, pre-packaged, modular chilled water and CHP systems. They supply chiller packages from 200 to 8,000 tons and CHP systems from 1 to 10 MW. TAS is currently developing a series of pre-engineered, modular waste heat ORC systems in the 1, 3 and 7 MW size range. TAS's initial market focus appears to be geothermal and industrial waste heat applications, but they are searching for developer partners to pursue the compressor drive market. The TAS ORC design has the potential to deliver more power per gas turbine hp than the current Ormat systems. TAS is working with Ridgewood Power on an initial commercial demonstration of their technology in an industrial waste heat application.

UTC Power, South Windsor, CT. UTC has commercialized a 250 kW ORC system named the PureCycle. Market focus has been on geothermal applications exclusively. The current design is focused on small, medium-temperature applications. UTC has announced plans to develop a 1 MW system, but status of this development is unknown.

WOW Energies, Houston, TX. WOW is developing the WOWGen ORC power unit. WOW's unique cascading heat recovery design has the potential for increased efficiency and power output compared to conventional ORC systems on the market. There are no WOWGen systems in commercial operation at this time.

Turboden, Italy. Turboden manufactures and sells a broad range of ORC units ranging in size from 500 kW to 2 MW. They have over 90 systems in operation in Europe, primarily in biomass recovery systems. They have no systems operating on reciprocating engines or gas turbines. They do not appear to be active in North America or in the compressor drive market.

Barber-Nichols, Inc., Arvada, CO. Barber-Nichols is a broad-based turbomachinery manufacturer that produces a line of ORC units for waste heat recovery and geothermal applications. They have commercial units as large as 2 MW producing geothermal power.

GMK, Germany. GMK produces modular ORCs in the 0.5 to 5 MW size range for geothermal and biomass applications. They are developing the INDUCAL unit for industrial and engine waste heat recovery. No commercial INDUCAL units are in operation at this time.

TransPacific Energy, Carlsbad, CA. TransPacific is developing a multi-refrigerant ORC that has the potential for greater efficiency and power output than commercially available systems. They do not appear to have any systems in commercial operation.

Infinity Turbine, LLC, Madison, WI. Infinity markets a 225 kW modular ORC package. They do not appear to have any systems in commercial operation.

Turbo Thermal Corp., Austin, TX. Turbo Thermal markets ORC packages in the 100 kW to 5 MW size range. Information on their web page suggests the system needs a $0.10/kWh power price for sufficient project economics. They do not appear to have any systems in commercial operation.

NRGreen Power, Alberta, Canada. NRGreen Power Limited Partnership, an entity related to Alliance Pipeline Limited Partnership (Alliance Pipeline), was established in 2002 to pursue the commercial development of electrical generation opportunities associated with the Alliance Pipeline system. They have four operating systems on pipeline compressors in Saskatchewan under long-term (20 year) power agreements with SaskPower. They have plans to construct three additional units on the Alberta portion of the pipeline.

EnPower Green Energy Generation, Inc., British Columbia, Canada. EnPower is an independent power producer (IPP) owned by Pristine Power (an independent IPP) and Enmax Corp (an energy distribution, supply and service company wholly owned by the City of Calgary). They currently have two compressor ORC systems in operation, one under construction and two under contract and in advanced planning.

Recycled Energy Development (RED), Westmont, IL. RED designs, builds and operates industrial heat recovery power projects. They have no ORC installations or systems installed on pipeline compressor drives at this time.

Ridgewood Renewable Power, LLC. Ridgewood, NJ. Ridgewood is an owner/operator of renewable energy projects including landfill gas and biomass. They have expressed interest in pursuing the compressor drive market with ORC technologies but to date have no installations in place. Ridgewood is working with TAS to on a commercial demonstration of the TAS ORC in an industrial waste heat application.

Electra-Therm, Carson City, NV – Electra-therm has developed a packaged waste heat ORC generator for low temperature heat recovery called The Green Machine based on their screw expander. The power The 50 kW system has been installed at a community college in Kalamazoo, MI, a solar farm in Hawaii, and Southern Methodist University in Dallas, TX.

Calnetix Power Solutions – Waste heat power generator (EPA CHP Partner). For more information, see http://www.calnetixps.com/.

Kalina Cycle Equipment Suppliers and Developers

Global Geothermal Limited, technical engineering arm Recurrent Engineering – GGL offers both packaged and modular Kalina cycle power systems. GGL provides 50 kW packaged systems to modular systems of several megawatts for recovered energy in industrial applications and binary geothermal applications. The company focus is on medium and low temperature heat sources. Recovered energy power generation includes capturing unused waste heat from industrial processes and converting it to electricity for sale to third parties or for use on site without additional fuel costs and zero emissions. GGL has provided systems for a number of commercial installations:

- 1991 – 5 MW demonstration power plant – Canoga Park demonstration project in southern California – In this 5-year demonstration project of a Kalina cycle operating from the exhaust of a gas turbine which heated the cycle working fluid directly. No intermediate heat transfer fluid is required.
- 1999 – 3.5 MW power plant at Sumitomo Metal Industries in Japan – This energy recovery power plant utilizes 208 °F hot water as a source of heat and is cooled with seawater.
- 2005 – 4 MW power plant at Fuji Oil in Chiba, Japan – The plant recovers waste heat from two sources, a lightweight hydrocarbon vapor and low pressure steam. The project is the first successful integration of a waste heat generation technology with the Eureka process for hydrocarbon processing.
- 2009 – 3.4 MW geothermal project –Siemens completed a turn-key geothermal power plant for the town of Unterhaching, Germany. After successful acceptance tests, the plant was transferred into the ownership of, and operation by, the town of Unterhaching at the beginning of April 2009. Siemens has worked with Recurrent Engineering, which is also a part of Global Geothermal Ltd, in the commissioning of the project, although Siemens retained responsibility for the design and construction phases.
- 2010 – 50 kW packaged system production agreement with Johnson Controls – GGL with Johnson Controls is providing two packaged systems for Japanese geothermal energy developer, Geothermal Energy Research and Development (GERD). GERD received funding for its project from NEDO, Japan's department of energy. Both of the geothermal fluid powered, Kalina Cycle technology units are sized for 50 KW of continuous electrical output, and will be deployed at Japanese hot springs resorts to offset power purchased from the local utility.

- 2010 – 50 kW solar heat recovery – Shanghai Shenghe New Energy (SSNE) planning solar thermal application for the Kalina Cycle. Traditional solar water heaters will be placed on the 3000 m^2 roof of a Chinese pavilion, and the resultant hot water will transform into electricity to power the pavilion. A novel storage array will also be demonstrated to allow the pavilion to be powered up from when the sun goes down until the exhibition closes.
- 2010 – 50 kW geothermal demonstration – GGL and SSNE have designed and manufactured a 50kW demonstration geothermal plant for an area in south western Tibet currently without power. This plant, assembled in two weeks from standard industry components, was reportedly shipped to the site, located at an elevation of 15,000 feet (4,600 meters), for commissioning in mid 2010.

An ammonia absorption unit whose main output is electrical power is currently under development at Energy Concepts. Absorption is the most efficient mode of converting low-grade heat into electricity. This cycle can be designed to provide power solely or in addition to refrigeration.

Energy Power Products, Annapolis, MD – Energy Power Products is primarily engaged in providing packaged absorption chiller equipment for a variety of applications. They are also developing an absorption power product. A 25 kW prototype was scheduled for testing at the University of Alaska in Fairbanks during the winter of 2010. A commercial 150 kW unit was scheduled for demonstration at an Alaskan fishing village in mid 2010.

Thermoelectric Technology: Equipment Suppliers and Developers

Alphabet Energy, Inc:, Berkeley, CA – This startup company, housed at the UC Berkeley Haas School of Business incubator has the development rights to thermoelectric technology and concepts developed by the University of California at Berkeley and Lawrence Berkeley National Laboratory. The company has received $320,000 in Small Business Innovation Research (SBIR) grants from the U.S. Army, Air Force, and the Department of Energy. They have also raised a million dollars from venture capital funds. The company is planning a pilot installation at an industrial facility in 2011 with commercial marketing to begin in 2012. http://www.alphabetenergy.com/)

Market Penetration

Market penetration of WHR to power projects is very limited compared to other types of distributed generation. Currently, there are 60 projects in place totaling 753 MW of power generation capacity. **Table 5–12** shows the breakdown of this capacity by industry. Existing systems are concentrated, for the most part, in the industries identified previously as having the most potential for WHR to power. Small capacity systems in the commercial market are based on steam pressure reduction systems where the back pressure steam turbine is used in place of a pressure reducing valve. **Table 5–13** shows the breakdown by state. There are 29 states with existing CHP projects.

Table 5–12
Existing Waste Heat to Power Projects by Industry

Industries	Sites	Capacity MW
Oil and Gas Extraction	1	1
Food	2	4

Furniture and Fixtures	2	0
Paper	2	1
Chemicals	18	334
Petroleum Refining	5	100
Non-metallic Mineral Industries	4	54
Primary Metals	4	183
Miscellaneous Manufacturing	1	7
Gas Compressor Stations	14	66
Health Services	3	2
Education	1	0
Engineering, Accounting, Research	1	0
Justice, Public Order, Safety	1	0
National Security and International Affairs	1	1
Total	**60**	**753**

Source: *ICF CHP Database*

Table 5–13
Existing Waste Heat to Power Projects by State

States	Sites	Capacity MW	States	Sites	Capacity MW
CA	7	48.3	NC	1	0.2
CO	1	4.0	ND	4	22.0
DE	1	4.5	NE	1	2.0
FL	7	293.1	NV	1	5.5
ID	1	2.8	NY	1	1.4
IL	1	78.0	OH	1	46.0
IN	1	94.0	PA	4	8.3
KS	2	8.0	SD	4	21.5
LA	2	26.4	TX	3	47.6
MA	3	1.4	UT	1	7.5
MD	1	3.0	VA	1	0.1
MI	1	0.5	VT	1	0.03
MN	5	14.0	WI	1	0.6
MS	1	6.0	WY	1	0.4
MT	1	5.5	---	---	---
Total				**60**	**752.6**

Source: *ICF CHP Database*

Barriers

Barriers to successful implementation of WHR to power projects include technical issues, business considerations, and regulatory issues.

Technical/Economic Barriers

The principal technical issues for WHR to power systems lie with the heat recovery itself. The power generation equipment is commercially established and relatively standardized, but each heat recovery situation presents unique challenges. The principal technical/economic issues relating to heat recovery are as follows;

- Inability to economically capture/recover low-temperature heat with existing heat exchanger or heat-storage technology
- Inability to cost-effectively capture very high temperature exhaust heat
- Need to integrate power system control with existing process controls
- Plot limitations making WHR to power systems difficult or impossible to site economically

Business and Market Barriers

Moving out of the severe recessionary period 2007-2008, the focus of industry is on survival. Businesses are focused on restarting or continuing existing production. Industry is reluctant to make investments, especially in energy recovery systems that are outside of their core business. These concerns lead to unrealistically high project hurdle rates. Many industries are now requiring paybacks of one year or less.

There is a lack of end-user awareness of the technologies or how to implement them. There are few technology demonstrations or case studies. There is a resistance to accept new, unproven technology that could benefit or jeopardize existing processes.

Banks are reluctant to finance WHR to power projects because they are technically complicated, and they combine the risk associated with the power plant with the risk inherent in the primary business. There is no heat to recover if the plant shuts down. Financing is also difficult for small projects (less than $4 million) because the returns do not cover the fixed time needed for due diligence, permitting, and siting.

The current low natural gas prices are also a barrier. There is less economic incentive for WHR.

Regulatory Barriers

There are also regulatory barriers to WHR to power project deployment. Some projects require a power purchase agreement with the utility. All such projects installed to date are in states with renewable portfolio standards that recognize waste heat as a renewable or "renewable equivalent" resource. Currently, only 10 states recognized WHR as a renewable resource.

There are also few incentives for WHR to power projects like investment tax credits or incentive payments for carbon emissions reduction, economic development, grid support, or other external benefits.

Research and Development

There are three areas of research needs in WHR to power systems:

- Heat recovery and heat transfer
- Power generation including direct heat to power systems

- Control, integration, and packaging

The research needs in heat recovery parallel the previously stated technical barriers. There is a need to develop more cost effective heat recovery systems for both low and high temperature applications. Cost effective heat recovery in hot, dusty, corrosive environments requires work on materials that can withstand these conditions, automatic methods of cleaning heat exchanger surfaces, better design tools for predicting and designing heat transfer equipment, and design approaches that deal with corrosion by making it easy to isolate and replace sacrificial heat exchanger zones without the need to remove the entire system.

Steam and organic Rankine cycle power generation are both fairly mature technologies. There is a need for design and packaging improvements that will bring the capital costs down for small systems. Developments in power electronics can help systems to optimize the speed of the turbines without the need for mechanical gearing. Early Kalina cycle power systems experienced operational problems that affected reliability and longevity of components. Additional development and demonstration in this area is warranted.

The direct heat to power systems – thermoelectric, piezoelectric, thermionic, and thermophotovoltaic – all need extensive R&D to make them commercially viable. As previously noted, start-up company, Alphabet Energy, Inc. is planning a thermoelectric pilot facility at an industrial installation in 2011. There are a two current developments being funded by the Advanced Research Projects Agency – Energy (ARPA-E) within the U.S. DOE. ARPA-E waste heat projects include:

- Advanced Semiconductor Materials for High Efficiency Thermoelectric Devices, Phononic Devices, Inc. – Phononic Devices' design concepts are projected to dramatically improve thermoelectric efficiency from less than 10 percent today to more than 30 percent, resulting in significant energy savings for power generation and cooling. If successful, this project would open new opportunities for domestic power generation
- Harvesting Low Quality Heat Using Economically Printed Flexible Nanostructured Stacked Thermoelectric Junctions, University of Illinois – The University of Illinois is developing flexible, thermoelectric modules composed of silicon nanotubes and an economic and highly scalable approach to fabricate such modules. The modules' structural flexibility will enable their deployment in diverse settings with minimal customization of heat exchangers and use of real estate. For example, the modules could be put to immediate use in power plants, data centers, and automobiles.

There is also a need for controls development in target applications to allow integration of process control with the control of the WHR to power system.

6
INDUSTRIAL HEAT PUMPS

Heat pumps are a well established technology for heating and cooling buildings, and millions of units have been installed in residential and commercial applications. Heat pumps are also used in many industrial plants. Similar to residential and commercial systems, industrial heat pumps have the unique ability to move heat from a low temperature heat sink to a high temperature heat source (i.e., move energy up the temperature gradient). However, there are important distinctions between industrial heat pumps and residential and commercial units, including:

- Industrial heat pumps operate predominantly in a heating mode (residential and commercial systems frequently provide both space heating and space cooling)
- For industrial applications, the heat source is typically a waste heat stream, and the heat sink is generally a process stream used elsewhere in the plant (most residential and commercial heat pumps move heat from outside air to indoor air)
- While not a strict definition, industrial heat pumps typically have a heat output of greater than 250,000 Btu/hr (EPRI, 1988, p. 1-3).
- Industrial heat pumps are generally custom engineered to meet site specific conditions (most residential and commercial heat pumps are produced as packaged systems and manufactured in large volume).

While heat pumps have achieved significant market penetration in residential and commercial markets, the adoption of industrial heat pumps has been limited. Factors that have contributed to low market penetration include lack of awareness and unfavorable performance from some early generation industrial heat pumps installed in the 1970s and 1980s (EPRI, 1988, p. 1-7; IEA, 1995, p. XIII). However, current generation heat pump technology provides high reliability, and modern heat pumps can be a cost effective option for recovering energy from waste heat streams.

This chapter is intended to provide information to utility personnel, plant engineers, and other stakeholders that are interested in applying industrial heat pump technologies. This chapter is organized as follows:

- Technology Descriptions
- Applications
- Economic and Environmental Considerations
- Commercialization Status

Technology Descriptions

Industrial heat pumps use a working fluid, or refrigerant, to move heat from a relatively low temperature fluid stream (heat source) to a higher temperature fluid stream (heat sink). Work is required to move heat “uphill” against the temperature gradient, and in heat pumps this work can be provided in the form of either mechanical energy (e.g., a compressor) or thermal energy. The refrigerant flow path and the type of energy input are two distinguishing features that are frequently used to group common commercially available heat pumps into the four categories shown in **Table 6–1**. As indicated, the four primary types of heat pumps are (all four types are described in more detail after the table):

- Closed cycle vapor compression
- Open cycle vapor compression
- Open cycle thermocompression
- Closed cycle absorption (Type 1 and 2)

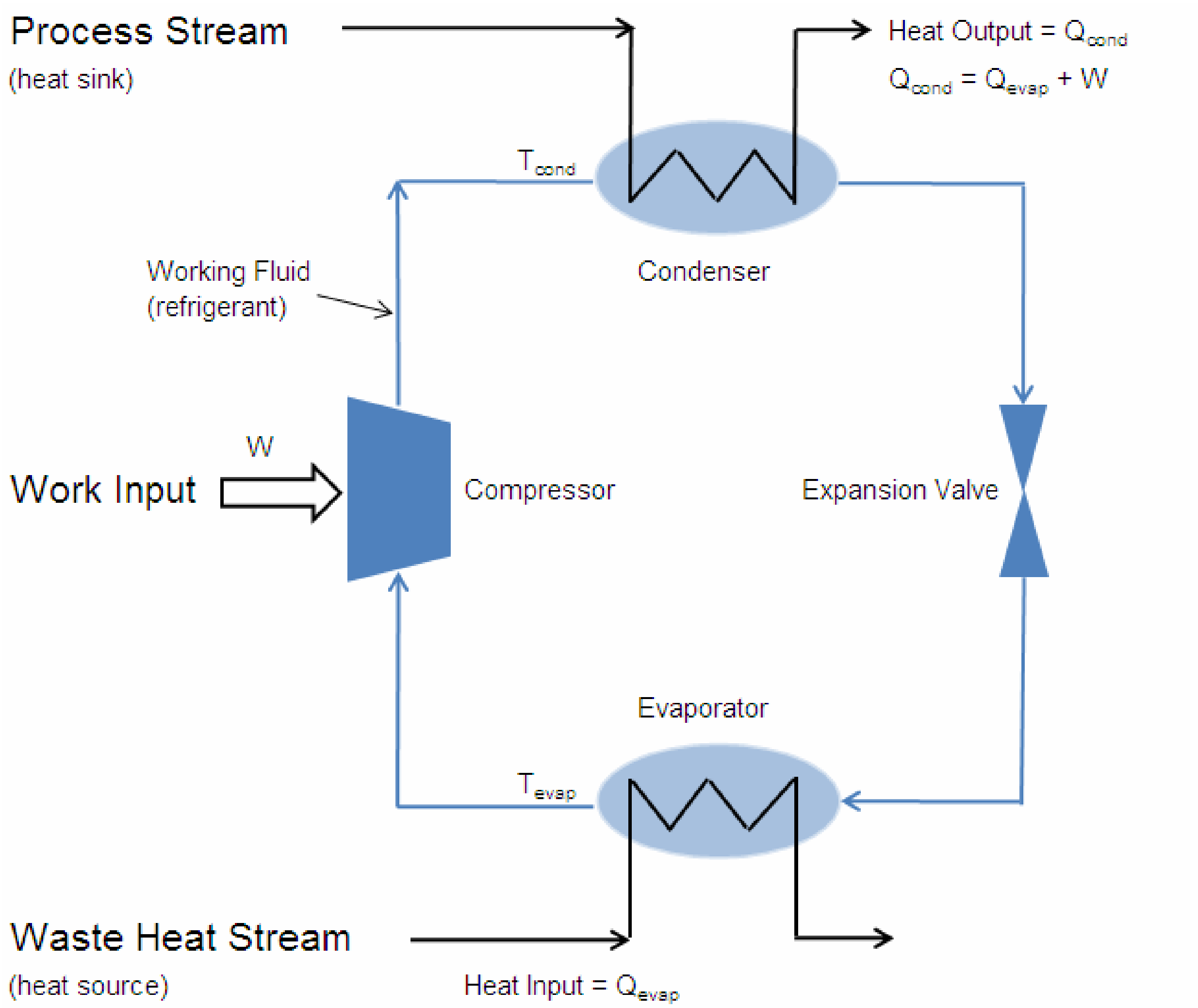
Table 6–1
Common Types of Industrial Heat Pumps

Refrigerant Path	Type of Drive	
	Mechanical	Thermal
Closed cycle	Closed cycle vapor compression	Closed cycle absorption (Type 1 and 2)
Open cycle	Open cycle vapor compression – also called mechanical vapor recompression (MVR)	Open cycle thermocompression – also called thermal vapor recompression (TVR)

Closed Cycle Vapor Compression

Closed cycle mechanical vapor compression heat pumps use mechanical compression of a working fluid (refrigerant) to move heat. A simple flow diagram for this type of heat pump, which operates in much the same way as a typical residential or commercial heat pump, is shown in **Figure 6-1**. As indicated in this figure, a waste heat stream provides the heat source, and a process stream, which is at a higher temperature than the waste heat stream, serves as the heat sink. Compression (work input) is achieved with a mechanical compressor typically driven with an electric motor. The compressor can also be driven by a steam turbine, internal combustion engine, or combustion turbine. The term "closed cycle" means that the refrigerant is recirculated and physically separated from the waste heat and process streams. Common refrigerants for closed cycle vapor compression heat pumps are R-22, R-134a, R-416A, and R-717[3] (Nyle, 2010; Lewis, 2009). The maximum temperature that can be reached for the heat sink (process stream in **Figure 6-1**) is usually limited to 250 ^{o}F, and the COP typically ranges from 2 to 6 (Lewis, 2009).

[3] R-717 is the designation for ammonia (NH_3).



Source: *Adapted from DOE, 2003, p. 2*

Figure 6-1
Closed Cycle Mechanical Vapor Compression Heat Pump

As indicated in **Figure 6-1**, the four main hardware components are:

- **Evaporator** – Heat is extracted from the waste heat stream and used to evaporate a refrigerant.
- **Compressor** – The compressor increases the temperature and pressure of the refrigerant vapor.
- **Condenser** – The refrigerant vapor is condensed, which librates heat. This heat is added to a process stream at the plant site, increasing the temperature of this process stream.
- **Expansion valve** – The refrigerant pressure is reduced to the evaporator operating conditions.

The efficiency of a mechanical vapor compression heat pump – and most other types of heat pumps – is reported in terms of the coefficient of performance (COP), which is the ratio of energy added to the process stream to the work added (COP = Qout / W). The maximum theoretical efficiency that can be achieved with a heat pump is described by the Carnot efficiency, which is a function of the condenser and evaporator temperatures. The Carnot COP is derived from the first law of thermodynamics, and is defined as (temperatures are absolute):

$$COP_{Carnot} = T_{cond} / (T_{cond} - T_{evap})$$

The term "$T_{cond} - T_{evap}$" is referred to as the temperature lift of the heat pump. Temperature lift should not be confused with the temperature change of either the waste heat stream or the process stream. Due to heat transfer limitations, the temperature lift will always be greater than the temperature difference between the heat source (waste heat stream) and the heat sink (process stream being heated).

The Carnot COP equation shows that the efficiency of a heat pump declines as the temperature lift increases (see **Figure 6-2**). In practice, actual heat pump efficiency is always lower than the Carnot efficiency. For many heat pumps, experience has shown that actual efficiencies are 65% to 75% of the Carnot efficiency (DOE, 2003, p. 13).

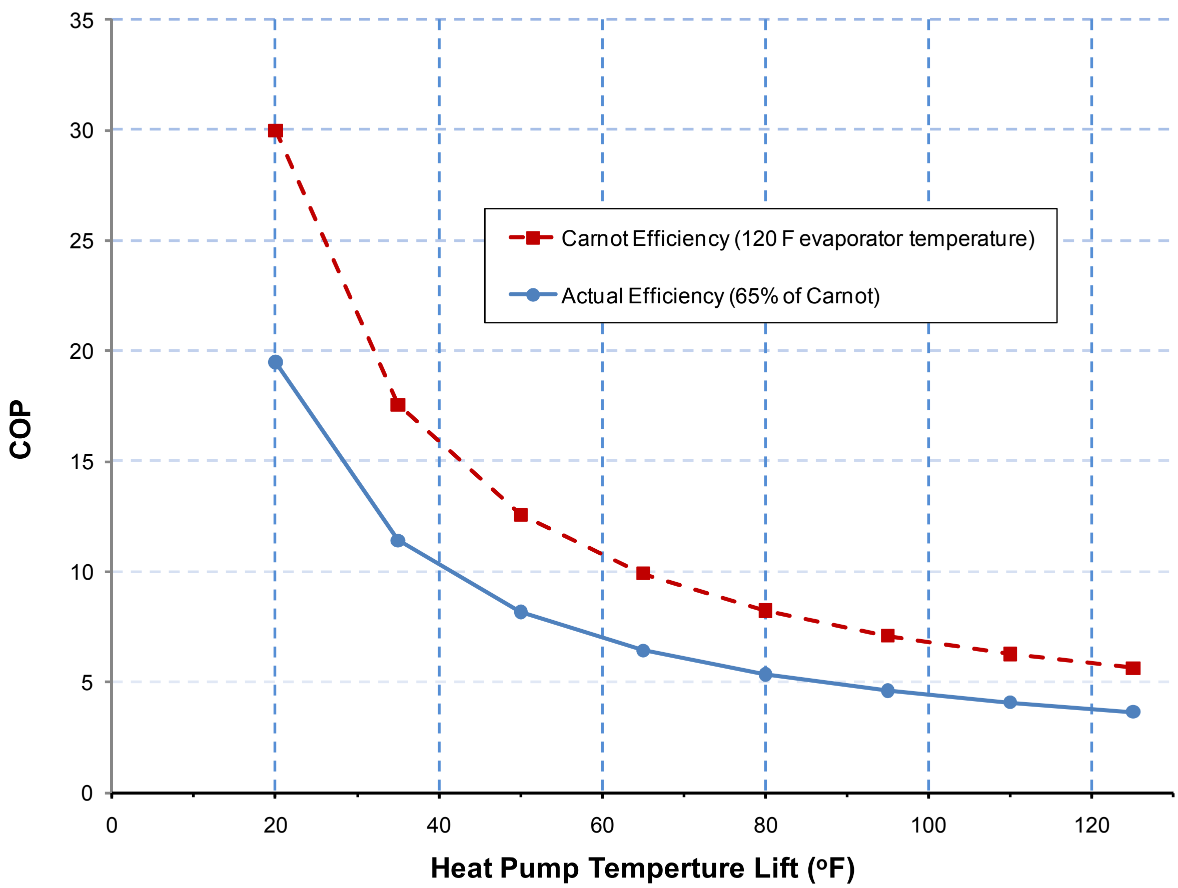
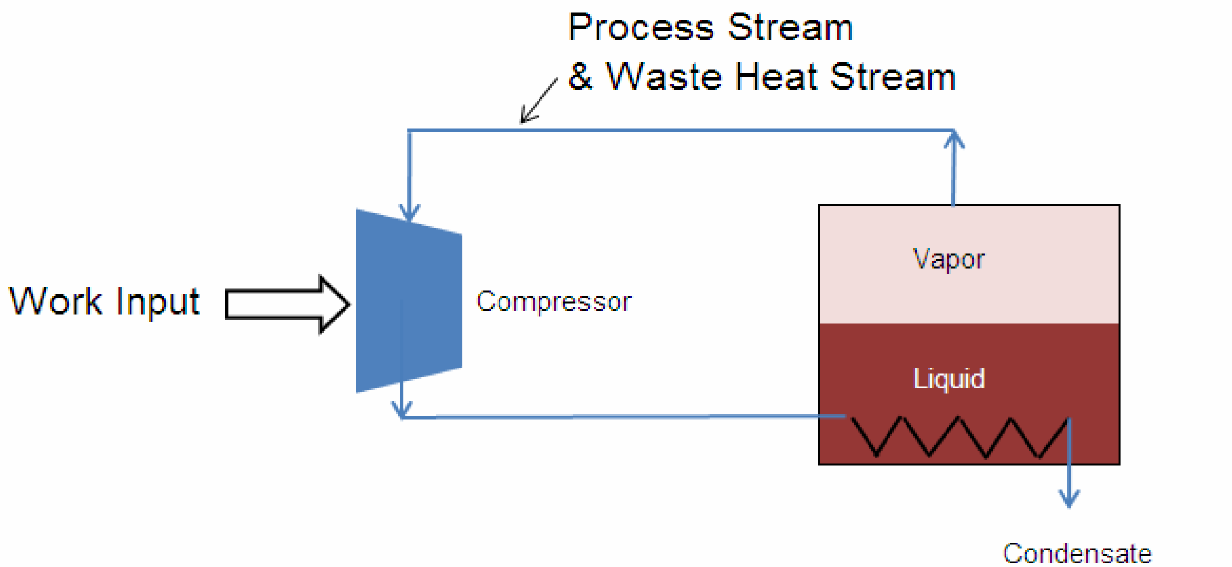


Figure 6-2
Relationship of Temperature Lift and COP

Open Cycle Vapor Compression

Open cycle vapor compression heat pumps are also referred to as mechanical vapor recompression (MVR) systems. In an MVR heat pump, the process stream (vapor) acts as both the waste heat stream and the heat pump working fluid (see **Figure 6-3**). These heat pumps are frequently used in evaporation and distillation operations.

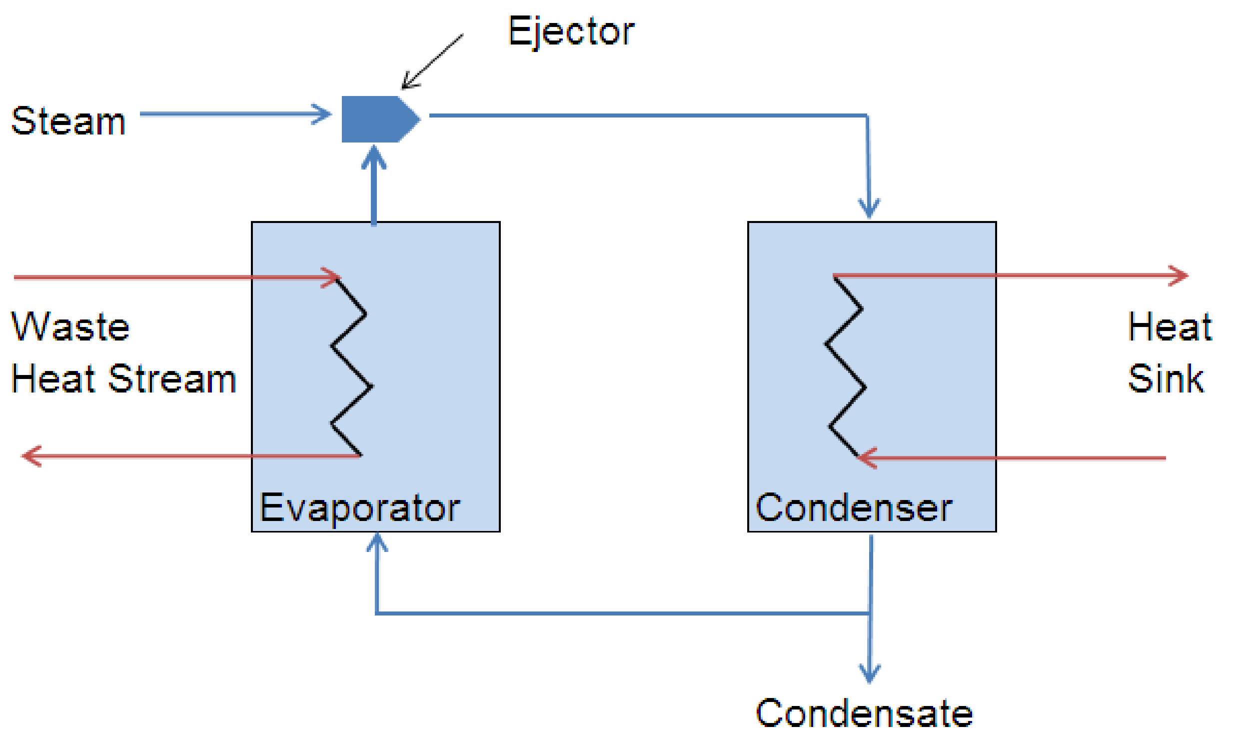


Source: *Adapted from EPRI, 1988, p. 2-5*

Figure 6-3
Open Cycle Vapor Compression Heat Pump

Open Cycle Thermocompression

Open cycle thermocompression heat pumps are also referred to as thermal vapor recompression (TVR) systems, jet compressors, vapor jet heat pumps, or steam ejectors. These heat pumps normally use jet-ejector technology that is steam driven. TVR heat pumps are simple mechanical designs with no moving parts. Required steam pressures are typically in the range of 100 to 200 psi. **Figure 6-4** shows a typical thermocompression heat pump used in an evaporation process.

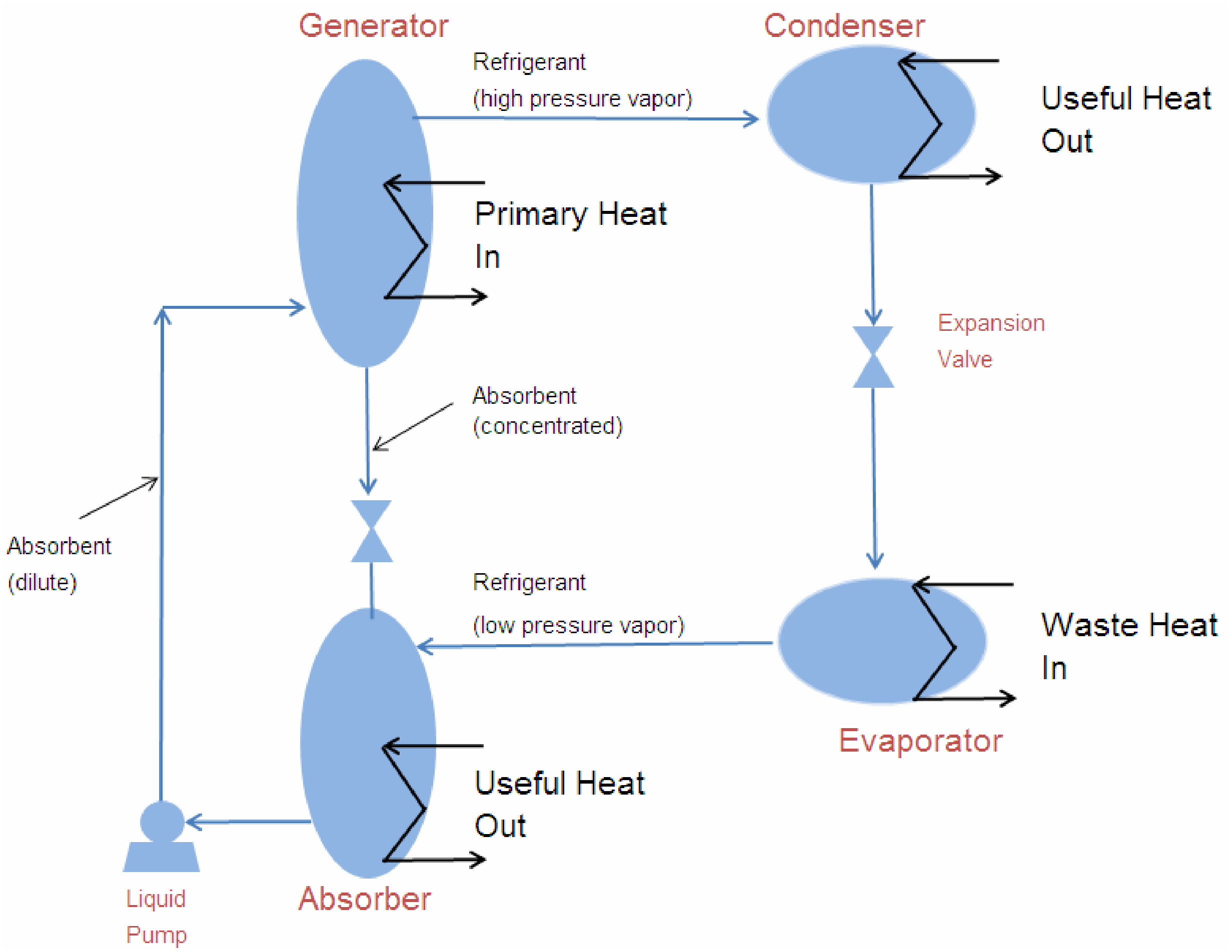


Source: *Adapted from IEA, 1995, p22*

Figure 6-4
Thermal Vapor Recompression (TVR) Heat Pump

Absorption

Absorption heat pumps are thermally driven closed cycle systems. The major components of an absorption cycle are shown in **Figure 6-5**. In an absorption cycle, there are two working fluids; a refrigerant and an absorbent (e.g., water and lithium bromide). The waste heat stream supplies energy to the evaporator where the refrigerant is evaporated (much like a closed cycle mechanical compression heat pump). The refrigerant vapor is then absorbed at low pressure by the absorbent, generating useful medium temperature heat. The absorbent, now diluted with refrigerant, is pumped to a higher pressure using a liquid pump. High pressure refrigerant vapor is then produced by heating the mixture in a generator using a primary energy source (e.g., a natural gas fired burner). The refrigerant vapor is then condensed in a condenser, and this process produces medium temperature heat, which can be recovered. The refrigerant is then passed back to the evaporator.



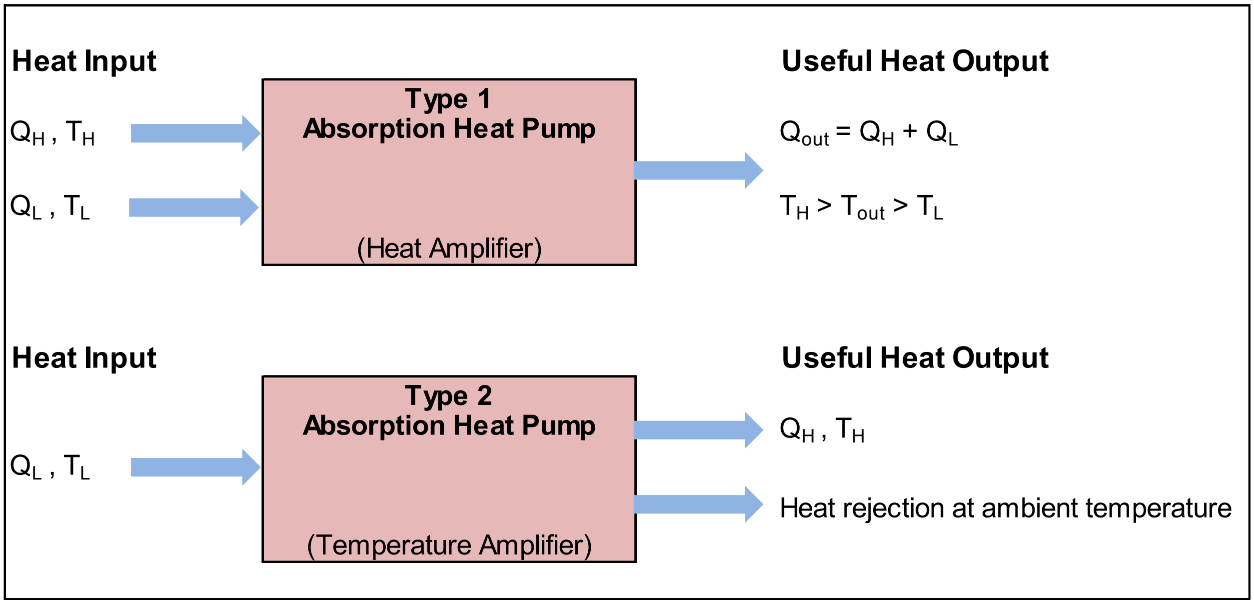
Source: *Adapted from EPRI, 1988, p2-7*

Figure 6-5
Absorption Heat Pump

Absorption heat pumps have been commercialized in two different arrangements

- Type 1 (heat amplifier)
- Type 2 (temperature amplifier)

Figure 6-5 corresponds to a Type 1 heat pump. In a Type 1 absorption heat pump, two separate thermal input streams are effectively combined to create a single output stream. One of the input streams is a waste heat stream, and the other is a primary energy input stream (e.g., a natural gas fired burner). In a Type 1 absorption heat pump, the output stream has a higher heat flow than either of the input streams, and the heat is delivered at an intermediate temperature. Type 1 absorption heat pumps are sometimes referred to as heat amplifiers. In contrast, Type 2 absorption heat pumps have a single input stream, but produce two output streams – one at a higher temperature than the input stream and one at ambient temperature. Type 2 absorption heat pumps are sometimes referred to as temperature amplifiers. **Figure 6-6** shows energy balances for both Type 1 and Type 2 configurations.



Key

Heat Duty		Temperarture	
Q_H	High temperature heat source	T_H	High temperature heat source
Q_L	Low temperature heat source	T_L	Low temperature heat source
Q_{out}	Intermediate temperaure heat source	T_{out}	Intermediate temperaure heat source

Source: *Adapted from DOE, 2003, p6*

Figure 6-6
Type 1 and 2 Absorption Heat Pumps

A key distinguishing feature of an absorption heat pump is that this technology can deliver a significantly higher temperature lift compared to other industrial heat pumps. The temperature lift (i.e., difference between condenser and evaporator temperatures) for a Type 1 absorption heat pump (see **Figure 6-5**) can be on the order of 200 to 300 °F (DOE, 2003). As a result of the relatively high temperature lift capability, absorption heat pumps are well suited for producing process streams with a temperature in the range of 200 to 400 °F (WSU, 2009b). Compared to closed cycle vapor compression heat pumps, absorption systems require more maintenance, and they have a higher capital cost (Lewis, 2009).

Applications

Heat pumps are used in a diverse range of industrial applications, including dryers and kilns for lumber, food plant evaporation processes, and many industrial processes. **Table 6–2** shows several applications for industrial heat pumps.

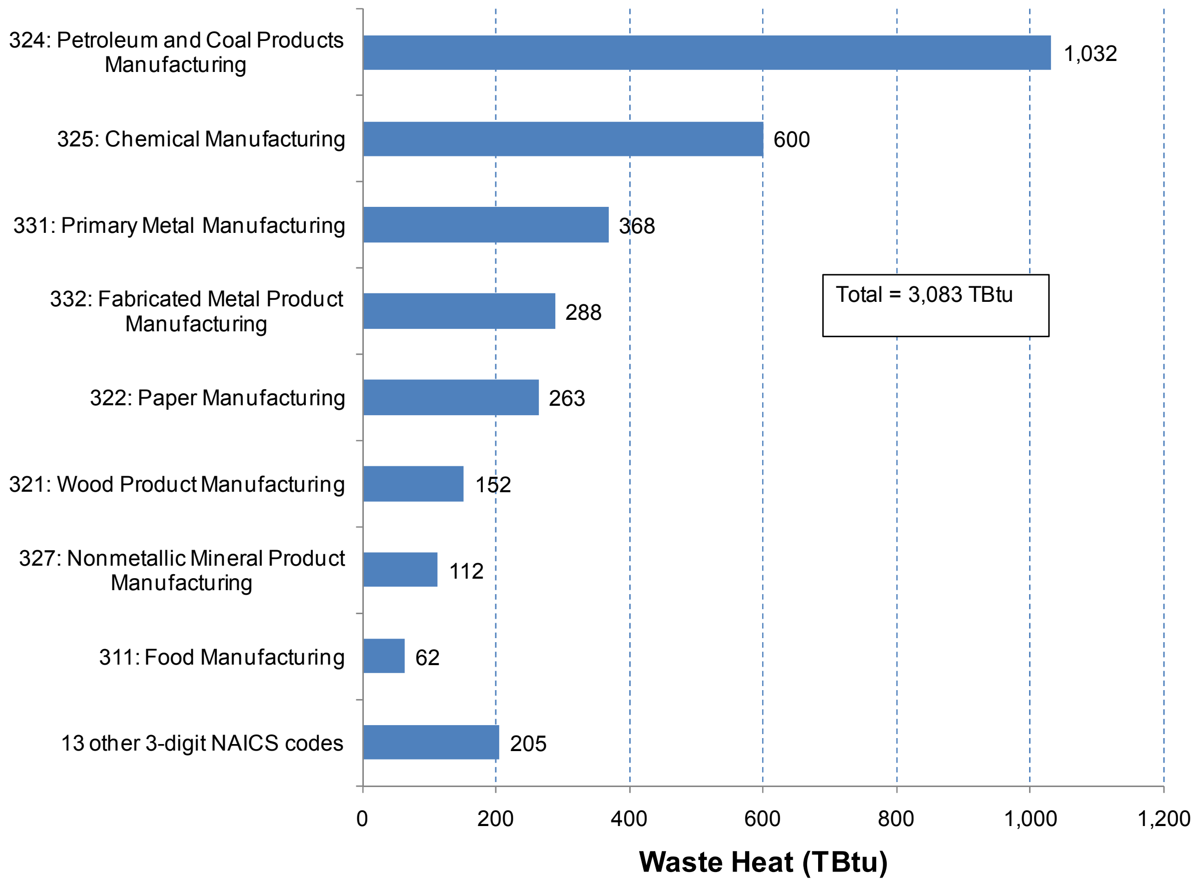
Table 6–2
Heat Pump Applications

Industry	Manufacturing Activity	NAICS	Process	Heat-Pump Type
Paper and Wood Products	Lumber	3211	Product drying	Vapor compression, closed cycle
	Pulp and paper	32211	Concentration of black liquor	Vapor compression, open cycle
		32212	Process water heating	Vapor compression, closed cycle
		---	Flash steam recovery	Thermocompression
Food and Beverage	General food products	311	Heating of process and cleaning water	Mechanical compression, closed cycle
	Alcohol	312140	Concentration of waste liquids	Vapor compression, open cycle
	Beer brewing	312120	Concentration of waste beer	Vapor compression, open cycle
	Wet corn milling and corn syrup	311221	Concentration of steep water and syrup	Vapor compression, open cycle and thermocompression
	Sugar refining	31131	Concentration of sugar solution	Vapor compression, open cycle and thermocompression
	Dairy products	31151	Concentration of mil and whey	Vapor compression, open cycle and thermocompression
	Juice	31142	Juice concentration	Vapor compression, open cycle
	Soft drinks	312111	Concentration of effluent	Vapor compression, closed cycle
	Drinking water	312112	Desalination of sea water	Vapor compression, open cycle
Petroleum Refining and Petrochemicals	Distillation	325110	Separation of propane/propylene, butane/butylene and ethane/ethylene	Vapor compression, open cycle
Chemicals	Salt, sodium sulfate, sodium carbonate, boric acid	3251	Concentration of product salt solutions	Vapor compression, open cycle
	Industrial waste treatment	---	Concentration of waste streams	Vapor compression, open cycle
	Heat recovery	---	---	Vapor compression, open cycle
	Pharmaceuticals	3254	Process water heating	Vapor compression, closed cycle
Textiles	---	314	Process and wash-water heating	Mechanical Compression
			Space heating	Mechanical Compression
			Concentration of dilute dope stream	Mechanical Compression

Source: *Adapted from DOE, 2003.*

Notes: *Temperature ranges for applications were not available.*

Low temperature (< 450 °F) waste heat streams account for the largest fraction of industrial waste heat, and these low temperature streams are a good match for industrial heat pumps. In **Chapter 4**, the waste heat inventory was evaluated, and a summary of the results for the top eight industrial manufacturing sectors is shown in **Figure 6-7** (data also shown in **Figure 4-3**). The values in **Figure 6-7** are based on a 60 °F reference temperature.



Source: *UTRC study, NEI methodology (ORNL, 2004)*

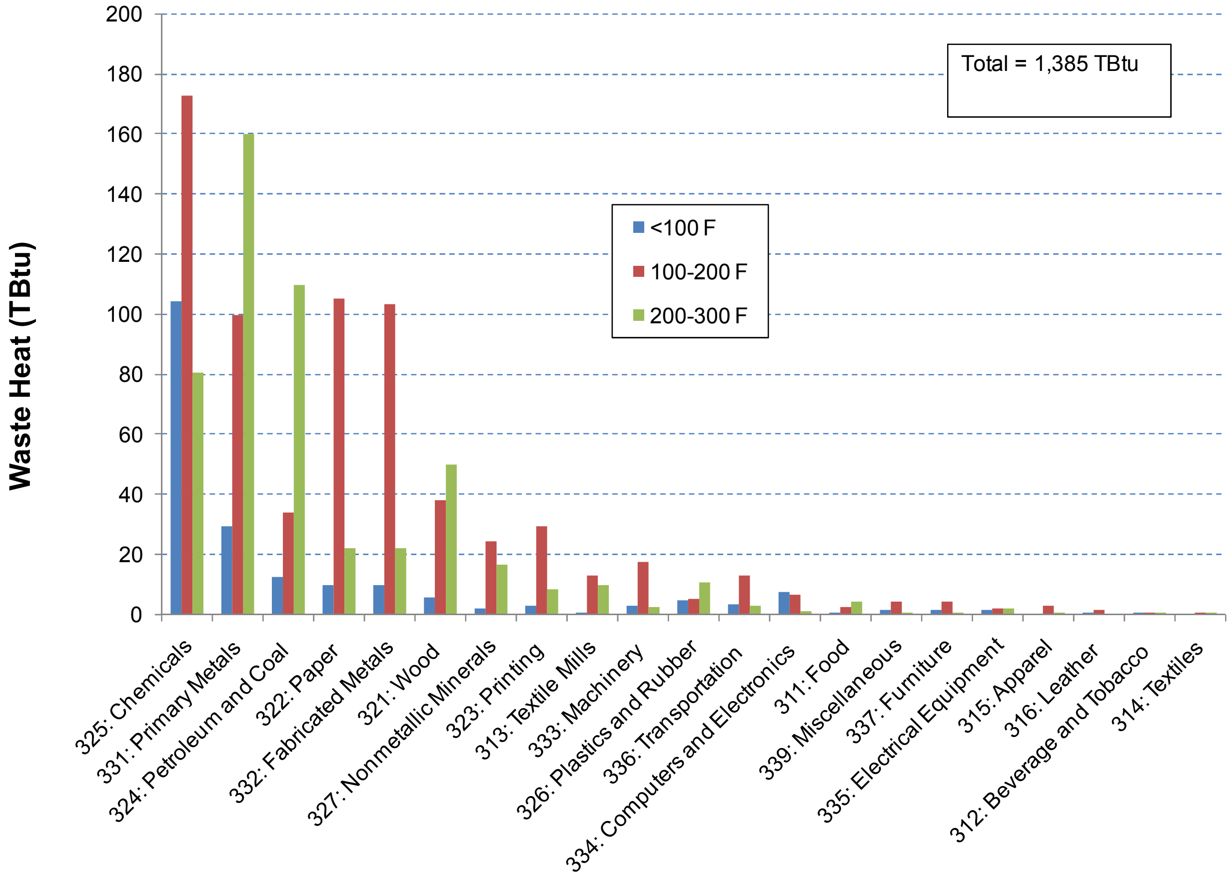
Figure 6-7
Waste Heat for Top 8 Industrial Sectors (60 °F reference temperature)

For heat pumps, it is interesting to analyze the amount of waste heat available at temperatures below 300 °F. This analysis shows that of the 3,083 TBtu of waste heat over all temperature ranges, approximately 45%, or 1,385 TBtu, is below 300 °F (referenced to a baseline temperature of 60 °F). A breakdown of the waste heat available under 300 °F is shown in **Table 6–3** and **Figure 6-8**. For the waste heat below 300 °F, approximately 14% is below 100 °F, 49% is in the range of 100-200 °F, and 37% is in the range of 200-300 °F.

Table 6–3
Waste Heat Inventory Below 300 °F (reference temperature of 60 °F)

Manufacturing Sector (arranged by 3-digit NAICS code)	**Waste Heat by Temperature Range (TBtu)**			
	Temperature Range (°F)			Total
	<100	100-200	200-300	<300 °F
311: Food Manufacturing	0.3	2.4	4.3	7.0
312: Beverage and Tobacco Product Manufacturing	0.1	0.3	0.2	0.6
313: Textile Mills	0.4	12.9	10.0	23.2
314: Textile Product Mills	0.0	0.2	0.3	0.5
315: Apparel Manufacturing	0.0	2.8	0.0	2.9
316: Leather and Allied Product Manufacturing	0.0	1.5	0.0	1.5
321: Wood Product Manufacturing	5.6	38.0	49.9	93.6
322: Paper Manufacturing	9.8	105.3	22.2	137.3
323: Printing and Related Support Activities	2.7	29.2	8.4	40.3
324: Petroleum and Coal Products Manufacturing	12.5	34.1	109.7	156.3
325: Chemical Manufacturing	104.5	172.8	80.7	358.0
326: Plastics and Rubber Products Manufacturing	4.7	5.0	10.5	20.2
327: Nonmetallic Mineral Product Manufacturing	2.1	24.2	16.7	43.0
331: Primary Metal Manufacturing	29.4	99.7	160.0	289.1
332: Fabricated Metal Product Manufacturing	9.8	103.2	22.1	135.1
333: Machinery Manufacturing	3.0	17.3	2.3	22.6
334: Computer and Electronic Product Manufacturing	7.4	6.8	1.2	15.3
335: Electrical Equipment, Appliance, and Component Manufacturing	1.5	2.0	2.1	5.6
336:Transportation Equipment Manufacturing	3.5	13.1	2.8	19.4
337: Furniture and Related Product Manufacturing	1.4	4.5	0.8	6.6
339: Miscellaneous Manufacturing	1.4	4.5	0.8	6.6
	200 *(14%)*	**680** *(49%)*	**505** *(37%)*	**1,385**

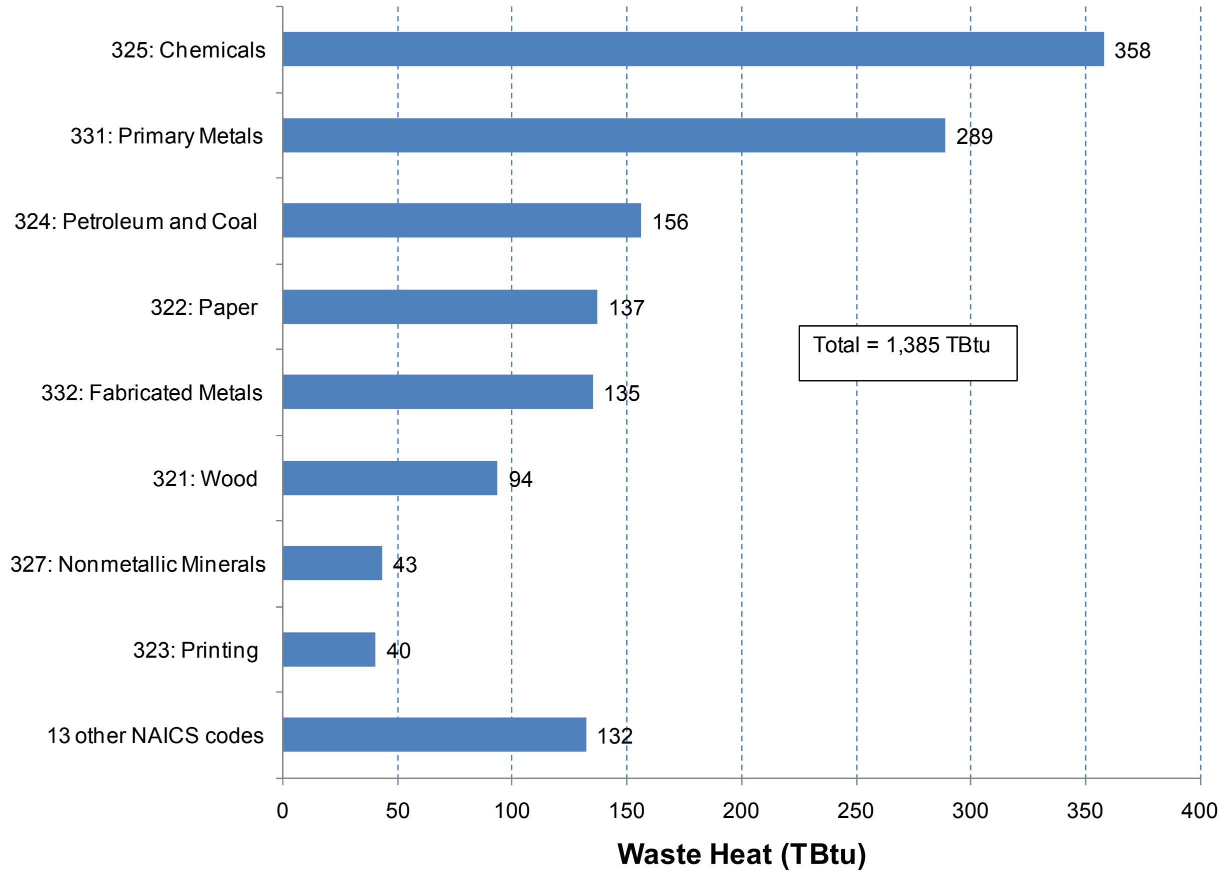
Note: *Totals and percentages may differ slightly due to rounding.*



Source: *UTRC study, NEI methodology (ORNL, 2004)*

Figure 6-8
Waste Heat Inventory Below 300 °F for 21 Manufacturing Sectors

Figure 6-8 shows the waste heat inventory below 300 °F for 21 industrial manufacturing sectors, and **Figure 6-9** shows the same information arranged by the top eight 3-digit NAICS codes. The top two industrial sectors for waste heat under 300 °F are chemicals and primary metals. These two sectors account for 47% of the waste heat inventory below 300 °F. The top eight sectors account for 90 % of the waste heat.



Source: *UTRC study, NEI methodology (ORNL, 2004)*

Figure 6-9
Waste Heat Inventory Below 300 °F for Top 8 Manufacturing Sectors

In the United States, lumber drying is the most common use of industrial heat pumps, specifically closed-cycle mechanical vapor compression. In this application, heated air, usually in the range of 85 to 160 °F (Nyle, 2006), is circulated over the lumber, evaporating the water in the wood. The hot, moist air is passed over the heat-pump evaporator, or refrigerator coil, cooling the air, typically to around 60°F. The evaporated vapor condenses into liquid and is drained. The heat removed from the air when it is cooled is used to heat the air that is recirculated in the dryer.

A promising application that is emerging for heat pumps is recovery of waste heat from refrigeration systems. Refrigeration waste heat recovery with heat pumps is a growing market in Europe, and there appears to be interest in the United States. Industrial refrigeration plants often have a high duty cycle (long hours of use), which is ideal for heap pump applications. Energy in the refrigeration waste heat stream can be recovered with a heat pump to heat hot water for plant cleaning or to meet other on site heating needs.

Economic and Environmental Considerations

In this section, the economic and environmental benefits of industrial heat pumps are discussed. The economics are illustrated for a hypothetical example that involves heating process water. The environmental advantages are discussed in the context of reduced CO_2 emissions.

Economics

The economics for an industrial heat pump are illustrated for a hypothetical example that involves heating 100 gallons per minute of process water from 180 °F to 210 °F. Two alternatives are compared:

- Natural gas fired hot water boiler
- Closed cycle mechanical vapor compression heat pump.

The boiler configuration is shown in **Figure 6-10**. Assumptions and results for energy cost calculations and CO_2 emissions production are summarized in **Table 6–4**. As indicated, the cost of natural gas to operate the boiler is slightly under $1 million per year (based on a gas rate of $10/MMBtu), and the CO_2 emissions are approximately 5,200 metric tons per year.

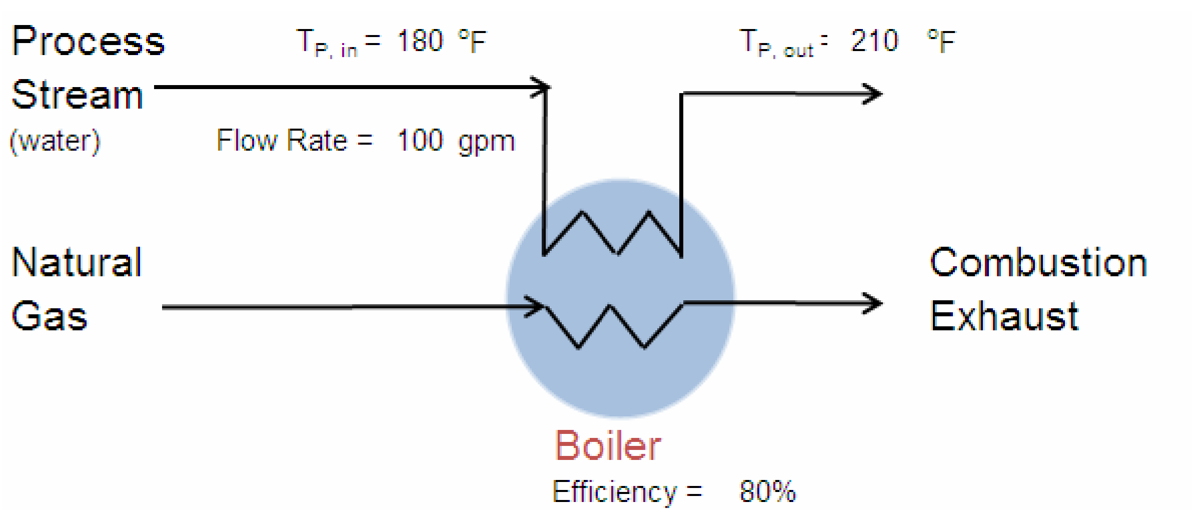


Figure 6-10
Boiler Used for Heating Process Water Stream

Table 6–4
Assumptions and Results for Boiler Calculations

Water Properties	Heat Capacity	1	Btu/lb-ºF
	Density	62.4	lb/gal
	Temperature Gain	30	ºF
Energy Added to Process Stream	Mass flow rate	374,400	lb/hr
	Energy required	11.2	MMBtu/hr
Natural Gas Consumption	Boiler Efficiency	80%	
	Natural Gas Required	14.0	MMBtu/hr
	Plant Schedule	7,000	hrs/yr
	Annual Gas Usage	98,280	MMBtu/yr
Cost of Natural Gas	Utility Rate	10.00	$/MMBtu
	Annual Cost	982,800	$/yr
CO_2 Emissions	Emission Factor[4]	53.06	kg/MMBtu
		116.98	lb/MMBtu
	Annual CO_2 Emissions	5,748	short tons/yr
		5,215	metric tons/yr

In contrast to the boiler arrangement, a closed cycle mechanical vapor compression heat pump is illustrated in **Figure 6-11**. The heat pump delivers the same amount of energy to the process stream (11.2 MMBtu/hr) as the boiler, but rather than consuming natural gas, the heat pump uses electricity to move energy from a waste heat stream to the process water stream. Heat is extracted from the waste heat stream in the evaporator section, and delivered to the process stream in the condenser section.

For the heat pump, it is assumed that the compressor is driven by an electric motor. To compare the energy costs and CO_2 emissions between the boiler and heat pump alternatives, it is necessary to determine the electricity consumption of the electric motor. Assumptions related to the physical configuration of the heat pump that are necessary to complete the calculations are shown in **Table 6–5** (values are also reflected in **Figure 6-11**).

[4] EIA, 2010b.

Table 6–5
Assumptions for Heat Pump Configuration

Item	Description	Notes
Compressor Drive	Electric Motor	---
Process Stream Inlet and Outlet Temperatures (heated)	180 / 210 °F	Same as boiler
Waste Heat Stream Inlet and Outlet Temperatures (cooled)	170 / 140 °F	---
Condenser Approach Temperature	20 °F	Minimum temperature difference between condenser and process stream
Evaporator Approach Temperature	20 °F	Minimum temperature difference between evaporator and waste heat stream

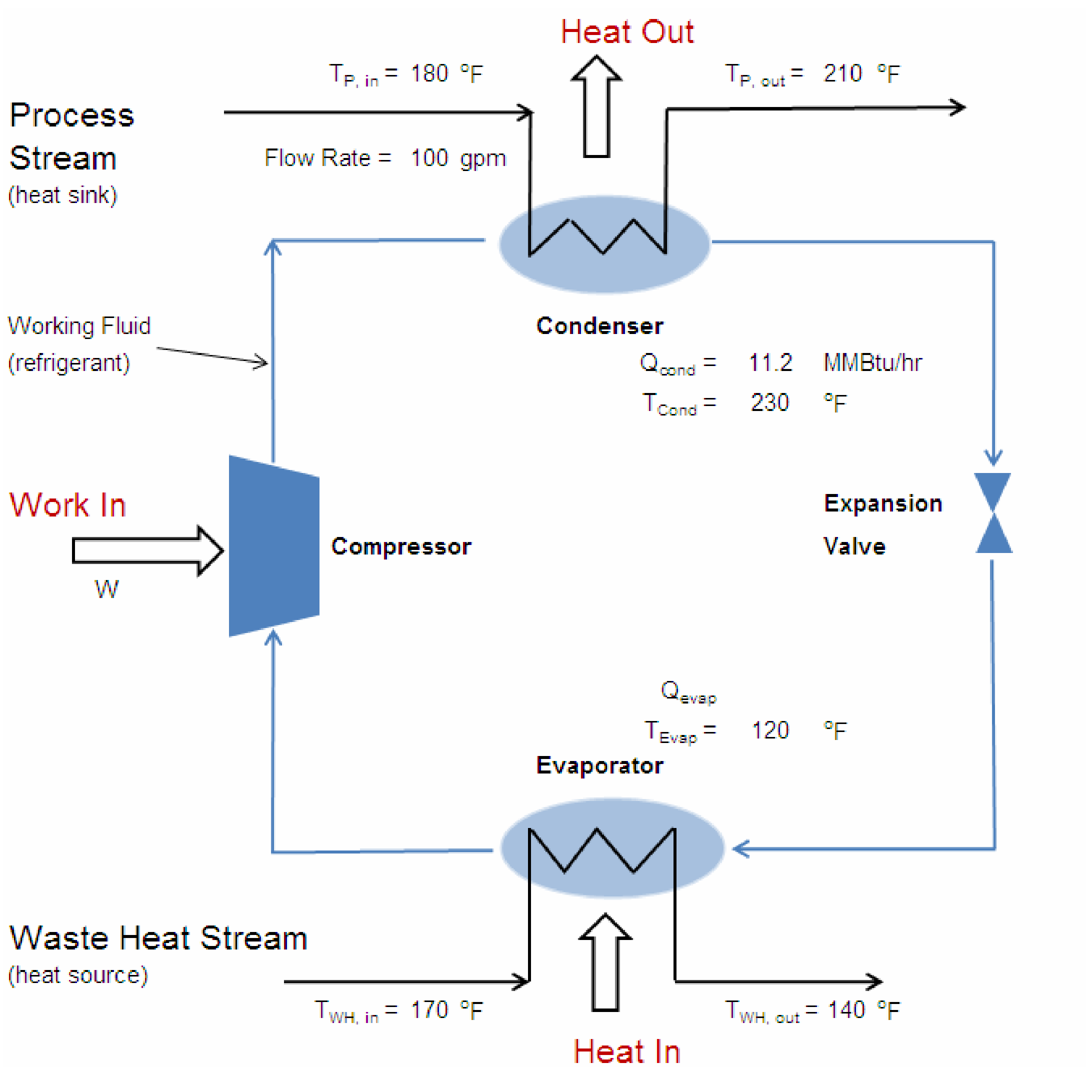


Figure 6-11
Heat Pump Used for Heating Process Water Stream

The data in **Table 6–5** can now be used to calculate the power required by the electric motor that drives the compressor. The first step in determining the motor power is to calculate the heat pump efficiency, which is a function of the evaporator and condenser temperatures given by the following relationship (temperatures expressed in absolute units):

$$COP_{Carnot} = T_{cond} / (T_{cond} - T_{evap}) = 6.3$$

The Carnot COP is the maximum possible efficiency for a heat pump. In practice, actual heat pump performance is always lower. For this example, the ratio of actual to maximum efficiency is assumed to be 65%, which leads to the following heat pump COP:

$$COP_{actual\ HP} = (COP_{Carnot}) \text{ X } 65\% = 4.1$$

The definition of COP for a heat pump is given by the ratio of energy (work) supplied divided by the energy delivered, which is expressed as:

$$COP_{actual\ HP} = Q_{cond}/W$$

And therefore:

$$W = Q_{cond}/COP_{actual\ HP} = 2.7 \text{ MMBtu/hr} = 807 \text{ kW}$$

Now that the power of the electric motor has been calculated, the heat required by the evaporator can be calculated using the following energy balance that applies to the complete heat pump:

$$W + Q_{evap} = Q_{cond}$$

which leads to an evaporator heat input of:

$$Q_{evap} = Q_{cond} - W = 8.5 \text{ MMBtu/hr}$$

Key results from the preceding calculations are shown in **Table 6–6**. This table also shows annual energy costs based on an average electricity cost of 12 ¢/kWh and 7,000 hrs/yr of operation (same operating schedule as the boiler). Carbon dioxide (CO_2) emissions are indicated based on an average annual emissions rate for electricity production including transmission line losses.

Table 6–6
Summary of Heat Pump Performance

Technical Performance	Carnot COP	6.3
	Actual COP	4.1 (65% of Carnot COP)
	Electrical Power for Compressor	807 kW (2.7 MMBtu/hr)
	Heat Extracted from Waste Heat Stream at Evaporator	8.5 MMBtu/hr
	Heat Added to Process Stream at Condenser	11.2 MMBtu/hr
Cost	Average Electricity Cost	12 ¢/kWh
	Operating Schedule	7,000 hrs/yr
	Annual Cost	$678,200
CO_2 Emissions	At Power Plant	1,329 lb CO_2/MWh[5]
	Transmission Line Losses	6.15% / 6.55%[6]
	At Industrial Plant	1,416 lb CO_2/MWh
	Annual Amount	3,630 metric tons / yr

Energy costs and CO_2 emissions for the heat pump and the boiler alternatives are shown in **Table 6–7**. As indicated, the heat pump is estimated to save over $300,000 per year in energy costs and reduce CO_2 emissions by nearly 1,600 metric tons per year compared to the natural gas fired boiler.

Table 6–7
Comparison of Energy Costs and CO_2 Emissions

		Boiler	Heat Pump	Savings
Type of energy input		Natural Gas	Electricity	---
Efficiency		80%	---	---
Energy cost	($/yr)	982,800	678,200	304,600
CO_2 emission	(metric tons/yr)	5,215	3,630	1,584

Most industrial heat pumps are custom engineered, and consequently there is a great deal of variation in capital costs. To obtain accurate installed costs, it is generally necessary to develop a detailed description of site specific conditions, and then have heat pump vendors bid to these specifications. As a rough guideline, historical costs for closed cycle mechanical vapor compression systems have been reported to fall in a wide range of $50,000 to $200,000 per MMBtu/hr of capacity (DOE, 2003, p. 15). Using these capital cost metrics, the payback for the hypothetical heat pump in this example ranges from 1.8 to 7.4 years (see **Table 6–8**).

---

[5] EPA, 2007
[6] EIA, 2010c. Line loss calculated based on difference between total supply (4,162,326 thousand MWh) and total consumption (3,906,443 thousand MWh). Loss is 6.15% based on supply, or 6.55% based on consumption.

Table 6–8
Heat Pump Payback

Capital Cost	($ per MMBtu/hr)	$50,000	$200,000
System Size	(MMBtu/hr)	11.2	same
Capital Cost	($)	$561,600	$2,246,400
Savings	$/yr)	$304,600	same
Payback	(yrs)	1.8	7.4

In this hypothetical example, the heat pump delivers 11.2 MMBtu/hr of useful heat to the process stream at an electricity cost of $96.89/hr ($678,200/yr divided by 7,000 hrs/yr). The cost of the delivered heat, excluding capital costs and operating and maintenance (O&M) costs, turns out to be $8.63/MMBtu ($96.89/hr divided by 11.2 MMBtu/hr). **Figure 6-12** shows how the cost of delivered heat varies as a function of electricity costs and temperature lift. As expected, the cost of delivered heat from the industrial heat pump increases as temperature lift increases and as the cost of electricity increases.

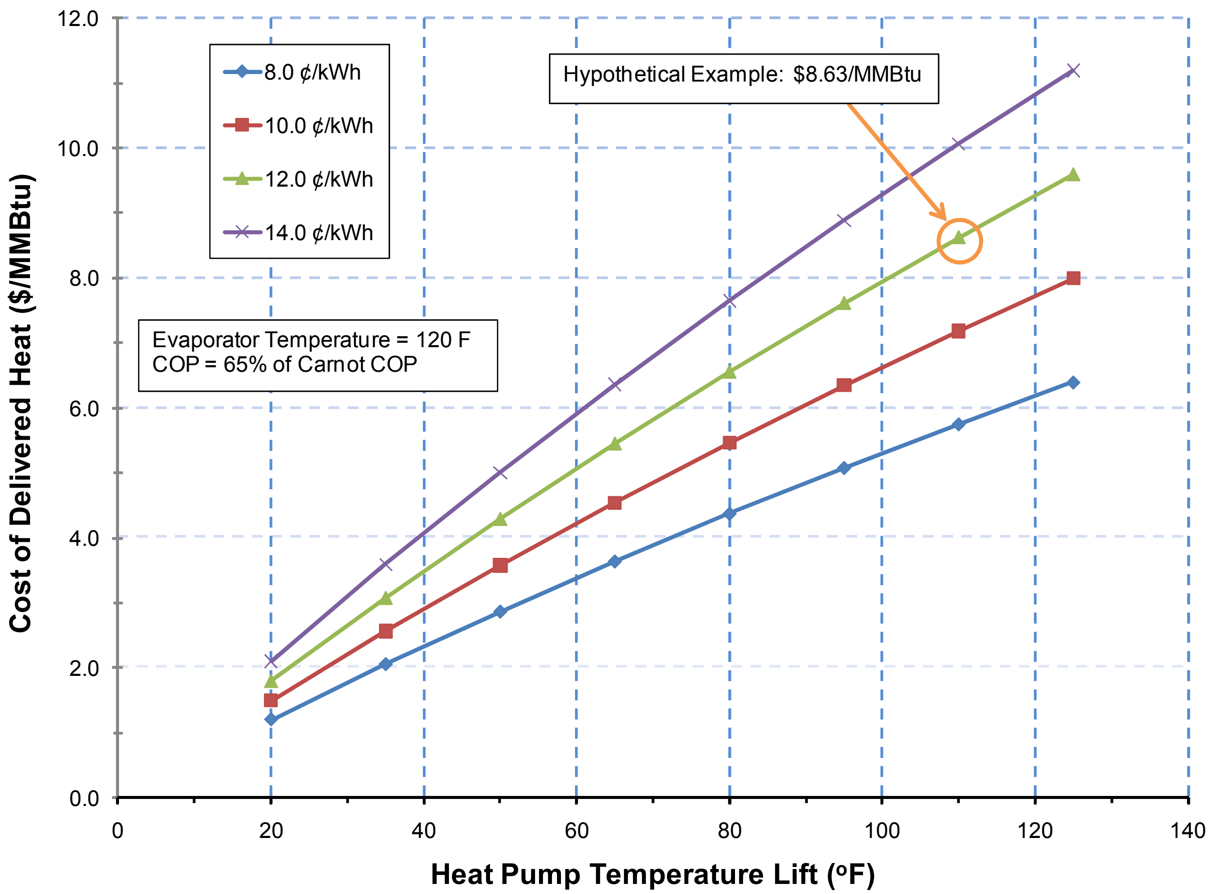


Figure 6-12
Impact of Electricity Prices and Temperature Lift on Heat Pump Economics

Industrial heat pumps consume electricity, and therefore increase electric load. **Table 6–9** shows the potential added electric load if the entire waste heat inventory under 300 °F is utilized by heat pumps with characteristics identical to the hypothetical heat pump described in the preceding paragraphs. This assumption is a gross simplification, but it does provide a rough estimate of the upper bound for the load building potential of industrial heat pumps. As indicated in **Table 6–9**, over 23,000 industrial heat pumps would be required, producing an aggregate electric load of nearly 19 GW.

Table 6–9
Potential Added Electric Load for Industrial Heat Pumps

Waste heat used by one heat pump	8.5	MMBtu/hr
	0.0593	TBtu/yr
Electric energy use per heat pump	807	kW
Total waste heat inventory	1,385	TBtu/yr
Total number of heat pumps based on entire waste heat inventory	23,340	
Total added load	18.8	GW

CO_2 Emissions

As indicted in **Table 6–7**, the example industrial heat pump reduces CO_2 emissions by 1,584 metric tons per year. This calculation is based on the difference between the CO_2 emissions generated by a natural gas fired boiler and the CO_2 emissions associated with the electricity consumption of the heat pump. The heat pump utilizes a waste heat stream with an initial temperature of 170 °F (waste heat stream inlet and outlet temperatures are shown in **Figure 6-11**).

An upper bound on the potential to reduce CO_2 emissions with industrial heat pumps can be calculated by assuming that the entire waste heat inventory under 300 °F is utilized by the example heat pump. This approach is a rough approximation only. Industrial plants have a wide range of process heating needs, and there is a wide range of technical performance characteristics for industrial heat pump configurations. The example heat pump only represents a single heat pump configuration for a single set of plant conditions.

The potential reduction in CO_2 emissions from industrial heat pumps is summarized in **Table 6–10**. As indicated, the potential reduction is 37 million MT/year.

Table 6–10
Potential Carbon Dioxide Emissions Savings from Industrial Heat Pumps

CO_2 Savings Based on One Hypothetical Heat Pump	Net CO_2 emissions	1,584	MT/yr
		0.0016	million MT/yr
CO_2 savings based on entire waste heat inventory under 300 °F	Total number of heat pumps (see **Table 6–9**)	23,340	
	Total CO_2 savings	37.0	million MT/yr

Commercialization Status

The commercialization of industrial heat pumps is discussed in the following sections:

- Products and vendors
- Market penetration
- Commercialization barriers
- Research and development

Products and Vendors

Table 6–11 shows a few companies that supply complete industrial heat pump systems along with a few companies that supply key components (e.g., compressors). In the United States, Nyle is the largest supplier in terms of the units sold. Nyle reports that since starting business in 1978 they have shipped approximately 4,800 industrial heat pumps, primarily for lumber drying (Nyle, 2010). Following the table, there are brief descriptions for each company.

Table 6–11
Selected Suppliers of Industrial Heat Pumps and Key Components
(representative list only, not intended to be all inclusive)

Colmac Coil Manufacturing
Emerson / Vilter
Friotherm
GEA Group
Johnson Controls / York
Kobelco
Mayekawa / MYCOM
Nyle Systems
Toyo Engineering

Colmac (www.colmaccoil.com). Colmac has offices and manufacturing facilities in Washington State and Illinois. The company manufacturers a range of heat transfer products, including plate fin heat exchangers, cooling coils, condensers, heat pipe heat exchangers, and heat pump water heaters. Industrial heat pumps are a small fraction of the company's business. Colmac supplies equipment to a diverse set of industries, including aeronautics, beverage, communications, dairy, electronics, energy reclamation, food processing, gas compression, health care, hospitality, pharmaceutical, petrochemical, power generation, pulp and paper, and waste water treatment.

Emerson / Vilter (www.emerson.com) Emerson is a global manufacturing and technology company, and offers a wide range of products and services to industrial, commercial, and consumer markets through several business units, which include process management, industrial automation, climate technologies, and tools and storage. The Emerson Climate Technologies business unit provides heating, ventilation, air conditioning, and refrigeration equipment for residential, industrial, and commercial applications. There are several brands in this business unit, including Vilter, which manufacturers a complete line of compressors for industrial refrigeration, gas compression, and industrial heat pump applications. Vilter is primarily a compressor manufacture, but has teamed with Star Refrigeration to offer a complete ammonia heat pump for industrial refrigeration applications.

Friotherm (www.friotherm.com). Friotherm is based in Switzerland, and has expertise in designing, constructing, servicing, and refurbishing centrifugal chillers and heat pumps. The company offers a wide range of turbo compressors, heat pumps, and chillers for district heating (DH) and district cooling (DC) applications. In addition to DH and DC applications, Friotherm supplies equipment to other industries, including nuclear power stations, chemical plants, and petroleum refineries.

GEA (www.geagroup.com). GEA is a German company with global operations related primarily to the food and energy industries. The GEA Refrigeration Technologies division provides equipment for industries including food and beverage, marine, oil and gas, and leisure (e.g., indoor ski centers and ice-skating rinks). In addition to offering refrigeration equipment such as compressors and chillers, the company also provides industrial heat pumps,

Johnson Controls / York (www.johnsoncontrols.com). Johnson Controls is a global corporation that serves the building and automotive industries through three business units: 1) Building Efficiency – controls for heating, ventilating, air-conditioning and refrigeration, as well as security systems for buildings, 2) Automotive Experience –automotive seating, overhead systems, door and instrument panels, and interior electronics, and 3) Power Solutions – vehicle batteries. York is one of the Johnson Control companies, and York products include a wide range of heat pumps and chillers.

Kobelco (http://www.kobelco.co.jp/english/index.html). The Kobe Steel Group is a Japanese corporation that operates in a wide range of industrial fields, including construction materials (iron and steel, welding, aluminum and copper) and heavy equipment (excavators, cranes, and other construction machinery). The company has a machinery business unit, and this business unit supplies compressors (air and gas), heat pumps, uninterruptible power supplies, and gas turbines.

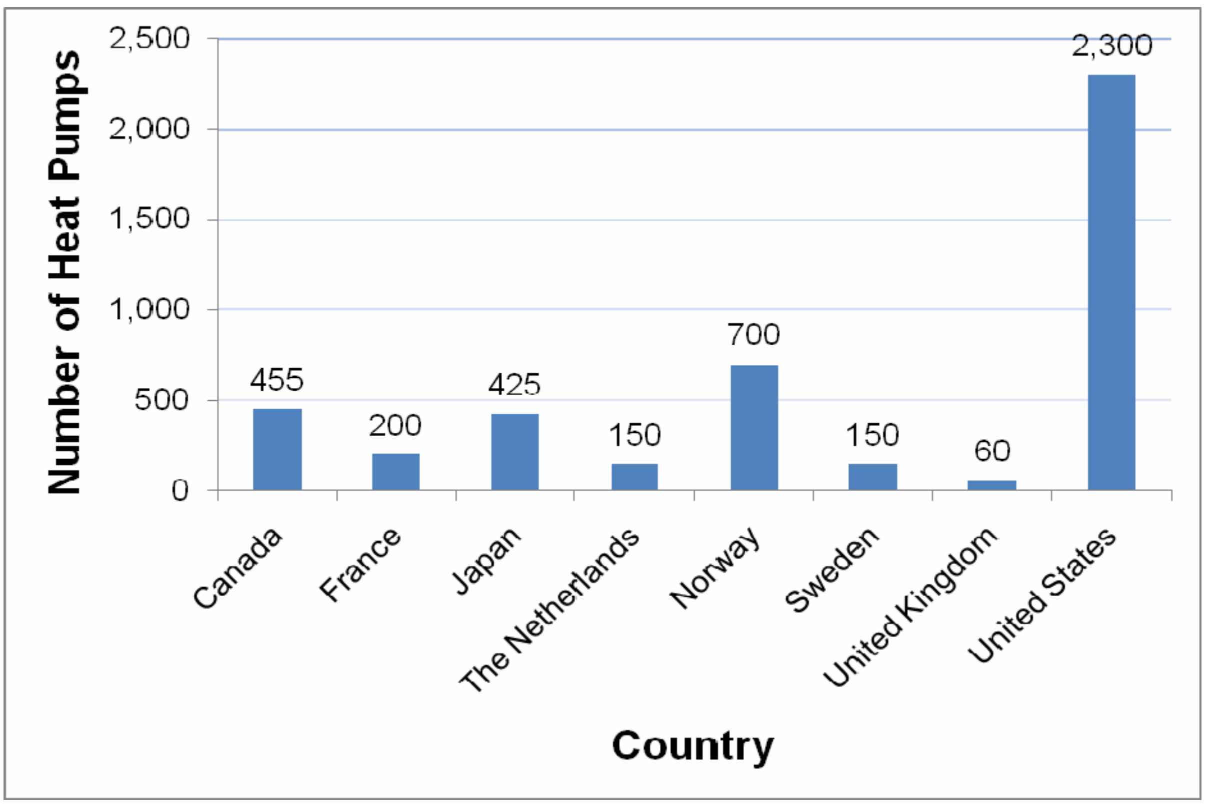
Mayekawaa / MYCOM (www.mayekawa.com). Mayekawa is a Japanese firm that manufactures industrial refrigeration compressors under the MYCOM brand name. Mayekawa offers a wide range of products for several markets, including food, dairy, beverage, petrochemical, marine, and leisure (e.g., ice and hockey rinks). In addition to industrial refrigeration equipment, Mayekawa manufacturers Eco Cute heat pumps. These heat pumps use CO_2 as the refrigerant, and are available as either air source or water source units with capacities up to 100 kW.

Nyle (www.nyle.com). Nyle designs, manufactures, installs, and services heat pump technologies for industrial, commercial, and residential applications. The company has offices and facilities in Connecticut and Maine. The largest market for Nyle is the lumber industry, where Nyle supplies industrial heat pumps for kilns. Nyle's first lumber drying kiln was installed in 1978. In addition to lumber drying, Nyle is active in other markets, including; drying and dehumidification in the food industry, water heating, and energy recovery systems.

Toyo (http://www.h.toyo-ew.co.jp/english/engineering.html). The Japanese firm Toyo Engineering provides a variety of refrigeration technologies for a wide range of industries. The company serves a diverse set of industrial fields, stretching from the automotive sector to clean room applications. Toyo has introduced environmentally friendly refrigerants, such as ammonia and CO_2, into their product line. The Mr. Eco Steam is one of Toyo's heat pump products. This heat pump is capable of generating steam and hot water based on recovering energy from low-temperature waste hot water streams.

Market Penetration

Comprehensive market evaluations for industrial heat pump were conducted in the late 1980s and in the mid 1990s by the Electric Power Research Institute (EPRI, 1988) and the U.S. DOE (DOE, 1994). The results of these market studies are discussed in an International Energy Agency report (IEA, 1995). The IEA report shows market penetration numbers for industrial heat pumps in eight countries (see **Figure 6-13**).



Source: *IEA, 1995, p47*

Figure 6-13
Number of Industrial Heat Pumps in Use for 8 Countries in 1995

As indicated in **Figure 6-13**, the United States was estimated to have approximately 2,300 heat pumps in operation in 1995. The majority (2,000) of these heat pumps were estimated to be used in lumber drying. Industrial heat pumps used for lumber drying are closed cycle mechanical vapor compression machines, and most have relatively small heat outputs (e.g., <500 MBtu/hr). Regional data on the market penetration of industrial heat pumps across the United States was not reported.

ICF contacted a small sample of companies and industry stakeholders to collect market data, including:

- Nyle
- Vilter
- Colmac
- Purdue University (Dr. Frederick T. Sparrow)
- University of Texas at Austin (Dr. Philip Schmidt)

Based on information obtained from these contacts, it is believed that the industrial heat pump market has shown modest growth over the past 15 years (1995 to 2010). As mentioned previously, Nyle has shipped a total of approximately 4,800 industrial heat pumps. Nyle further reported that about 40% of their systems are exported, and that about 90% of their systems are believed to be still in operation. These values lead to an estimated population of approximately 2,600 Nyle industrial heat pumps currently operating in the U.S. (4,800 X 60% X 90%). If the 2,000 heat pumps operating in 1995 for lumber drying are all assumed to be Nyle units, then the population of Nyle heat pumps has grown by approximately 30% since 1995. If the 30% growth figure for Nyle is applied to the entire heat pump market, the 2010 population of industrial heat pumps in the United States is estimated to be near 3,000.

There is a large size range for industrial heat pumps. Closed cycle vapor compression systems tend to be relatively small, and open cycle vapor compression units tend to be much larger. An IEA study (IEA, 1995, p. 49) reported an average output energy for heat pumps in the U.S. to be 0.5 MW (1.7 MMBtu/hr of heat output). Research was not conducted within the scope of this project to validate this number. However, based on this average heat output, the estimated 3,000 heat pumps in the U.S. would have a total heat output capacity of 1,500 MW (5,100 MMBtu/hr)

Commercialization Barriers

Barriers to increased market penetration of industrial heat pumps include:

- Lack of knowledge and experience with industrial heat pump technologies
- High initial costs
- Volatile energy prices
- Negative perceptions of heat pumps

Limited Knowledge and Experience – The population of industrial heat pumps is relatively low in all industries except lumber drying. As a result, there is limited information for many industrial applications regarding proven engineering designs, actual field performance, and economics. This lack of awareness inhibits the growth of industrial heat pump installations.

High Initial Costs – Industrial heat pumps are typically custom engineered to meet site specific conditions. As a result, there can be significant costs associated with design and engineering, in addition to the hardware and installation costs. The total installed cost for many industrial heat pump applications is a barrier that limits market penetration.

Volatile Energy Prices – Energy price uncertainty is another factor that can impact the adoption of industrial heat pumps. An industrial heat pump can represent a major capital expenditure, and plant managers expect the investment to provide near term financial benefits. The financial benefits are directly tied to energy prices, and if energy prices are volatile, risk averse decision makers may shy away from an industrial heat pump investment.

Negative Perceptions – There are also lingering doubts created from first generation industrial heat pumps installed in the 1970s and 1980s. Some of these early heat pump systems were improperly designed and did not perform as expected. However, a properly designed modern heat pump system will provide high reliability, often with a payback period in the range of 2 to 5 years.

Research and Development

Factors that limit the expanded use of industrial heat pumps include:

- Need refrigerants that operate at higher temperatures and over larger temperature ranges.
- Need more field installations that demonstrate technical performance, long term hardware reliability, and verified energy savings
- Need more information to help identify opportunities and match site requirements to available heat pump technologies.

Research, development, and demonstration (RD&D) projects can play an important role in addressing these factors.

Refrigerants – The maximum operating temperature for mechanical vapor compression heat pumps is currently in the range of 200 to 250 °F (temperature of waste heat stream). Absorption heat pumps can be used up to about 400 °F , but absorption systems are more expensive compared to vapor compression systems. If higher temperature refrigerants can be developed, it is possible that cost competitive vapor compression heat pump technologies could be deployed for heat recovery with waste heat streams above 250 °F. Researchers have identified several refrigerants for higher temperature applications, including R-717 (ammonia), R-718 (water), R-744 (carbon dioxide), R-245fa, R-365mfc, and mixtures of these refrigerants (e.g., ammonia and water). It is unclear how much research activity is currently directed at refrigerant development, or what the technical bottlenecks might be.

Field Installations – Additional field installations, particularly for emerging industrial heat pump technologies, would be helpful in demonstrating technical and economic performance. Field data can be valuable to plant engineers and other stakeholders that are interested in applying heat pump technologies, but are uncertain how these systems will actually perform.

A field demonstration that might be of interest would be to evaluate emerging ammonia heat pump systems in a relatively large potential market, such as waste heat recovery from refrigeration applications. A field demonstration of this type would be valuable in determining if refrigeration waste heat recovery might be a viable large market for industrial heat pumps, similar to the success seen in lumber drying.

At their test labs in Les Renardières in France, Electricite de France (EDF) is working with Johnson Controls to develop a 1-MW industrial heat pump that could heat a process flow up to 100°C (212 F) , using the heat from a low temperature process stream.

The current testing involves the use of refrigerant R245FA (Pentafluoropropane) and is already delivering 100°C (200F) by recovering waste heat from a stream at 30°C (90F). This high temperature heat pump should then be transferred for instance to a cheese factory for demonstration.

Another on-going project at EDF is targeting to deliver up to 140°C (280 F) using water as a refrigerant or an HFC mixture.

Information – Information development is not necessarily an RD&D activity. However, there does appear to be a lack of recent data concerning the use of industrial heat pumps. Much of the publicly available data is 10 to 20 year old, or even older. Up to date case studies with current economics would be valuable in helping decision makers understand the financial benefits of industrial heat pumps. Guidelines on identifying industrial opportunities, and matching these opportunities to available technologies would be valuable for utility personnel and other stakeholders that are seeking to increase energy efficiency in the industrial sector. It would also be helpful to develop better information on the population of installed industrial heat pumps. This information could be valuable in understanding historical market penetration patterns, and assessing growth opportunities and challenges.

The International Energy Agency (IEA) plans to form an Annex 35 group to support industrial heat pumps (Jakobs, 2010). Annex 35 is a follow-on program to earlier IEA industrial heat pump programs (Annex 9 and Annex 21). Annex 35 activities are expected to address information and other needs related to industrial heat pumps.

7
SUMMARY

Industrial energy use accounts for about 30%, or 28 Quads per year, of total energy use in the U.S. economy (2009 data). The waste heat generated from the industrial sector is difficult to quantify. However a review of previous waste heat studies suggests that the industrial sector waste heat inventory is on the order of 1.5 to 3 Quads/yr (quadrillion Btu/yr), or 1,500 to 3,000 TBtu/yr (trillion Btu/yr). This estimate is based on a ambient temperature reference point. With a higher temperature reference value of 300 °F, the waste heat inventory is significantly smaller, and is estimated at 250 to 420 TBtu/yr.

One of the studies examined to develop an estimate of the waste heat inventory was completed for Oak Ridge National Laboratory (ORNL, 2004). This study examined 21 three digit NAICS codes for industrial manufacturing (NAICS codes 31-33), and provides insights into the temperature ranges for waste heat and the industrial sectors that produce waste heat. Based on this study, **Table 7–1** shows a breakdown of the waste heat inventory by temperature range for both ambient (60 °F) and 300 °F reference temperatures. Based on a reference temperature of 60 °F, 45% of the waste heat inventory is below 300 °F, 65% is below 450 °F, and 99% is below 1,200 °F. With a reference temperature of 300 °F, 14% of the waste heat inventory is below 450 °F and 96% is below 1,200 °F. At a 300 °F reference temperature, there is no usable waste heat below 300 °F.

Table 7–1
Waste Heat Inventory by Temperature Range

Temperature Range (°F)	Waste Heat (TBtu / % of total)	
	Temperature Baseline (°F)	
	60	300
<300	1,385 / 45%	0 / 0%
300-450	600 / 20%	57 / 14%
450-1,200	1,053 / 34%	349 / 82%
>1,200	46 / 1%	17 / 4%
Total	**3,083**	**424**

Source: *UTRC study, NEI methodology (ORNL, 2004)*

Note: *Totals may differ due to rounding*

Table 7–2 shows a ranking of the top eight manufacturing sectors, along with the energy consumption of these sectors. As indicated, there are some differences in ranking between the two reference temperatures. For example, textile mills (NAICS 313) are not in the top eight with a reference temperature of 60 °F, and wood products are not in the top eight with the higher reference temperature of 300 °F. However, there is consistent agreement at the top of the list. For both reference temperatures, petroleum and coal products (NAICS 324) clearly has the highest waste heat inventory, followed by chemical manufacturing. These categories account for 53% of the waste heat inventory at a reference temperature of 60 °F, and 85% of the waste heat inventory at a reference temperature of 300 °F (see **Table 7–3**).

Table 7–2
Waste Heat Inventory by Industrial Manufacturing Sector – Top 8

Manufacturing Sector (with 3 digit NAICS code)	Temperature Baseline (°F)			
	60		300	
	Rank	Energy (TBtu)	Rank	Energy (TBtu)
324: Petroleum and Coal Products Manufacturing	1	1,032	1	290
325: Chemical Manufacturing	2	600	2	72
331: Primary Metal Manufacturing	3	368	6	8
332: Fabricated Metal Product Manufacturing	4	288	4	13
322: Paper Manufacturing	5	263	5	11
321: Wood Product Manufacturing	6	152	---	---
327: Nonmetallic Mineral Product Manufacturing	7	112	7	8
311: Food Manufacturing	8	62	3	13
313: Textile Mills	---	---	8	4
13 other NAICS codes	---	205	---	6
TOTAL	**---**	**3,083**	**---**	**424**

Source: *UTRC study, NEI methodology (ORNL, 2004)*

Note: *Totals may differ due to rounding*

Table 7–3
Waste Heat Inventory by Sector Rank

Manufacturing Sector Rank	**Waste Heat (TBtu / % of total)**	
	Temperature Baseline (°F)	
	60	300
1 and 2	1,632 / 53%	362 / 85%
3 through 8	1,246 / 40%	55 / 13%
9 through 21	205 / 7%	6 / 2%
Total	**3,083**	**424**

Note: *Totals may differ due to rounding*

Combined heat and power (CHP) applications are generally based on recovering waste heat from combustion exhaust streams with temperatures above 450 °F. Processes that produce these temperatures include calcining operations (cement, lime, alumina, and petroleum coke), metal melting, glass melting, petroleum fluid heaters, thermal oxidizers, and exothermic synthesis processes. The estimated power potential from industrial process heating and boilers is over 5,800 MW. An additional 6,300 MW of power production potential is identified for nonindustrial waste heat recovery and industrial and non-industrial steam pressure reduction applications. While there is over 12,000 MW of identified power potential for CHP, to date only 60 projects totaling 753 MW of waste heat recovery CHP projects have been installed in the United States. There are technical, economic, and regulatory barriers to increased market penetration of CHP systems for waste heat recovery.

Industrial heat pumps have the ability to move heat from a relatively low temperature waste heat stream to a higher temperature process stream. Work is required to move the heat, and this work is most frequently supplied by electric motors that drive the heat pump. Industrial heat pumps are well suited for energy recovery from low temperature waste heat streams (up to 250 °F with vapor compression heat pumps; up to 400 °F with absorption units). There are an estimated

3,000 industrial heat pumps operating in the U.S., with the majority of these systems being used for lumber drying. The heating output capacity for all 3,000 heat pumps is estimated to be roughly 1,500 MW (average of 0.5 MW per heat pump). Market penetration of industrial heat pumps could be increased with the development of higher temperature refrigerants, expanded field demonstrations, and the development and dissemination of information to support decision makers and other stakeholders that seek to apply industrial heat pumps.

CHP waste heat recovery systems and industrial heat pumps are frequently custom designed to meet site specific conditions, and hence there is a wide range of capital costs for these technologies. As a general guideline, capital costs for CHP systems that are driven with waste heat are estimated to be in the range of $2,000 to $2,500 per kW of power production for large systems (>5 MW), and $3,500 to $4,500 per kW for small systems (<400 kW). For industrial heat pumps, capital costs are estimated to be in the range of $50,000 to $200,000 per MMBtu/hr of heat delivered to the process fluid stream.

Waste heat recovery yields lower CO_2 emissions. The upper bound on reducing CO_2 emissions is estimated to be approximately 88 million metric tons per year (MMT/yr) – almost 51 MMT/yr from CHP technologies and 37 MMT/yr from industrial heat pumps.

In addition to reducing CO_2 emissions, industrial heat pumps consume electricity, and therefore provide beneficial electrification to the society. The available waste heat under 300 ^{o}F is estimated to be sufficient to power over 23,000 industrial heat pumps based on an average heat output of 11.2 MMBtu/hr per heat pump (average value – lumber drying heat pumps are generally smaller, while food processing and petrochemical heat pumps may be larger). These heat pumps represent an aggregate beneficial electric load of nearly 19 GW.

8
REFERENCES

BCS, 2006. *Engineering Scoping Study of Thermoelectric Generator Packages for Industrial Waste Heat Recovery*, BCS, Incorporated.

Colmac, 2010. Personal communication between John Wold, Colmac Coil, and Megan Douglas, ICF, September 2010.

DOE, 1994. *IHP Efficiency, Productivity Experiences and Opportunities in Key Process Industries: Directory of Case Studies on Industrial IHP Opportunities*, prepared by RCG/Hagler Bailly, Inc., prepared for Oak Ridge National Laboratory and the U.S. Department of Energy.

DOE, 2003. *Industrial Heat Pumps for Steam and Fuel Savings*, U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, http://www1.eere.energy.gov/industry/bestpractices/pdfs/heatpump.pdf .

DOE, 2008. *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*, prepared by BCS, Incorporated, prepared for U.S. Department of Energy, Industrial Technologies Program, March 2008.

DOE, 2010, *Waste Heat Recovery for Power and Heat Workshop*, sponsored by U.S. DOE Clean Energy Application Centers, Chicago, Illinois, September 29-30, 2010.

Duffy, 2005. Daniel P. Duffy, "Better Cogeneration through Chemistry: The Organic Rankine Cycle," *Distributed Energy*, November/December 2005.

EIA, 2009. *Annual Energy Review 2009*, U.S. Energy Information Administration, DOE/EIA-038 (2009), August 2010.

EIA, 2010a. *Trend Data from Manufacturing Energy Consumption Survey (MECS) – 1998, 2002, 2006*, U.S. Energy Information Administration, http://www.eia.doe.gov/emeu/efficiency/mecs_trend_9802/mecs_trend9802.html, May 2010.

EIA, 2010b, Voluntary Reporting of Greenhouse Gases Program, Carbon Dioxide Emission Factors for Stationary Combustion, U.S. Energy Information Administration, Weighted National Average, www.eia.doe.gov/oiaf/1605/coefficients.html, August 2010.

EIA, 2010c, *Electric Power Annual 2008*, U.S. Energy Information Administration, http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html, January 2, 2010.

EPA, 2007. *GHG Annual Output Emission Rate*, U.S. Environmental Protection Agency, 2007 eGRID data, www.epa.gov/egrid.

EPA, 2008. eGRID2007 Version 1.0, Year 2005 Summary Tables, September 2008.

EPA, 2010. U.S. EPA Landfill Methane Outreach Program Website, http://www.epa.gov/lmop/.

EPRI, 1988. *Industrial Heat Pump Manual – Technical and Applications Resource Guide for Electric Utilities*, Prepared by Linhoff March, Inc., Electric Power Research Institute, EM-6057.

EPRI, 1990. *Pinch Technology: A Primer*, Electric Power Research Institute, CU-6775.

Global Geothermal, 2010. Online information, http://www.globalgeothermal.com/Applications.aspx.

Graymont, 2009. *New Kiln Gives Back Power, Provides New Products*, *Grayzette*, *Vol. 5., No. 2*, Graymont, Ltd, Richmond, BC, Fall-Winter 2009.

Hedman, 2008. Bruce Hedman, *Waste Energy Recovery Opportunities for Interstate Natural Gas Pipelines*, Interstate Natural Gas Association of America, February 2008.

Hjartarson, 2009. Hjartarson, Heimir, *Waste Heat Utilization at Elkem Ferrosilicon Plant in Iceland*, University of Iceland.

IEA, 1995. *Industrial Heat Pumps – Experiences, Potential and Global Environmental Benefits*, Prepared by RCG/Hagler Bailly, Inc., IEA Heat Pump Centre, HPP-AN21-1.

Jakobs, 2010. *Status and Outlook: Industrial Heat Pumps*, 3rd European Heat Pump Forum, Brussels, Presentation from Rainer Jakobs, Information Centre on Heat Pumps and Refrigeration, Germany, May 20, 2010.

LBNL, 2000. *Emerging Energy-Efficient Industrial Technologies*, prepared by Lawrence Berkeley National Laboratory and American Council for an Energy-Efficient Economy, LBNL 46990.

LBNL, 2005. *Clean Energy Technologies: A Preliminary Inventory of the Potential for Electricity Generation,* Lawrence Berkeley National Laboratory.

Leonardo, 2007. *Power Quality & Utilisation Guide, Section 7: Energy Efficiency,* Leonardo Energy, http://www.leonardo-energy.org/webfm_send/180 .

Lewis, 2009. *Industrial Heat Pumps – A Reexamination in Light of Current Energy Trends*, N. Lewis, M. Simon, S. Terry, J. Leach, North Carolina State University Industrial Assessment Center, Proceedings of the 31st Industrial Energy Technology Conference, ESL-IE-09-24.

Goldstick, 1986. *Principles of Waste-heat Recovery*, R. Goldstick and A. Thumann, Fairmont Press, 1st Edition.

Nyle, 2006. *Introduction to Kiln Drying*, Nyle Corporation

Nyle, 2010. Personal communication between Don Lewis, Nyle Corporation, and Megan Douglas, ICF.

ORNL, 2004 Andrew Dasinger, Rajul Misra, *An Inventory of Industrial Waste Heat and Opportunities for Thermally Activated Technologies*, prepared by United Technologies Research Center, prepared for Oak Ridge National Laboratory.

PG&E, 1997. *Industrial Heat Recovery Strategies, Application Note*, Pacific Gas and Electric Company,

PNNL, 2006. V.V. Viswanthan et al., *Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions*, Pacific Northwest National Laboratory, April 2006.

RED, 2010. Recycled Energy Development, Westmont, IL, Private Communication, July 2010.

Saxton, 1997. Patrick C. Saxton, Thermophotovoltaic Emitter Material Selection and Design, U.S. Naval Academy, Annapolis, MD, 1997.

TESPL, 2010. Transparent Energy Systems Private Ltd., Cement Plant Case Studies, http://www.heatrecovery-system.com/case-study-1-cement-plant.

Thekdi, 2007. *Waste Heat to Power: Economic Tradeoffs and Considerations,* Arvind Thekdi, 3rd Annual Waste Heat to Power Workshop, Houston, TX.

Vilter, 2010. Personal communication between Sam Gladis, Vilter, and Megan Douglas, ICF.

WSU, 2009a. *Industrial Heat Pumps for Low Temperature Heat Recovery*, Washington State University Extension Energy Program, WSUEEP08-035, http://www.energy.wsu.edu/documents/industrialservices/IndustServFactsheet-HeatPumps-May%2009.pdf .

WSU, 2009b. *An Overview of Industrial Waste Heat Recovery Technologies for Moderate Temperatures Less Than 1000 °F*, C.J. Roos, Northwest CHP Application Center, WSUEEP09-26, http://www.chpcenternw.org/NwChpDocs/AnOverviewOfIndustrialWasteHeatRecoveryTechForModerateTemps.pdf .

A

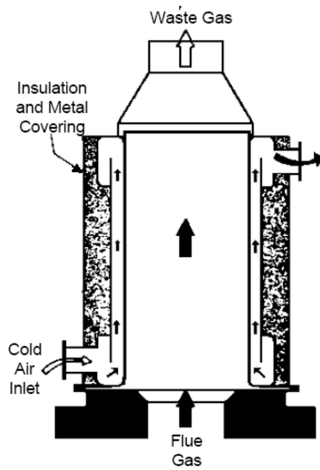
OVERVIEW OF HEAT EXCHANGERS

There are several heat exchanger configurations that are used for waste heat recovery depending on application requirements. A few common designs include:

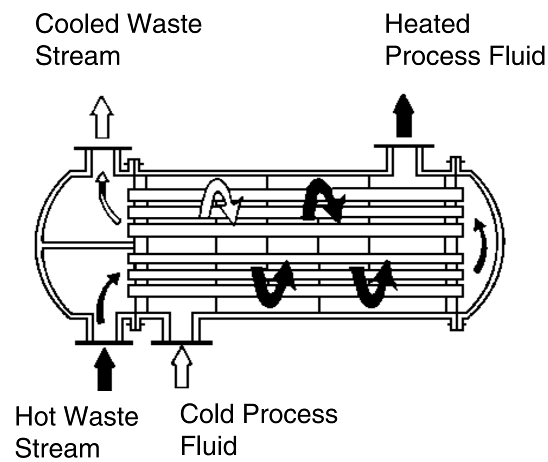
- Recuperators
- Regenerators
- Economizers
- Air preheaters
- Waste heat boilers
- Load preheating

Recuperators

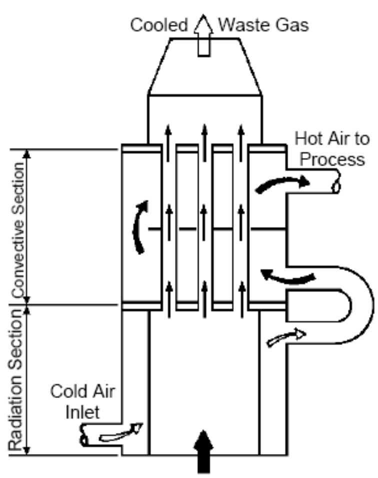
Recuperators and regenerators are both generally configured to transfer energy from medium to high temperature combustion exhaust streams to combustion air. Recuperators and regenerators have fundamental design differences, but both types of heat exchangers can be used in conjunction with industrial furnaces, ovens, incinerators, and other process equipment that produces medium to high temperature combustion products. A few recuperators are shown in **Figure A-1**.



(a) Radiation Recuperator



(b) Convection Recuperator



(c) Radiation & Convection Recuperator

(d) Radiation Recuperator for Glass Melter

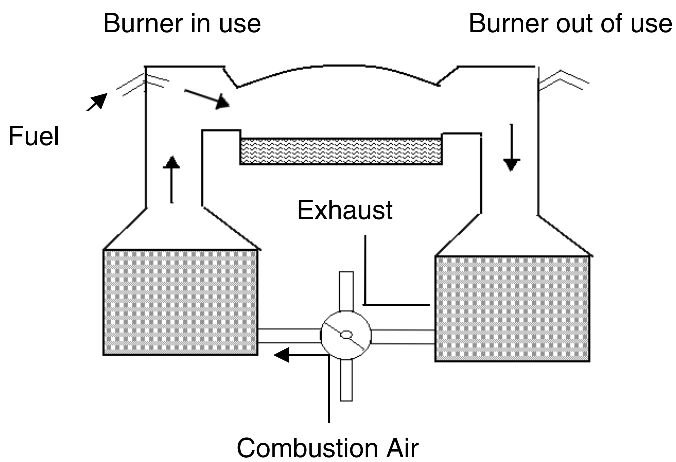
Source: *DOE, 2008, p13; PG&E, 1997, p4*

Figure A-1
Recuperators

Recuperators can be constructed with either metal or ceramic materials. Metal recuperators are used in applications with temperatures below 2,000ºF, and ceramic recuperators can be used at temperatures up to 2,800ºF.

Regenerators

There are various configurations for regenerators, and a common arrangement is shown in **Figure A-2**. In this illustration, the regenerative system consists of two chambers, and each chamber contains ceramic bricks or other material that can store heat at high temperatures. As combustion exhaust passes through one chamber, the bricks absorb heat from the combustion products. The flow of air is then reversed, so that the incoming combustion air passes across the hot bricks, which transfers heat to the combustion air entering the furnace. The direction of airflow is altered about every 20 minutes in a typical regenerator.



Source: *DOE, 2008, p14*

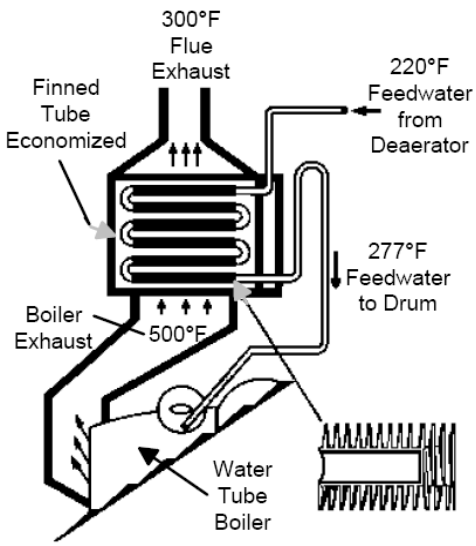
Figure A-2
Regenerative Furnace

Regenerators are 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 iron making. 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.

Economizers

Recuperators and regenerators are designed to recover energy from medium to high temperature combustion exhaust that is generated from industrial furnaces, ovens, and other process equipment. In industrial plants, boilers are by far the most common type of equipment encountered. Compared to ovens and furnaces, fossil fired boilers generally operate at higher efficiencies (e.g., 80%), and therefore produce lower temperature flue gases.

For low to medium temperature flue products, such as those generated by boilers, different types of heat recovery equipment are used. One of the most common types of boiler heat recovery equipment is the economizer (see **Figure A-3**). An economizer is used to transfer heat from the combustion products to the boiler feedwater, and consists of a finned tube heat exchanger placed in the flue exhaust. The term "economizer" implies that the boiler feedwater is heated. However, economizer type designs can be used to meet other plant liquid heating needs, including hot process liquids, hot water for space heating, and domestic hot water.



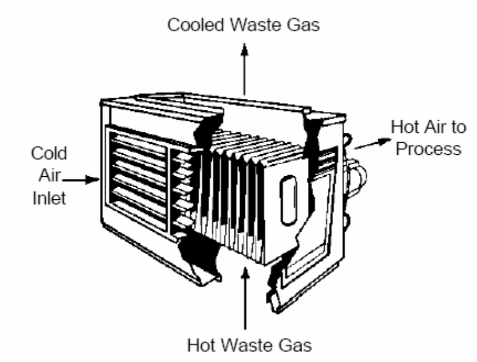
Source: *DOE, 2008, p16*

Figure A-3
Boiler Economizer

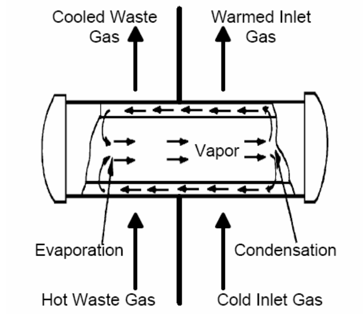
Air Preheaters

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.

Passive preheaters can be of two types – the plate type and heat pipe. The plate type exchanger (**Figure A-4a**) 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. The heat pipe heat exchanger consists of several pipes with sealed ends (**Figure A-4b**). Each pipe contains a capillary wick structure that facilitates movement of the working fluid between the hot and cold ends of the pipe.



a. Flat Plate



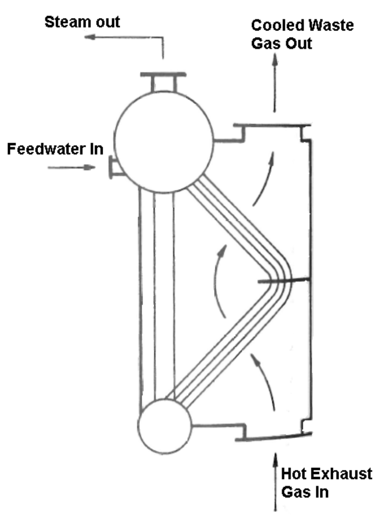
b. Heat Pipe

Source: *DOE, 2008, p15-16*

Figure A-4
Aire Preheaters

Waste Heat Boilers

Figure A-5 shows waste heat recovery in a water tube boiler. In this configuration, medium to high temperature combustion products are delivered to the boiler, and the boiler generates steam. Waste heat boilers are available in a wide range of capacities. If 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.



Source: *DOE, 2008, p17*

Figure A-5
Waste Heat Boiler

Load Preheating

Industrial processes often involve heating solid feedstocks to high temperatures. For example, ceramic materials are processed at high temperature in kilns, and aluminum mills, metal factories, and glass plants use melting furnaces to produce high temperature liquids from solid feedstocks. Waste heat streams can be used to preheat solid loads. **Figure A-6** shows an example where hot combustion gases are used to preheat metal ingots prior to melting in a die casting operation.

Source: *DOE, 2008, p17*

Figure A-6
Stack melter in Die-casting Operation

B
CONVERSION FACTORS

1 exajoule (EJ)	=	10^{18} J	=	0.948 Quads
1 kJ	=	10^{3} J	=	0.948 Btu
1 kWh	=	3,412 Btu		
1 MWh	=	1,000 kWh	=	3.4 MMBtu
1 MBtu	=	10^{3} Btu		
1 MMBtu	=	10^{6} Btu		
1 TBtu	=	10^{12} Btu		
1 Quad	=	10^{15} Btu	=	1.055 EJ

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute Inc., (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent more than 90 percent of the electricity generated and delivered in the United States, and international participation extends to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

1020134

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com