Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

Additive Manufacturing

Advanced Materials Manufacturing

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Combined Heat and Power Systems

Composite Materials

Critical Materials

Direct Thermal Energy Conversion Materials, Devices, and Systems

Materials for Harsh Service Conditions

Process Heating

Process Intensification

Roll-to-Roll Processing

Sustainable Manufacturing - Flow of Materials through Industry

Waste Heat Recovery Systems

Wide Bandgap Semiconductors for Power Electronics

U.S. DEPARTMENT OF ENERGY

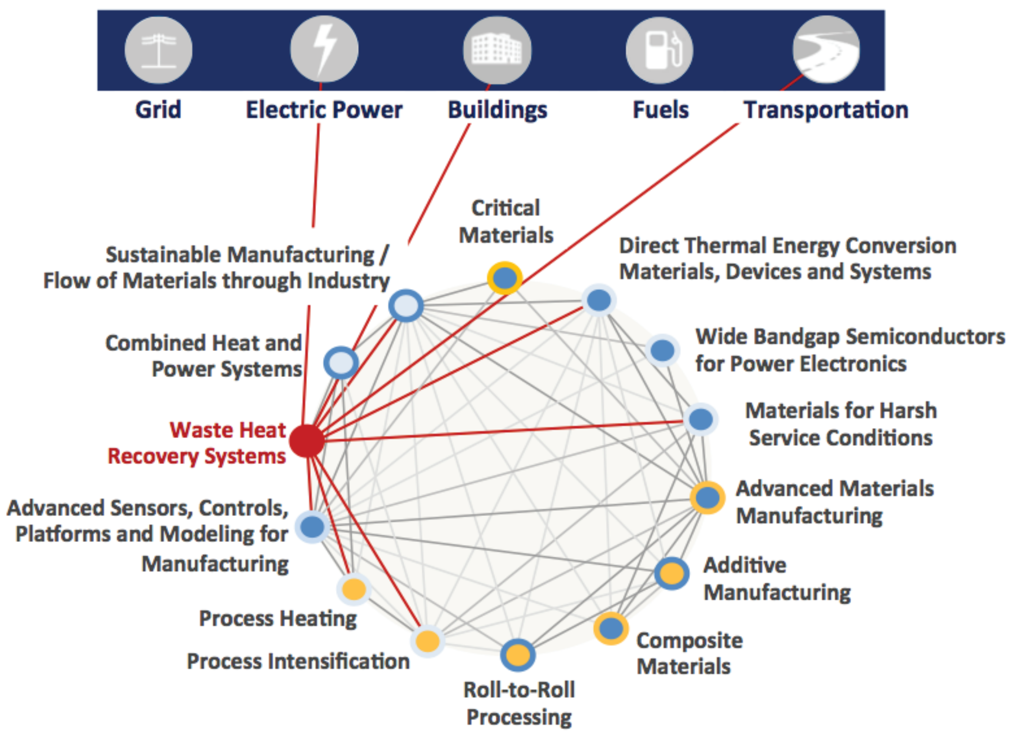
Quadrennial Technology Review 2015

Waste Heat Recovery Systems

Chapter 6: Technology Assessments

NOTE: This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). Waste Heat Recovery Systems is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections	Representative Extra-Chapter Connections
■ **CHP:** heat recovery in CHP systems ■ **Sustainable Manufacturing:** optimization of heat flows to maximize production intensity and minimize waste heat losses ■ **Direct Thermal Energy Conversion:** novel energy conversion materials, devices and systems for waste heat to power ■ **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing:** sensors to monitor temperature, humidity, and lower explosion limits to enable increased exhaust gas recycling; predictive models for combustion ■ **Process Intensification:** integrated control systems; replacement of batch operations with continuous ones ■ **Process Heating:** waste heat recovery from process heating equipment; facility integration to enable re-use of exhaust gases in lower-temperature processes	■ **Electric Power:** waste heat recovery opportunities in electric generation ■ **Buildings:** heat exchangers in HVAC systems; advanced materials for building envelopes to reduce waste heat losses ■ **Transportation:** waste heat recovery from internal combustion engines

Introduction to the Technology/System

Introduction to Waste Heat Recovery

Waste heat is generated from a variety of industrial systems distributed throughout a manufacturing plant. The largest sources of waste heat for most industries are exhaust and flue gases and heated air from heating systems such as high-temperature gases from burners in process heating; lower temperature gases from heat treating furnaces, dryers, and heaters; and heat from heat exchangers, cooling liquids, and gases. While waste heat in the form of exhaust gases is readily recognized, waste heat can also be found within liquids and solids. Waste heat within liquids includes cooling water, heated wash water, and blow-down water. Solids can be hot products that are discharged after processing or after reactions are complete, or they can be hot by-products from processes or combustion of solid materials. Other waste heat sources that are not as apparent include hot surfaces, steam leaks, and boiler blow-down water. Table 6.M.1 shows a number of major sources of industrial waste heat along with the temperature range and characteristics of the source.[1]

Table 6.M.1 Typical Temperature Range and Characteristics for Industrial Waste Heat Sources[1]

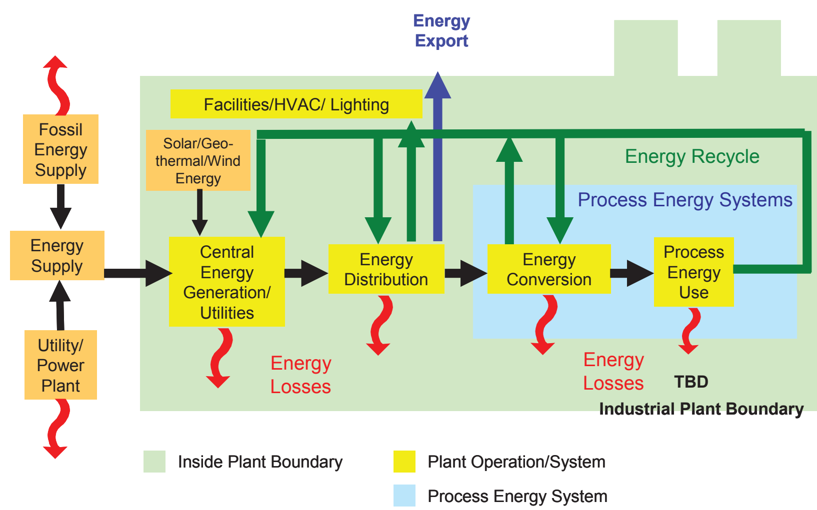
Waste Heat Source	Temperature Range (°F)	Cleanliness[2]
Furnace or heating system exhaust gases	600 – 2,000	Varies
Gas (combustion) turbine exhaust gases	900 – 1,100	Clean
Reciprocating engines		
Jacket cooling water	190 – 200	Clean
Exhaust gases (for gas fuels)	900 – 1,100	Mostly clean
Hot surfaces	Post-intercooler water	Clean
Compressor post-intercooler water	100 – 180	Clean
Hot products	200 – 2,500	Mostly clean
Steam vents or leaks	250 – 600	Mostly clean
Condensate	150 – 500	Clean
Emission control devices – thermal oxidizers, etc.	150 – 1,500	Mostly clean

Various reports prepared for the Department of Energy (DOE) and other organizations[1,3,4,5,6,7,8] have studied sources of waste heat, primarily from industrial heating systems. The scope of these reports varied from estimating annual energy losses from industrial heating systems, to reviewing waste heat from various industries and identifying general R&D opportunities. The following is an overview of several waste heat reports that were used as references in this Technology Assessment, with key RDD&D opportunities highlighted that may lead to improved waste heat recovery (WHR). Added to each report overview are comments, considerations and/or updates intended to improve alignment with this Technology Assessment.

Energy Use, Loss, and Opportunities Analysis[3]

The Energy Use, Loss, and Opportunities Analysis report[3] describes total energy used by major manufacturing sectors identified by North American Industry Classification System (NAICS) codes, using Manufacturing Energy Consumption Survey (MECS) data published by the U.S. Energy Information Administration (EIA) that were available at the time the report was prepared. MECS data were used to estimate plant energy use for major function areas, as shown Figure 6.M.1, along with associated subsystem losses. Subsystem losses were determined by applying equipment loss factors to the energy used in selected functional categories within the major energy consuming systems, as shown in Table 6.M.2, including some that generate waste heat.

Figure 6.M.1 Major Areas of Energy Use in a Manufacturing Plant[3]



Five of the twenty energy savings opportunities identified in the report were WHR opportunities within the plant boundaries. These include WHR from: (1) gases and liquids in chemicals, petroleum, and forest products, including hot gas cleanup and dehydration of liquid waste streams; (2) drying processes; (3) gases in metals and non-metallic minerals manufacture (excluding calcining), including hot gas cleanup; (4) calcining (not flue gases); and (5) metal quenching/cooling.

Table 6.M.2 Typical Energy Losses for Major Energy Systems in a Manufacturing Plant (1998)[3]

Energy System	Percent Energy Lost	Estimated Annual Energy Loss
Steam systems (generation + distribution)	30% - 35%	2,220 TBtu
Power generation	24% - 45%	270 TBtu
Energy distribution (except steam)	~ 3%	340 TBtu
Energy conversion	10% – 50%	2,860 TBtu
Motor systems	30% – 80%	1,120 TBtu

Comments on the report Energy Use, Loss, and Opportunities Analysis[3] for the purposes of this Technology Assessment:

This report provides estimates of energy losses for major energy use areas in manufacturing facilities. It evaluated a limited number of process systems, and indicated that the major energy losses take place in process heaters (includes steam and direct heaters), motor driven systems (compressed air, pumps, and fans), and steam generation systems. More efficient systems can avoid some of these losses.

It is important to note that energy losses do not equate to recoverable energy. There are practical limits (technical and economic) with respect to the recovery potential of those losses. The factors impacting the feasibility of WHR options include heat quantity, heat temperature (quality), composition, minimum allowed temperature, and logistical constraints like operating schedules and availability. Depending on these factors, waste heat can have a number of uses including combustion air preheating, boiler feedwater preheating, load preheating, power generation, steam generation, space heating, water preheating, and transfer to liquid or gaseous process streams.[4]

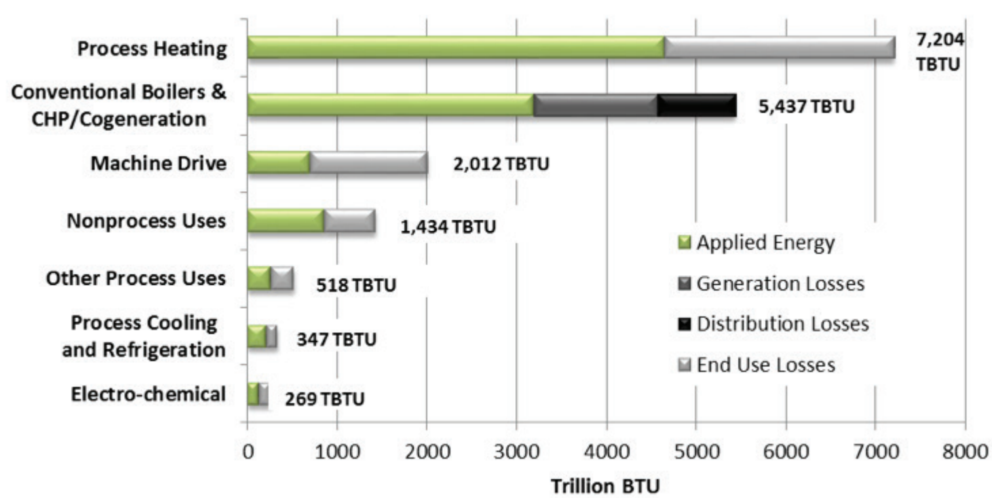
The energy loss factors for major energy systems used in this report have been updated and refined in the latest energy footprints assumptions/definitions document released in 2014.[9] The updated and refined energy loss factors are provided in Table 6.M.3 below. Figure 6.M.2 shows these onsite losses across different industrial systems, including onsite generation losses, onsite distribution losses, and end use losses. Applied energy (applied toward direct production or end use at the plant) is also shown, determined by subtracting from the offsite generation and transmission losses, onsite generation and distribution losses, and end use losses from the primary energy consumption for the facility.

These loss factors are represented visually in the DOE Manufacturing Energy and Carbon Footprints, which map energy use and carbon emissions in manufacturing from energy supply to end use.[10] By combining energy consumption data with energy loss factors, each footprint visualizes the flow of energy (in the form of fuel, electricity, or steam) to major end uses in manufacturing, including boilers, power generators, process heaters, process coolers, machine-driven equipment, facility HVAC, and lighting.[11] For more details, including references, please refer to Table 1 in the "2010 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions" document.[9] In addition, Appendix F of the 2013 report U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis[12] provides a detailed examination of the methodology used to determine process heating losses shown below in Table 6.M.3.

Table 6.M.3 Typical Energy Losses Associated with Selected Energy Consuming Systems in Manufacturing Facilities

Energy System	Percent Energy Lost
Energy Generation, Transmission and Distribution Losses	
Offsite Generation	Offsite (grid) electricity generation and transmission – 66.8% Offsite steam generation – 20% Offsite steam transmission – 10%
Onsite Generation	Onsite steam generation (conventional boiler) – 18% to 22% Onsite CHP/cogeneration – 18% to 29% Onsite steam distribution – 20%
Onsite Direct End Use (Process and Non-process) Losses	
Process Energy	Process heating (direct and indirect) – 18% to 72% Process cooling, refrigeration – 35% Electro-chemical – chemicals 35%, aluminum 60%, other 48% Other processes – Electric 5%, Fuel 70%, Steam 40% Machine drive i.e., shaft energy – Electric 6% to 8%, Fuel 63%, Steam 60% Machine driven systems: ■ Pumps – 40% ■ Fans – 40% ■ Compressed air – 85% ■ Materials handling – 15% ■ Materials processing (e.g., grinders) – 80% ■ Other systems – 52%
Non-process Energy	Facility HVAC – 40% Facility lighting – 40% Other facility support – 80% Onsite transportation – 5% Other non-process e.g., cleaning equipment, maintenance tools – Electric 33%, Fuel 35%, Steam 30%

Figure 6.M.2 Estimates of Energy Losses for Major Energy Use Areas in Manufacturing[9, 10, 11]

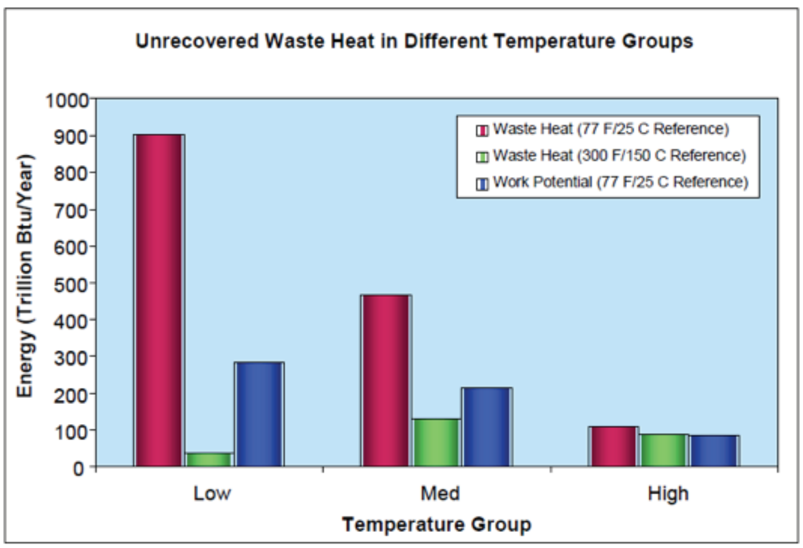


Waste Heat Recovery: Technology and Opportunities in U.S. Industry[4]

The *Waste Heat Recovery: Technology and Opportunities in U.S. Industry* report provides information on waste heat sources in major industrial sectors. The report details the nature of waste heat; available WHR equipment currently used by the industry; and research, development, and demonstration (RD&D) needs. The report classifies waste heat sources in three categories: high temperature (>1,200°F), medium temperature (450°F – 1,200°F), and low temperature (<450°F).

The study investigated a range of industrial processes, consuming a total of ~8,400 TBtu/yr, as a basis to estimate WHR opportunities. Estimates of total unrecovered waste heat are shown in Figure 6.M.3, which indicates that the majority of waste heat losses (based on a 77°F [25°C] reference) are in the low temperature range. Though low temperature waste heat is lower quality, it is present in sufficiently large magnitudes that its work potential exceeds that of other waste heat sources.

Figure 6.M.3 Unrecovered Waste Heat in Different Temperature Groups (2002).[4] The temperature groups are defined as: High – 1200°F [650°C] and higher; Medium - 450°F [230°C] to 1,200°F [650°C]; and Low - 450°F [230°C] and lower.



For the sectors and uses examined, this study also identified unrecovered waste heat in different temperature ranges, concluding that the amount of heat wasted in U.S. industry above a 300°F reference temperature is 276 TBtu per year, whereas 1,478 TBtu per year is lost if the reference temperature is lowered to 77°F.[13] This indicates significant heat recovery opportunities in the 77°F - 300°F temperature range, which represents more than 80% of the total estimated waste heat. Cost-effective technologies need to be advanced in order to access the energy savings from low temperature waste heat.

Comments on the report Waste Heat Recovery: Technology and Opportunities in U.S. Industry[4] for the purposes of this Technology Assessment:

Analysis of waste heat sources and recovery is greatly affected by the waste heat temperature. Therefore it is necessary to clearly identify the temperature regimes for waste heat related discussions. While this study identifies three temperature ranges to classify waste heat sources and opportunities, there is no general agreement on or basis for this definition of the temperature ranges. The report identified a range of key unit operations across industrial sectors from which WHR estimates were based (see Figure 6.M.4).

Figure 6.M.4 Waste Heat Losses and Work Potential from Selected Process Exhaust Gases (2002)[4]

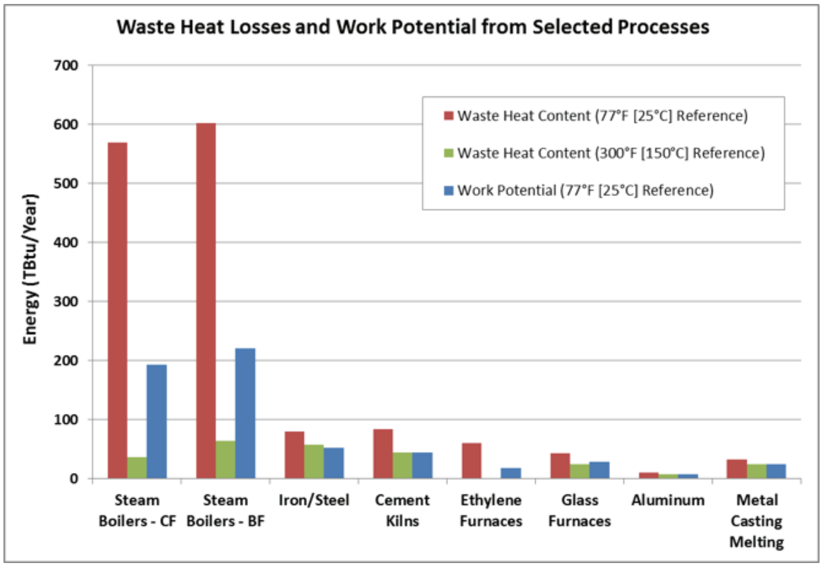


Figure 6.M.4 shows steam boilers divided into conventional fuels (CF) and byproduct fuels (BF). While steam boilers have high total waste heat losses, attributable to the large number of industrial boilers (approximately 43,000 total units) rather than boiler inefficiency. Typical boiler efficiencies (80-85%) are higher than other fired units such as glass furnaces. Heat losses from boilers are in the low temperature range, as evidenced by the low heat content from a 300°F [150°C] reference. Values do not reflect total waste heat losses by industry, but rather the waste heat losses from selected processes. Iron/Steel includes coke ovens, blast furnaces, basic oxygen furnaces, and electric arc furnaces. Aluminum includes primary refining cells and secondary melting furnaces. Metal casting melting includes aluminum reverberatory furnaces, stack melters, and iron cupolas in metal casting facilities. Aluminum includes primary and secondary refining furnaces.

This taxonomy provides a useful framework for future estimates; however, a greater understanding of R&D opportunities is revealed if the temperature ranges are expanded. In this Technology Assessment, the temperature ranges have been expanded on both sides (high and low) of the spectrum. This expansion suggests additional R&D is needed in the temperature ranges below 250°F (ultra-low temperature) and higher than 1,600°F (ultra-high temperature), where cost-effective WHR methods or equipment are currently limited. Hence, this technology assessment targets the following five temperature ranges:

- Ultra-low temperature: below 250°F. An example of the lower temperature for this range is the temperature of a cooling medium such as cooling tower water or other water used for cooling systems. Recovery of the waste heat is affected by factors such as the condensation temperature of combustion products or flue gases (usually below 180°F for natural gas combustion products); the applicability of low-temperature, non-oxidizing materials such as aluminum or non-metallic materials such as polymers or plastics; or the usage of low-temperature WHR systems such as heat pumps.
- Low temperature: 250°F – 450°F, as defined in the study.
- Medium temperature: 450°F – 1,200°F, as defined in the study.
- High temperature: 1,200°F – 1,600°F, a new range for high temperature is proposed in this TA. Based on input from industry experts and WHR equipment suppliers, it is suggested that the study definition of the "high" temperature range (historically all temperatures >1,200°F) be divided in two temperature ranges – high temperature (1,200°F – 1,600°F) and ultra-high temperature (>1,600°F), which are based on distinctions of equipment and materials for use in these ranges.
- Ultra-high temperature: >1,600°F. A new temperature range is proposed in this TA for WHR from streams above 1,600°F, which require use of special high-temperature materials that can be metallic or nonmetallic, such as ceramics. Selection of material and equipment design becomes critical in many cases, as such streams contain a large amount of contaminants.

Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions[5]

A Pacific Northwest National Laboratory (PNNL) report titled *Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions* discussed waste energy availability.[5] This report analyzed barriers and pathways to recovering chemical and thermal emissions from U.S. industry, with the goal of more effectively capitalizing on such opportunities.

This study characterized the quantity and energy value of these chemical and thermal losses, surveyed publicly available literature to determine the amount of energy embedded in the losses, and identified technology opportunities to capture and reuse this energy. Approximately 1,400 TBtu of residual chemical fuel energy value was identified in the industrial sector—approximately 4.3% of total U.S. industrial energy use.

The study also considered advanced energy technologies using improved materials (e.g., thermoelectric, thermionic, piezoelectric, and solid oxide fuel cells) that are candidates for recovering chemical and thermal losses. The study recommended additional research and development as well as industry education to make these technologies sufficiently cost effective and widely commercialized.

Comments on the report Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions[5] for the purposes of this Technology Assessment:

This study showed that the manufacturing processes and related energy consumption yields waste products in the form of chemical emissions (CH_4, CO, H_2, etc.) and thermal emissions (sensible waste heat). Hence this TA includes both chemical and sensible enthalpies while quantifying total waste heat opportunity in manufacturing sector. The study determined the amount of energy in industrial emissions and identified technology opportunities for capturing and redeploying this energy. The study identified 2 quads of residual energy from chemical emissions for potential capture. Since landfills are not traditionally considered industrial organizations, the industry component of the emissions that had residual chemical fuel value was 1.4 quads. This represents approximately 4.3% of the total energy used by U.S. industry. The Energy Use, Loss, and Opportunities Analysis: U.S. Manufacturing & Mining report on opportunities to reduce energy use and loss in industry[3] quantified total thermal emissions (chemical and sensible) from U.S. industry. As shown in Table 6.M.4, more than 10 quads of thermal emissions were identified from U.S. industrial processes. The table also describes the origin of these emissions, which represent approximately 30.8% of the total energy used by U.S. industry.

Table 6.M.4 Waste Heat Recovery Opportunities – from Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions Report (2006)[5] and Energy Use, Loss, and Opportunities Analysis: U.S. Manufacturing & Mining[3]

Description of Opportunity Area	Estimated Energy Available (TBtu)	Estimated Recovery Efficiency	Estimated Recovery Opportunity (TBtu)	Economic Benefit if Realized $ billion (2005)
WHR from gases and liquids in chemicals, petroleum, and forest products, including hot gas cleanup and dehydration of liquid waste streams	~7,000	~12%	851	$2.15B
Heat recovery from drying processes (chemicals, forest products, food processing)	~3,700	~10%	377	$1.24B
WHR from gases in metals and non-metallic minerals manufacture (excluding calcining), including hot gas cleanup	~1,600	~15%	235	$1.23B
WHR from calcining (not flue gases)			74	$0.16B
Heat recovery from metal quenching/cooling processes			57	$0.28B
Total	**>10,000**		**1,594**	**$5.06B**

Engineering Scoping Study of Thermoelectric Generator (TEG) Systems for Industrial Waste Heat Recovery[14]

The *Engineering Scoping Study of Thermoelectric Generator (TEG) Systems for Industrial Waste Heat Recovery*[14] report evaluated waste heat recovery opportunities for TEG systems in industrial applications, focusing on opportunities in the glass, ethylene, iron and steel, and aluminum industries. Three processes were selected as case studies to explore the potential for TEG waste heat recovery: glass furnaces (905°–2,550°F), aluminum Hall-Hèroult cells (~1,760°F), and reverberatory furnaces (~1,400°F). These applications have high potential for TEG waste heat recovery, as they have high-temperature waste heat discharges and are in many cases poorly suited for conventional fluid-to-fluid heat exchange operations. The study found that:

- Waste heat recovery systems based on existing TEG materials with a figure of merit (ZT) of ~1 are not generally cost effective for waste heat recovery in industrial applications. Device efficiency rarely exceeds 5% at this level of performance. However, if ZT values could be boosted to ZT=2 or higher, a business case could be made in many industries.[15]
- Energy conversion efficiencies as high as 20% may be possible for TEG systems with a hot-side temperature of at least 1340°F (1000 K) and a ZT value of at least 2. (For further discussion of TEG energy efficiency and materials, see the QTR technology assessment 6.G, *Direct Thermal Energy Conversion Materials, Devices, and Systems*.)
- Within the industries considered, an estimated 10 TBtu of energy could be saved annually through the application of TEG technologies with ZT=2.

To realize these benefits, key identified R&D needs include the development of advanced thermoelectric materials (with ZT=2 or higher), high-performance heat exchange surfaces, high-heat-flux interface materials, and cost-effective manufacturing techniques for TEG modules.

Comments on the Engineering Scoping Study of Thermoelectric Generator (TEG) Systems for Industrial Waste Heat Recovery[14] for the purposes of this Technology Assessment:

The lack of moving parts in thermoelectric generators holds the promise of reduced operation and maintenance costs and longer times between failures. These potential benefits make thermoelectric generators important to consider for industrial WHR applications. Estimates of energy recovery potential from thermoelectric technologies have varied depending on assumptions. The *Direct Thermal Energy Conversion Materials, Systems and Devices Technology Assessment* (6.G) estimated a potential savings of 6.5 to 16 TWh of electrical energy annually, which is 0.9 to 2.3% of the 710 TWh of onsite electrical energy used at manufacturing plants (based on 2010 data). This is 1.5–3.7% of the 430 TWh of waste heat predicted for the 2,470 TWh worth of annual industrial energy consumption in the *Waste Heat Recovery: Technology and Opportunities in U. S. Industry* report.[4] The utilization of thermoelectrics for WHR in industrial settings will require not only materials advances to achieve sufficient *ZT*, but also durable devices with systems and operating costs low enough to provide a return on investment.

Technologies and Materials for Recovering Waste Heat in Harsh Environments[16]

The *Technologies and Materials for Recovering Waste Heat in Harsh Environments* report[16] identified industries and industrial heating processes in which the exhaust gases are at high temperature (>1,200°F), and contain reactive gases, liquid vapors, volatiles from low-melting-temperature solid materials, particulates, or condensable materials. It also identified specific issues related to WHR for each of these processes or waste heat streams. In addition to this study, the 6.H *Materials for Harsh Service Conditions* Technology Assessment which is available as an appendix to the 2015 Quadrennial Technology Review (QTR) expanded in more detail on some of issues summarized here. Key insights from the report are excerpted below.

The temperature of the exhaust gases discharged into the atmosphere from heating equipment depends on the process temperature and whether a WHR system is used to reduce the exhaust gas temperature. The temperature of discharged gases varies approximately from as low as 150°F to as high as 3,000°F. Combustion products themselves, generated from well-designed and well-operated burners using gaseous and light liquid fuels, are relatively clean and do not contain particles or condensable components that may require "cleanup" before discharge into the atmosphere. However, during the heating process, the combustion products may react or mix with the product being heated and may pick up constituents such as reactive gases, liquid vapors, volatiles from low-melting-temperature solid materials, particulates, condensable materials, and the like. Some or all of these constituents, particularly at high temperatures, may react with materials used in the construction of downstream WHR equipment and create significant problems. Potential issues include chemical reaction of exhaust gases and their solid or vapor content with the materials used in the WHR equipment; deposition of particulates in or on surfaces of WHR equipment; condensation of organics such as tars and inorganic vapors such as zinc oxides and boron on heat exchanger surfaces; and erosion of heat exchanger components by the solids in the exhaust gases. Many of these problems are compounded by the high temperature of the exhaust gases, uneven flow patterns of the hot gases inside the heat exchanger, and operating variations such as frequent heating and cooling of the heat exchanger. The study identified industries and heating processes in which the exhaust gases are at high and ultra-high temperatures (>1200°F), contain all of the types of reactive constituents described, and can be considered as harsh or contaminated. The study also identified specific issues related to WHR for each of these processes or waste heat streams.

The following are common characteristics of the conditions classified as harsh environments:

1. **Ultra-high gas temperature (>1,600°F):** Even if the process temperature is less than 1,600°F, the presence of combustible components such as CO, H_2, or hydrocarbons in flue gases could increase localized temperatures to exceed the temperature limit of the heat recovery system components. An example is when combustible components are in the presence of air that could leak into the flue gas ducts or into a WHR system such as a recuperator; examples might include electric arc furnace (EAF) and basic oxygen furnace (BOF) exhaust gases, and flue gases from "over-fired" aluminum melting furnaces.
2. **Presence of highly corrosive fluxing agents (e.g., salts, calcium, chlorides, fluorides):** The types and amounts of fluxing agents or their compounds depend on the heating process and the final product specifications. These fluxing agents introduce highly corrosive elements that promote degradation of WHR equipment materials. For example, chemical reactions between

the corrosive gases and metal tubes in a recuperator could result in an extremely short life for the recuperator. The use of advanced materials that would extend the recuperator life is currently uneconomical for most applications.

3. **Presence of particulates (e.g., metal oxides, carbon or soot particles, fluxing materials, slag, aluminum oxide, magnesium oxide, manganese):** Fine particles entrained in flue gases may react with the heat exchanger materials (metallic or nonmetallic), resulting in reduction of heat transfer and in damaging reactions with heat exchanger materials. The net effect of these reactions is a shorter life for recuperator parts and, often, premature failure of metals at critical locations. In some cases, such as in boilers, it is possible to remove the material buildup by periodic maintenance to remove soot, but this is not practical for all types of heat recovery systems.
4. **Presence of combustibles (e.g., CO, H_2, hydrocarbons):** As mentioned above, the presence of combustibles in flue gases could result in higher-than-design temperatures for heat exchangers owing to air leaks or the addition of dilution or cooling air to flue gases. In cases where no cooling or dilution air is used, the presence of combustibles can still present severe problems. The combustibles may react with constituents (such as nickel) of high-temperature alloys to form soot that deposits on heat transfer surfaces and reacts with metal, leading to shortened life of equipment components.
5. **Presence of combustible volatiles from charge material such as scrap used for aluminum melting furnaces and EAF:** The scrap is obtained from a variety of sources and the plants use separation processing of scrap to remove combustible materials such as oils, paint, paper, plastic, and rubber. However, some of these materials end up in the charge material. Incomplete combustion, or breakdown of these organic materials results in the presence of combustible gases or solids, and they have the same effects on heat recovery equipment as the combustible materials described in item.[4]
6. **Variations in flow, temperature and composition of gases:** Large industrial heating equipment that uses a large amount of energy, such as EAFs, BOFs, and many aluminum melting furnaces, operate in a batch or semi-continuous mode. This results in variations in temperature, flow, and the composition of flue gases leaving the furnace. Variations in flue gases could result in cycling of materials (metal, in the case of a recuperator) and thermal fatigue of metals used in the heat recovery equipment. Thermal fatigue reduces the life of materials.

At this time the industry uses several practices for managing or dealing with exhaust gases classified as harsh environments:

1. No heat recovery, but treating (scrubbing, cooling by blending with cold air or mist cooling) exhaust gases to meet regulatory requirements. Examples are EAF and BOF exhaust gases.
2. Partial WHR due to materials limitations, design issues, and space considerations. An example is preheating of glass melting furnace combustion air using regenerators.
3. Partial WHR due to other limitations such as safety, maintenance, lifetime. Examples are use of scrap preheaters for EAFs and use of steam generation for BOF installations.
4. Partial or no WHR due to high capital cost, limited operating hours, or other operating and economic reasons. Examples are small glass and aluminum melting furnaces and cement and lime kilns.

5. Loss of sensible heat and loss of certain condensable organic materials (e.g., tar, condensable liquids, volatiles) during treatment of exhaust gases, and use of chemical heat after drying the gases as fuels. Examples are blast furnaces and coke ovens.

Table 6.M.5 summarizes information about the waste heat in exhaust gases identified as harsh environments resulting from selected processes in those industries. Calculations were performed for recoverable waste heat from harsh environment gases for each of these industrial sectors. The calculations were based on available information from various sources identified in the report. The results from the calculations are also provided in Table 6.M.5.

Table 6.M.5 WHR Potential from Selected Harsh Environment Waste Gas Streams[16]

Industry	Waste heat source*	Temp. range (°F)	Characteristics	Availability of WHR for Exhaust Gases	Production (million metric tons/yr)	Recoverable Potential (TBtu/yr)**			Process Heating Losses (TBtu/yr)[17]
						Sensible	Chemical	Total	
Steel	Blast furnace gases	750 to 1,100	Contain combustibles, particulates, etc.	Available and widely used–partial WHR	30	15.5	173	188	334
	EAF exhaust gases	2,700 to 3,000	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	64.3	27.2	34.9	62.1	
	Basic oxygen process	2,250 to 3,000	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	31.7	4.5	25.2	29.7	
Glass	Flat glass	800 to 2,600	Contain particulates, etc.	Available for air-fuel combustion only and widely used–partial WHR	5.0	12.4	Negligible	12.4	88
	Container glass	800 to 2,600	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and widely used–partial WHR	10.0	19.3	Negligible	19.3	
	Glass fiber (all types)	1,800 to 2,600	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and partially used–partial WHR	3.0	3.7	Negligible	3.7	
		800 to 2,600	Contain particulates, condensable vapors, etc.	Available for partial heat recovery but rarely used.	2.0	7.6	Negligible	7.6	

* Criteria: Exhaust gases considered either >1200°F and/or containing combustibles and contaminants

** For few waste heat sources (particularly in the steel, aluminum, and glass industries), a small quantity of waste heat is already being recovered using the existing WHR technologies.

Table 6.M.5 WHR Potential from Selected Harsh Environment Waste Gas Streams,[16] continued

Industry	Waste heat source*	Temp. range (°F)	Characteristics	Availability of WHR for Exhaust Gases	Production (million metric tons/yr)	Recoverable Potential (TBtu/yr)**			Process Heating Losses (TBtu/yr)[17]
						Sensible	Chemical	Total	
Aluminum	Aluminum melting furnaces (fuel fired)	1,400 to 1,700	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	10.0	15.9	Small - site specific	15.9	37
	Anode baking	570 to 930	Contain combustibles, particulates, polycyclic organic matter, etc.	Available but NOT demonstrated	2.2	1.9	Small/site specific (unknown)	1.9	
	Calcining	570 to 930	Particulates, fuel combustion products, etc.	Available but NOT demonstrated	Data not available at this time				
Cement (Clinker)	Cement kiln exhaust gases from modern clinker making operation	390 to 750	Contain particulates, etc. Relatively easy to handle	Available, not widely used–partial WHR	69.3	53.0	Negligible	53.0	84
Lime	Lime kiln exhaust gases based on commonly used rotary kiln type operation	390 to 1,100	Contain particulates, etc. Relatively easy to handle	Available, not widely used–partial WHR	20.9	40.7	Negligible	40.7	N/A
Total								**434**	**543**

* Criteria: Exhaust gases considered either >1200°F and/or containing combustibles and contaminants

**For few waste heat sources (particularly in the steel, aluminum, and glass industries), a small quantity of waste heat is already being recovered using the existing WHR technologies.

Findings from Previous Reports

Analysis of these previous studies along with direct contact with industry and equipment suppliers have shown that a significant amount of waste heat is not currently recovered across all temperature ranges, and there is an expanded need for R&D in two temperature ranges: ultra-low (<250°F) and ultra-high (>1,600°F). The lack of wide-scale heat recovery in these two temperature ranges appears to be primarily due to issues associated with technology, materials, and economics, such as the lack of economically justifiable measures and equipment to recover the low-grade heat, as well as heat contained in very high temperature and contaminated waste heat streams. In addition, for many existing WHR systems, especially in the medium-temperature range (600° – 1,200°F), there is an opportunity to further optimize these systems to improve the recovery rate and make the systems more cost-effective. For example, heat recovery opportunities are still available in the cement and glass industries, where exhaust gases from cement preheater kilns and recuperative glass furnaces are in the medium-to-high temperature range.

Technology Assessment and Potential

Commonly Used Waste Heat Recovery Systems

Industry uses a wide variety of WHR equipment offered by a number of suppliers in United States and from other countries. Much of this equipment is designed for specific industrial applications. There is no standard method to classify this equipment; in many cases the manufacturers offer application-specific designs.

The commonly used systems listed in this table are available from several suppliers to capture waste heat from a variety of industrial waste heat sources. While in most cases the systems are proven, the systems are continuously being improved in the following areas to offer better performance:

- Design changes to offer higher thermal efficiency and smaller footprint or size
- System cost reduction through improved design and manufacturing techniques
- Improved seals to reduce maintenance requirements and/or extend seal lifetimes
- Use of alternative materials to improve heat transfer performance or reduce maintenance costs
- Design changes to meet customer demands for different or previously untested applications

A summary of conventional or commonly used WHR technologies for various temperature ranges is found in Table 6.M.6.

Table 6.M.6 Commonly Used WHR Systems by Temperature Range[1]

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

Waste Heat to Power Technologies

Waste heat to power (WHP) is the process of capturing heat discarded by an existing process and using that heat to generate electricity. WHP technologies fall under the WHR category. In general, the least expensive option for utilizing waste heat is to re-use this energy in an on-site thermal process. If it is not feasible to recover energy from a waste heat stream for another thermal process, then a WHP system may be an economically attractive option.

Commonly used WHP technologies are:

- Rankine Cycle (RC) - The most common example of the Rankine cycle is the steam turbine, or steam Rankine cycle (SRC). In a SRC system, the working fluid is water, and steam is created to drive a turbine.
- Organic Rankine Cycle (ORC) - Organic Rankine cycle (ORC) systems are similar to SRC systems, but are typically used at lower temperatures, and instead of water the working fluid is a hydrocarbon, hydrofluorocarbon, or ammonia.
- Kalina Cycle (KC) - The Kalina cycle is a variation of the Rankine cycle, using a binary fluid pair as the working fluid (typically water and ammonia), and has the potential to have higher efficiency than the SRC.[18]
- Supercritical CO_2 Cycle - Another variation of the Rankine Cycle is the supercritical CO_2 (sCO_2) cycle, which utilizes carbon dioxide in place of water/steam for a heat-driven power cycle. The QTR Technology Assessment 4.R *Supercritical Carbon Dioxide Brayton Cycle* examines sCO_2 in more detail.

Emerging or Developing Waste Heat Recovery Technologies

Table 6.M.7 lists emerging technologies that may be used in a few cases, or are in an early stage of development and demonstration.

These technologies are being developed and tested at the laboratory or pilot scale in many different countries. The current status of the technology or product development depends on the local energy situation (cost and availability) and the availability of support from the local governments or funding agencies. In general, the following emerging WHR topics are receiving the most attention:

- Conversion of waste heat into a flexible and transportable energy source such as electricity
- Heat recovery from high-temperature gases with large amounts of contaminants such as particulates, combustibles, and condensable vapors (organic, metallic, or nonmetallic materials)
- Heat recovery from ultra-low temperature sources, primarily lower than 250°F
- Heat recovery from low- to medium-temperature exhaust gases or air with high moisture content to recover the latent heat of water vapor

Each of these emerging topics is discussed in more detail in the R&D opportunities section below.

Table 6.M.7 WHR Technologies, under Development or Demonstration, by Temperature Range[1]

Ultra-Low Temperature (< 250°F)	Low Temperature (250°F to 600°F)	Medium Temperature (600°F to 1200°F)	High Temperature (1200°F to 1600°F)	Ultra-High Temperature (>1600°F)
▪ Non-metallic (polymer or plastic) corrosion resistant heat exchangers of many different designs ▪ Systems with phase change material ▪ Desiccant systems for latent heat recovery from moisture laden gases ▪ Membrane type systems for latent heat recovery from water vapor ▪ Condensing water heaters or heat exchangers ▪ Thermally activated absorption systems for cooling and refrigeration	▪ Recuperators with innovative heat transfer surface geometries ▪ Advanced design of metallic heat wheel type regenerators ▪ Self-recuperative burners ▪ Systems with phase change material ▪ Advanced heat pipe exchanger ▪ Advanced design of metallic heat wheel ▪ Thermoelectric electricity generation systems	▪ Recuperators with innovative heat transfer surface geometries ▪ Advanced design of metallic heat wheel type regenerators ▪ Self-recuperative burners ▪ Systems with phase change material ▪ Advanced heat pipe exchanger ▪ Advanced design of metallic heat wheel ▪ Thermoelectric electricity generation systems	▪ Recuperators with innovative heat transfer surface geometries ▪ Thermo-chemical reaction recuperators ▪ Advanced design of metallic heat wheel type regenerators ▪ Advanced load or charge preheating systems ▪ Systems with phase change material ▪ Self-recuperative burners	▪ Regenerative burners ▪ Systems with phase change material ▪ Advanced regenerative systems ▪ Advanced load or charge preheating systems

Limitations of Currently Available Technologies

Table 6.M.8 and Table 6.M.9 depict limitations and barriers of currently available WHR technologies for ultra-high, high, and medium temperature ranges.

Table 6.M.8 Limitations of Currently Available WHR Technologies, High and Ultra-High Temperature Ranges[1]

Equipment	Limitations and Barriers
Metallic recuperators	■ Upper temperature limit of 1,600°F ■ Economically justifiable heat recovery efficiency limit of 40% to 60%[1] ■ High maintenance costs for use with gases containing particulates, condensable vapors, or combustible material ■ Reduced life expectancy in applications where the mass flow and temperature of the fluids vary or are cyclic ■ Fouling and corrosion of heat transfer surfaces ■ Difficulty in maintaining or cleaning the heat transfer surfaces
Ceramic recuperators	■ Reduced system life expectancy due to thermal cycling and the possibility of leaks from the high-pressure side ■ High initial cost ■ Relatively high maintenance ■ Size limitations – difficult to build large size units
Recuperative burners	■ Lower heat recovery efficiency (usually less than 30%) ■ Temperature limitation – exhaust gas temperature less than 1,600°F ■ Limited size availability (usually for burners with less than 1 MM Btu/hr) ■ Cannot be applied to processes where exhaust gases contain particles and condensable vapors
Stationary regenerators	■ Large system footprint ■ Declining performance over time ■ Plugging of exhaust gas passages when the gases contain particulates ■ Chemical reaction of certain exhaust gas constituents with the heat transfer surfaces ■ Possibility of leakage through dampers and moving parts ■ Cost can be justified only for high-temperature (>2,000°F) exhaust gases and larger size (>50 MM Btu/hr firing rate)
Rotary regenerators	■ Seal failure between the high-pressure and low-pressure gases (air) ■ Plugging of exhaust gas passages when the gases contain particulates ■ High pressure drop compared to recuperators ■ Maintenance and operation reliability issues for rotary mechanism
Regenerative burners	■ Large footprint for many applications ■ Complicated controls with dampers that cannot be completely sealed ■ Difficult pressure control for the furnace ■ Cost competiveness ■ Plugging of the bed when the gases contain particulates. Require frequent cleaning of the media and the bed.
Heat recovery steam generators - boilers	■ Limited to use for large size systems (usually higher than 25 MM Btu/hr) ■ Limited to use with only clean and particulate-free exhaust gases ■ Only viable for plants with need for steam use ■ Initial cost is very high compared to other options such as recuperators

Table 6.M.9 Limitations of Currently Available WHR Technologies, Medium Temperature Ranges[1]

Equipment	Limitations and Barriers
Metallic recuperators	■ Lack economic justification for exhaust gas temperature below 1,000°F in many cases ■ Economically justifiable heat recovery efficiency limit of 40% to 60% ■ High maintenance when used with gases containing particulates, condensable vapors, or combustible material ■ Fouling of heat transfer surfaces ■ Difficulty in maintaining or cleaning the heat transfer surfaces
Recuperative burners	■ Lower heat recovery efficiency (usually less than 30%) ■ Limited size availability (usually for burners with less than 1 MM Btu/hr) ■ Cannot be applied to processes where exhaust gases contain particles and condensable vapors
Rotary regenerators	■ Seal failure between the high-pressure and low-pressure gases (air) ■ Plugging of exhaust gas passages when the gases contain particulates ■ High pressure drop compared to recuperators ■ Maintenance and operation reliability concerns for rotary mechanism
Shell and tube heat exchanger for heating liquid (water)	■ Fouling of heat transfer surfaces when the gases contain particulates or condensable liquids ■ Condensation of moisture at selected cold spots and resulting corrosion

While the above tables show limitations and barriers by temperature range, an alternative approach would be to develop a matrix according to the type of equipment available in the market. Key considerations would include its application range (i.e., temperatures and heat source characteristics); performance level; and limitations with respect to industrial applications.

Technology Opportunities for Various Temperature Ranges[1]

R&D opportunities have been categorized according to the temperature regimes at which waste heat is available. All of these are focused on improving the efficiency of WHR and cost reduction through improved lower-cost materials, reduced maintenance, improved design, and other such factors.

Opportunities for High and Ultra-High Temperature Waste Heat Sources

R&D opportunities for both high temperature waste heat sources (1,200°F – 1,600°F), and ultra-high temperature waste heat sources (>1,600°F) include the following:

- Heat recovery systems that can handle high-temperature gases with solids and condensable contaminants. These systems can also have internal cleaning systems to enable long-term continuous operation without major maintenance time for cleaning or rebuilding. The systems can be recuperative or regenerative.
- Materials that can withstand high temperatures and chemical reactions with the waste heat source and the cyclic nature of waste heat in terms of mass flow rates, temperature, or composition. These materials will enable increased life-span heat recovery systems, such as ceramic recuperators.
- High-temperature phase change materials that can be used by high-temperature heat recovery systems to reduce the size of the system and allow tolerance of the cyclic nature of the waste heat source.
- Selective coatings or laminations that are compatible with base materials of construction and can withstand specific contaminants and combustibles in the waste gas streams.

- Systems with smaller footprints that allow retrofit installation for existing systems that are typically space-constrained in plants.
- Secondary heat recovery systems that can be used as supplementary or secondary recovery systems to enhance the performance of the existing systems. These systems should be compatible with the performance of the primary systems.
- A hot gas cleaning system with anti-fouling and anti-clogging capabilities to remove particulates from high-temperature gases, prevent fouling and corrosion of heat transfer surfaces, and reduce system maintenance requirements.
- Electrical power generation systems integrated with high-temperature waste heat sources or existing primary heat recovery systems. The electric power generation system must be able to handle variations in heat sources and the cyclic nature of the waste heat source. In most cases, the system must be able to tolerate some contaminants present in the waste heat source.
- Catalysts for reforming fuel gases or liquid fuel vapors for use in endothermic heat recovery units.

Opportunities for Medium-Temperature Waste Heat Sources

R&D opportunities for medium temperature waste heat sources (600°F – 1,200°F) include the following:

- Compact heat exchangers or micro-channel heat exchangers for clean gases that reduce the size or footprint of the heat recovery system, enabling the development of more cost-effective systems and greater adoption in applications that are space-constrained.
- High-performance heat recovery systems that integrate burners and eliminate the need for hot air piping and space for external heat recovery systems. This may require development and integration of micro-channel heat exchangers.
- Heat transfer systems for gases containing condensable vapors or combustible gases such as solvent vapors in coating ovens. This would reduce material corrosion issues, increase the life of the WHR systems, and reduce greenhouse gas emissions.

Opportunities for Low and Ultra-Low Temperature Waste Heat Sources

R&D opportunities for both low temperature waste heat sources (250°F – 600°F) and ultra-low temperature waste heat sources (<250°F) include the following:

- Condensing heat exchangers for gases containing high moisture levels with particulates, as discharged from paper machines, food drying ovens, or other sources. By addressing design and material issues associated with the existing condensing economizers, it would be possible to increase WHR below condensing temperatures in paper machines, food drying ovens, or other sources.
- Nonmetallic materials (polymers) that can withstand condensed water from combustion products containing acid gases. R&D of advanced polymers and composite materials would help in developing innovative WHR concepts. Efforts needs to be taken to make these materials more cost competitive.
- High-efficiency, liquid-gas heat exchangers for low-temperature flue gases or exhaust air from dryers.
- Liquid-to-liquid heat exchangers for heat recovery from waste water containing particulates and other contaminants. This would involve R&D in innovative designs and advanced materials.
- Dry coolers for cooling liquids that reduce or eliminate water use in heat exchangers. Operating and maintaining cooling water loops and towers is expensive. Air to liquid heat exchangers eliminate need for cooling towers and cooling loops.

A special category of heat recovery systems includes use of waste heat for electric power generation systems and absorption cooling systems for low- and medium-temperature WHR. R&D needs for this category of WHR systems include the following:

- Condenser units (heat exchangers) that replace water with air to reduce the cost of cooling towers and liquid cooling systems.
- Waste heat exchangers designed for fast startup, low-thermal stresses, low cost, and compact size.
- Evaporator section heat exchangers with "de-fouling" for glass and other particle-laden exhaust streams.
- Turbo machinery with variable area inlet nozzles for high turndown.
- A working fluid pump design with optimized efficiency for vapor compression. The exact design features will vary with the commonly used working fluids used in Rankine cycle systems. The unit may include alternates to the pump design, and could potentially crossover into CO_2 compression for sequestration.
- Heat recovery recuperators—advanced design and analysis methods to improve thermal stresses for fast startup.

Table 6.M.10 summarizes specific barriers to WHR, and the RD&D opportunities identified in the report that are needed to overcome those barriers to technology adoption.

Table 6.M.10 RD&D Opportunities and Barriers Addressed[1,4]

	Barriers Addressed[19]									
	Long Payback Periods	Material Constraints and Costs	Maintenance Costs	Economies of Scale	Lack of End-Use	Heat Transfer Rates	Environmental Concerns	Process Control and Product Quality	Process-Specific Constraints	Inaccessibility
Develop low-cost, novel materials for resistance to corrosive contaminants and to high temperatures		x	x							
Economically scale down heat recovery equipment	x	x		x						
Develop economic recovery systems that can be easily cleaned after exposure to gases with high chemical activity			x	x		x				
Develop novel manufacturing processes that avoid introducing contaminants into off-gases in energy-intensive manufacturing processes		x	x				x	x	x	
Develop low-cost dry gas cleaning systems		x	x			x	x	x		
Develop and demonstrate low-temperature heat recovery technologies, including heat pumps and low-temperature electricity generation		x			x					

Table 6.M.10 RD&D Opportunities and Barriers Addressed,[1,4] continued

	Barriers Addressed[19]									
	Long Payback Periods	Material Constraints and Costs	Maintenance Costs	Economies of Scale	Lack of End-Use	Heat Transfer Rates	Environmental Concerns	Process Control and Product Quality	Process-Specific Constraints	Inaccessibility
Develop alternative end-uses for waste heat					x					
Develop novel heat exchanger designs with increased heat transfer coefficients	x	x				x				
Develop process-specific heat recovery technologies				x		x	x	x	x	x
Reduce the technical challenges and costs of process-specific feed preheating systems	x			x		x		x	x	
Evaluate and develop opportunities for recovery from unconventional waste heat sources (e.g., sidewall losses)									x	x
Promote new heat recovery technologies such as solid-state generation										x
Promote low-cost manufacturing techniques for the technologies described above	x	x	x	x	x	x	x	x	x	x

Program Considerations to Support R&D

Challenges and Barriers for Waste Heat Recovery

The following section summarizes the barriers/challenges to WHR. These barriers, summarized in Table 6.M.11, are presented by type of waste heat stream and by industry.

Table 6.M.11 Summary of Waste Heat By Type and Associated Barriers[i]

Type of Waste Heat	Associated Barriers to Adoption in U.S. Industry
High-temperature combustion products or hot flue gases that are relatively clean	■ Reduced thermodynamic potential for the most efficient heat recovery due to materials limitations (particularly metallic) that require gases to be diluted ■ Heat transfer limits on the flue gas side in steam generation or other power generation (i.e., organic Rankine cycle) heat exchanger systems applications ■ Seal issues for heat exchanger designs with metallic and nonmetallic (ceramics) components (due to dissimilar thermal expansions)
High-temperature flue gases or combustion products with contaminants such as particulates or condensable vapors	■ Availability or cost of materials that are designed to resist the corrosive effects of contaminants ■ Lack of design innovation that will allow self-cleaning of the heat recovery equipment to reduce maintenance ■ Lack of cleaning systems (similar to soot blowing) that allow easy and on-line removal of deposits of materials on heat transfer surfaces ■ Heat transfer limitations on the gas side of heat exchange equipment
Heated air or flue gases containing high (>14%) O_2 without large amounts of moisture and particulates	■ Limitations on the heat exchanger size that prevent use on retrofit, which may be due to heat transfer limitations or design issues such as size and shape of heat transfer surfaces (e.g., tubes or flat plates) ■ Lack of availability of combustion systems for small (less than 1 MMBtu/hr) sizes to use low O_2 exhaust gases as combustion air for fired systems
Process gases or by-product gases and vapors that contain combustibles in gaseous or vapor form	■ Lack of available, economically justifiable vapor concentrators for recovery and reuse of the organic-combustible components, which would avoid the need for heating a large amount of dilution air and the resultant large equipment size. The concentrated fluids can be used as fuel in the heating systems (ovens). ■ Lack of availability of compact heat recovery systems that will reduce the size of the heat exchangers (large regenerators)
Process or make-up air mixed with combustion products, large amounts of water vapor, or moisture mixed with small amount of particulates but no condensable organic vapors	■ Rapid performance drop and plugging of conventional heat exchanger. Unavailability of designs that allow self-cleaning of heat transfer surfaces on units such as recuperators. ■ Lack of innovative designs that allow use of condensing heat exchangers (gas-water) without having the corrosive effects of carbonic acid produced from CO_2 in flue products
Steam discharged as vented steam or steam leaks	■ No major technical barriers. The major barriers are cost and return on investment for the collection of steam, the cooling system, condensate collection and, in some cases, the cleaning system.
Other gaseous streams	■ Application-specific barriers
Clean heated water discharged from indirect cooling systems such as process or product cooling or steam condensers. This stream does not contain any solids or gaseous contaminants	■ Lack of opportunities to use low-grade heat within the plant. Lack of economically justifiable heat recovery systems that can convert low-grade heat into a transportable and usable form of energy, such as electricity.

Table 6.M.11 Summary of Waste Heat By Type and Associated Barriers,[1] continued

Type of Waste Heat	Associated Barriers to Adoption in U.S. Industry
Hot water that contains large amounts of contaminants such as solids from the process or other sources, but does not contain organic liquids or vapors mixed with the water	■ No major technical barriers for cleaning the water (removing the solids) ■ Lack of opportunities to use low-grade heat within the plant or economically justifiable energy conversion systems.
Hot water or liquids containing dissolved perceptible solids, dissolved gases (e.g., CO_2, O_2,and SO_2) or liquids	■ No major technical barriers for filtering the water (removing the solids) ■ The presence of SO_2, CO_2, and other dissolved gases presents problems of high PH values for water use within a plant. Typical water degasification processes (vacuum deaeration, gas transfer membrane, hot water steam injection/stripping deaeration, etc.) are energy intensive and costly. ■ Lack of opportunities to use low-grade heat within the plant or economically justifiable energy conversion systems
Hot solids that are cooled after processing in an uncontrolled manner	■ Economically justifiable cooling air collection system ■ Lack of opportunities to use low-temperature heat within the plant or economically justifiable energy conversion systems. ■ Variations in cooling air temperatures and the presence of microscopic particulates prevent their use in combustion system (burners)
Hot solids that are cooled after processing using water or air-water mixture. Examples include hot coke, ash, slag, and heat treated parts	■ No major technical barriers for filtering the water (removing the solids) ■ Lack of opportunities to use low-grade heat within the plant or economically justifiable energy conversion systems
Hot liquids and vapors that are cooled after thermal processing. Examples include fluids heated in petroleum refining or the chemical, food, mining, or paper industries	■ No major technical barriers for recovering heat if there is sufficient temperature "head" ■ Lack of opportunities to use low-grade heat within the plant or economically justifiable energy conversion systems
By-products or waste that is discharged from thermal processes. These materials contain sensible, latent, and chemical heat that is not recovered prior to their disposal.[20]	■ Economically justifiable collection system for hot material ■ Economics of processing the material to recover recyclable or useful materials, or combustibles for use of chemical heat ■ Materials are often classified as hazardous materials and need special treatment ■ Cost of recycling or cleaning the residues and treatment of gases or other materials that are produced during the recovery or treatment process ■ Variations in the amount of recoverable materials
High-temperature surfaces	■ No practical way of recovering this heat, especially for systems such as rotary kilns or moving surfaces (i.e. conveyors) ■ Low efficiency and cost for advanced surface-mounted energy conversion technologies such as thermoelectric systems
Extended surfaces or parts used in furnaces or heaters	■ No practical way of recovering and collecting this heat, especially for systems such as rolls used for a furnace ■ Low efficiency and high cost for advanced surface-mounted energy conversion technologies such as thermoelectric systems

R&D Opportunities[1,20,21,22,23,24,25]

There is a significant opportunity for crosscutting R&D that could meet requirements of many different industries and at the same time fill the gaps in capabilities or performance of the currently available systems.

Opportunities in Applied Research

Heat transfer:

R&D opportunities in heat transfer area include:

- Enhancement of heat transfer for gases or air to reduce the size of heat exchangers. This could include advancements in heat transfer surfaces in shape, configuration, coatings, and changes in fluid flow patterns through innovative flow patterns, changes in gas compositions, or other methods that could make significant improvements in convection heat transfer for the gases.[1]
- Development of new types of compact heat exchangers. This includes the use of new materials and fabrication techniques to manufacture heat exchangers consisting of a large number of narrow channels. The performance of a heat exchanger in terms of heat transfer is directly related to the characteristic flow diameter. The smaller the diameter, the higher the heat transfer rate,[21] but this can also increase the energy used to move it through the channel.
- Radiation heat transfer enhancement to take advantage of thermal radiation emission properties of gases such as CO_2 and H_2O that are present in combustion products of commonly used fossil fuels. This may include using re-radiation surfaces or other geometrical modifications.[1]

Particulate removal or gas cleaning:

Particulate removal or gas cleaning related R&D opportunities include:

- Use of gas cleaning or particulate separation methods that do not require "intrusive" means such as filters for particulate laden exhaust gases in all temperature ranges. Of particular interest is cleaning or filtering of high-temperature gases encountered in industries such as EAF (mini-mills), glass, cement and lime kilns, aluminum melting, and steel melting. Candidate technologies may include: gravity settling chambers for large particles as used in drop-out boxes, mechanical/inertial collectors using aerodynamic separation such as high efficiency cyclones/multi-cyclones, ultra-sonic techniques, hoarer methods used for syngas particulate removal.[22]
- Innovative methods of avoiding or reducing particulate deposition on heat transfer surfaces. This can be used to retard or remove deposits of organic materials (e.g., oil vapors) or inorganic materials (e.g., Boron vapors) present in glass melting furnaces, ash in coal fired boilers, and oxides in steel or aluminum melting furnaces.
- Particulate removal methods for high-temperature heat transfer surfaces, particularly materials deposited at high temperatures.

Gas or vapor separation:

Gas or vapor separation related R&D opportunities include:

- Selective separation of water vapor or steam, CO_2, oil, or organic liquid vapors from exhaust gases at high temperatures (greater than the condensation temperature of the selected materials) without the need for cooling the entire gas mass. This may include membranes or other methods such as high-temperature desiccant or molecular sieves to absorb or adsorb water vapor or other gases selectively. For example, Transport Membrane Condenser (TMC) system for the separation of water vapor and recovery of heat from a clean, controlled gas stream.[23]

- Reactive systems (i.e., controlled combustion for organic vapors) to remove or collect organic vapors and combustible gases or vapors with controlled reaction rates and temperature increases. This includes developments in regenerative thermal oxidizers, catalytic oxidizers, and direct thermal oxidizers.[24]

Opportunities in Advanced Materials

WHR systems employ both metallic and nonmetallic materials with a variety of technical limitations. R&D opportunities in advanced materials include:

- Coating materials with greater thermal stabilities for higher temperature applications; reduced wear, and easier repair.[20]
- Corrosion-resistant coatings for low-temperature applications.
- High-temperature (>1,600°F) corrosion resistant materials for heat exchangers (recuperators).
- Heat storage materials with high latent heat, thermal capacity (specific heat), and thermal conductivity for all temperature ranges.
- Seal materials for high-temperature heat exchanger designs with moving parts (e.g., heat wheels or regenerators). The seal can be for metal-to-metal interface or metal-to-non-metallic materials (e.g., ceramics).
- Polymers or plastics with improved thermal conductivity for use in low-temperature corrosive environments (e.g., combustion products of fossil fuels). For example - ultra-high molecular weight polyethylene (UHMWPE) material for heat exchangers.[25]
- Cost-effective thermoelectric or thermoionic materials capable of producing electricity from heat with 15%–20% thermal efficiency. For example, future figure of merit (ZT) of 1.8, compared to 1 in 2011, leading to greater conversion efficiencies; thermal stability up to 1000°C.[20] As part of the 2015 QTR, a detailed evaluation of the potential of thermoelectrics is presented in the 6.G *Direct Thermal Energy Conversion Materials, Devices, and Systems* Technology Assessment.
- Working fluids for low-temperature power generation cycles that can withstand broader temperature ranges for use in ovens and furnaces. This also includes performance optimization of power generation cycles using low-global warming potential fluids (low GWP fluids). For example improving performance of regenerative supercritical ORCs (organic Rankine cycles) using low-GWP organic compounds as working fluid.[26]
- Advanced materials to increase temperature lift in absorption cycles and improve overall heating and cooling performance.
- Catalysts to support lower temperature "reforming" reactions for use in medium- to high-temperature (≥800°F) waste heat applications.
- Higher temperature materials to be used for "bag-houses," or gas cleaning systems. This will allow use of lower temperature electricity generation cycles.

Opportunities in Advanced Concepts and Designs

For maximum WHR, it is necessary to develop advanced concepts and new designs for WHR equipment. R&D opportunities include:

- Innovative heat transfer methods and heat exchanger geometries to reduce heat exchanger size (see the Opportunities in Applied Research section, above).
- Heat exchangers or regenerators with continuous surface cleaning to remove surface deposits resulting from particulates or fibers in waste gas streams.

- Air cooled (dry) heat exchangers to be used to replace or supplement currently used water cooled condensers or heat exchangers (see the Opportunities in Applied Research section, above, for heat transfer improvement).
- New concepts for recovering and collecting heat from gases containing particulates and high-temperature condensable materials as encountered in the glass, steel, cement, and aluminum industries.
- New regenerator designs to reduce the volume of high-temperature particulate laden gases, such as using a high surface-area-to-volume ratio or high thermal capacity materials that are easy to clean.
- Improved design of waste heat "boilers" that can utilize lower temperature (≥100°F) heat source. This allows use of "low grade" waste heat for thermally-activated refrigeration and heat pump systems to replace or supplement direct gas firing.
- Pumps and turbo-expanders with high turndown capability for use in low-temperature power generation systems.
- Self-cleaning filters for gases with relatively low particulate loading.
- Advanced heat exchangers for evaporators and condensers that are inexpensive to build, maintain, and operate compared to other furnace types of comparable heating capacity.
- Use of heat recovery absorption chillers for recovering waste heat from industrial process heating systems where currently heat is rejected to the cooling towers. Many industrial processes (and certainly most large commercial buildings) reject waste heat through cooling towers. At the same time, the same facility is generating hot water or steam for other needs. Waste heat from process heating systems could be used for generating hot water/steam or to drive the lithium bromide refrigeration cycle inside absorption chillers. Many studies[28,29] show that use of heat recovery chillers results in overall energy reductions, as well as a cost reduction.
- Methods to seal ends of a continuous furnace or oven to reduce or eliminate air leaks that result in excessive energy use in heating equipment; increased size for exhaust gas handling systems; and gas treatment, if necessary for meeting local environmental regulations.

Opportunities in Sensors and Controls

R&D opportunities in sensors and controls include:

- Reliable sensors and controls for high-temperature (>400°F) applications to measure and monitor humidity or lower explosion limits (LEL) in dryers and ovens to allow for recycling of exhaust gases and reduce the amount of make-up air.
- Systems for monitoring heat exchanger performance to detect performance degradation maintenance issues.
- A low-cost reliable system for monitoring oxygen and carbon monoxide in small applications (<5 MMBtu/hr fired systems).
- Continuous monitoring of energy intensity (Btu or kWh per unit of production) to identify performance problems.
- Other sensor and controls R&D opportunities, including sensor integration challenges, are discussed in more detail in the 2015 QTR Technology Assessment 6.C *Advanced Sensors, Control, Platforms, and Modeling for Manufacturing*.

Opportunities in Advanced High Efficiency Power Generation Systems

R&D opportunities in advanced high efficiency power generation systems include:

- High turndown systems for use in applications where the waste heat stream heat content (in terms of Btu/hr) changes significantly (due to mass flow or temperature fluctuations).
- Systems with non-water cooled condensers to avoid the need for water and cooling towers.

Risk, Uncertainty and Other Considerations

WHR has the potential to save energy costs, but industry may be reluctant to adopt WHR technologies if there is a perceived or real potential for the technologies to negatively impact production. In order to reduce risk, a comprehensive evaluation of WHR technologies is needed on a case-by-case basis; however, some general guidelines and considerations include:

- Identify waste heat sources and reduce generation of waste heat. This is the most cost effective and quickest way to reduce energy use and improve overall thermal efficiency of a heating system.
- Select appropriate methods of heat recycling where the waste heat is used within the heating system itself. Waste heat recycling is the use of waste heat from a process heating system for its use within the same system. This would eliminate issues related to matching of supply and demand of heat. The most commonly used method of waste heat recycling for fuel fired systems is to preheat combustion air where the flue gas temperature is relatively high – usually higher than 1000°F. However, preheating of makeup air or dilution air should be considered at all temperatures for processes using high volumes of air, as in the case of drying ovens. Possibility of load or charge preheating should be considered for new equipment and where available space and system configuration allows its use. A few examples of charge preheating include feed water heating for boilers, and drying and preheating of materials in metals and non-metal industries.
- If heat recycling is not possible then consider WHR within the plant. Common examples are: use of hot gases in lower temperature processes, to preheat water or cleaning liquids used in the plant, use of heat for space heating in plants located in colder climates, steam generation where waste heat streams contain large (>10 MM Btu/hr) amounts of recoverable heat.
- Consider use of electric power generation using steam turbine-generator systems or other systems such as organic Rankine Cycle (ORC) systems when it is not possible to use heat within the plant or there is a strong case based on economics to use on-site power generation.
- Evaluate waste heat characteristics such as temperature, flow rates, waste gas, presence of contaminants (solids, liquid vapors, and other condensable materials), and variations in in these characteristics.
- Evaluate the overall economics of the waste heat recycling or recovery system.

The uptake of WHR technologies is highly dependent upon the willingness of industrial subsectors to invest in technologies that can provide a return on investment (via energy efficiency) without risk to operational efficiency. During times of low energy costs, there is less incentive for companies to invest in energy efficiency technologies, and there are different drivers and barriers based on industry subsector.

Considerations by Major Industry

The following considerations have been identified where R&D could impact WHR in the specific major industries analyzed in this TA.

Considerations for the Chemicals and Petroleum Refining Industries

The chemicals and petroleum refining industries were the two largest energy-consuming U.S. manufacturing sectors in 2010, consuming 4,252 TBtu and 3,542 TBtu, respectively, of the 19,237 TBtu of manufacturing total primary energy use.[30,31,32] WHR related R&D issues in the Chemical and Petroleum industries include:

- Heat recovery from low-temperature (<200°F) but relatively clean gases, such as combustion products, from natural gas-fired heaters or boilers.
- Compact heat exchangers that allow condensation of water vapor and utilize mediums that require minimal water.
- Treatment of high-temperature gases containing corrosive gases (such as hydrochloric acid, etc.). This includes removing (or reacting) these compounds while allowing heat recovery using conventional heat exchanger equipment.
- Equipment to recover heat from exothermic processes. The system must be compact and reliable and deliver recovered heat in the form of high-pressure steam or another compact usable form.
- Development of compact heat exchangers such as micro-channel heat exchangers for use in industrial environments. A major requirement is tolerance of the minor and unpredictable presence of solids or other materials that may adversely affect heat exchanger performance.
- Development of air-cooled heat exchangers that can replace water-cooled units. This will reduce water use and associated energy use.
- Economically justifiable energy recovery from flared gases.

Considerations for the Forest Products Industry

The forest products industry was the third largest energy-consuming U.S. manufacturing sector in 2010 (following chemicals; and petroleum refining), consuming 3,152 TBtu of the 19,237 TBtu of manufacturing total primary energy use.[33,34] WHR related R&D considerations for the Paper industry include:

- Development of heat recovery or energy conversion systems for low-temperature (<140°F) heat sources, such as exhaust gases, that may contain water vapor and other contaminates, such as small amounts of fibers or particulates.
- A system for dehumidifying high-temperature (≥140°F) air containing fibers or particulates.
- Development of heat recovery from low-temperature water (<100°F) for use in the plant.
- Development of a drying system for solids, using waste heat from the exhaust gases.

Considerations for the Food and Beverage Industry

The food and beverage industry was the fourth largest energy-consuming U.S. manufacturing sector in 2010 (following chemicals; petroleum refining; and forest products), consuming 1,836 TBtu of the 19,237 TBtu of manufacturing total primary energy use.[35,36] The R&D issues for the Food or Snack manufacturing industry include:

- Heat recovery or energy conversion systems for low-temperature (<200°F) heat sources, such as exhaust gases, that may contain water vapor and other contaminates, such as small amounts of oil vapors.
- Heat recovery from low-temperature water (<100°F) for plant use.
- Improved efficiency heater systems to reduce energy intensity.

Considerations for the Iron and Steel Industry

The iron and steel industry was the fifth largest energy-consuming U.S. manufacturing sector in 2010 (following chemicals; petroleum refining; forest products; and food and beverage), consuming 1,460 TBtu of the 19,200 TBtu of manufacturing total primary energy use.[37,38] The R&D considerations most relevant to the iron and steel industry include:

- Secondary heat recovery devices that can supplement and enhance performance of the currently used systems, and are capable of recovering part (less than 50%, in most cases) of the waste heat available.
- Recovery of waste heat or increasing the value of available heat from blast furnace gas (removal of moisture).
- Recovery of waste heat in hot products such as hot slabs, rolled steel shapes downstream of the rolling mill, heat treated steel processed in furnaces, and coke discharged from coke oven batteries. In some cases, the technologies exist but are too difficult to implement due to space requirements in existing operations, cost, or lack of use of the low-grade heat produced after heat recovery. Further examination in partnership with industry would improve understanding of these opportunities.
- Recovery and use of waste heat from highly contaminated hot gases such as hot coke oven gas from the ovens. No technology exists or is commercially used in similar cases.
- Energy recovery through cleaning and recycling steam heat from degasifying systems used for liquid steel refining.
- Recovery or utilization of convective and radiant heat from furnace walls or openings, or from hot products such as hot steel shapes after rolling.
- Use of low-grade heat in the form of cooling water used in casters or in rolling operations.

Considerations for Steel Mini-mills (EAF Furnaces and Rolling Mill)

WHR related R&D considerations specific to EAF steel plants include:

- Heat recovery from EAF exhaust gases. Options could include hot gas clean-up, controlled combustion of combustibles to manage reaction temperatures while avoiding melting of steel oxides and other solid contaminants, and heat recovery from highly contaminated (e.g., particulate and condensable oil vapors) gases.
- Heat recovery from surfaces of hot ladles. The heat loss from hot ladles takes place through radiation and convective heat transfer to the surrounding environment.
- Heat recovery from cooling water used in the continuous casting process and reheat furnace cooling (e.g., walking beam furnaces or thin-slab reheating roller hearth furnaces).
- Secondary heat recovery from reheat furnaces downstream of conventional heat recuperators to recover additional heat. One option is preheating the product entering the furnace. Issues to be addressed include the location of the heat source and heat use, available space, and the infrastructure or logistics of transporting heat to the desired location.
- Heat recovery from hot cooled products. This could be medium- or low-grade heat.

Considerations for the Aluminum Industry

The aluminum industry was the tenth largest energy-consuming U.S. manufacturing sector in 2010 (following chemicals; petroleum refining; forest products; food and beverage; iron and steel; plastics; fabricated metals; transportation equipment; and computer, electronics, and electrical equipment), consuming 456 TBtu of the 19,200 TBtu of manufacturing total primary energy use.[39,40] To enable the aluminum industry to more effectively adopt WHR technologies, the following R&D issues need to be addressed:

- Cleaning high-temperature contaminated gases without cooling them to significantly lower (<570°F) temperatures.
- Thermoelectric system infrastructure to prepare for higher *ZT* value materials and for their use in recovering low- to medium-temperature heat, particularly for surface heat losses such as in electrolysis pots. Efficiencies of these systems are low, between 2 and 5%.[16] Durability, cost, and scalability are a few examples of the limitations on TEG implementation in industry.[41,42,43] Current research has been focused on producing more efficient devices.[16] WHR from exhaust gases requires the use of a heat exchanger, further reducing efficiency, increasing complexity, and adding to maintenance requirements.
- Improved efficiency or lower initial costs for lower temperature power generation systems, such as the Kalina cycle. The developments can include reducing the number of components (such as gas-liquid heat exchangers) or using alternate fluids for the cycle.
- Removal of tars and organic vapors from the exhaust gases without dropping their temperature to allow heat recovery from the "cleaner" gases.
- Materials and components that offer improved reliability and longer life for submerged heating devices for corrosive surroundings, such as molten aluminum or molten glass.

Considerations for Aluminum Recycling Operations

WHR related R&D consideration for the Aluminum recycling operations include:

- Cleaning of hot gases from rotary furnaces to allow heat recovery from exhaust gases.
- A heat recovery system for hot (>1,800°F) exhaust gases containing materials such as flux material and aluminum oxide particles.
- Secondary heat recovery from gases discharged from recuperators used for combustion air preheating. The gases could be in the temperature range of 400°F–800°F.

Considerations for the Cement Industry

The cement industry was the eleventh largest energy-consuming U.S. manufacturing sector in 2010 (following chemicals; petroleum refining; forest products; food and beverage; iron and steel; plastics; fabricated metals; transportation equipment; computer, electronics, and electrical equipment; and aluminum), consuming 307 TBtu of the 19,237 TBtu of manufacturing total primary energy use.[44,45] R&D issues in the Cement industry include:

- Heat recovery from hot surfaces or kiln shell surfaces.
- Cleaning (particulate removal) of air used to cool heated clinker prior to use of the now heated air in boilers or other heat recovery systems.
- Moisture control or reduction for the raw materials using exhaust gases from heat recovery systems.
- Use of an alternate (conventional steam boiler or generator) CHP system for generating power using hot air from cooling beds as well as exhaust gases from the system.

Considerations for the Glass Industry (including fiberglass and other glass products)

The glass industry was the twelfth largest energy-consuming U.S. manufacturing sector in 2010 (following chemicals; petroleum refining; forest products; food and beverage; iron and steel; plastics; fabricated metals; transportation equipment; computer, electronics, and electrical equipment; aluminum; and cement), consuming 294 TBtu of the 19,237 TBtu of manufacturing total primary energy use.[46,47] WHR related R&D issues in the glass industry include:

- Heat recovery from very high temperature gases (2,200°F) that contain condensable vapors and produce solid particles that need to be removed. Possible methods include fluidized bed or solid particle-gas heat transfer with a proper material handling system.
- Quenching methods for hot gases to control generation of condensates, and subsequent use of these clean gases in conventional boilers or air heaters.
- Electricity generation through direct contact or radiation from moderate temperature (300°F – 900°F) surfaces with economically justifiable paybacks. Possible methods are thermoelectric and thermophotovoltaic devices under development.
- Use of advanced heat exchangers for evaporators and condensers that use direct gas-air heating for the evaporators, and air for condensers. This would eliminate secondary heat exchanger loops that utilize hot water or steam for the evaporators, as well as the need for cooling towers for the condenser. This simplified approach would reduce costs as well as eliminate inefficiencies introduced with the use of secondary heat exchanger circuits.
- Secondary heat recovery systems for flue gases discharged from regenerators. These gases are at temperatures in the range of 800°F – 1,200°F. The gas temperature is cyclic and, in some cases, the gases contain very small amount of particulates, which are easy to remove.
- Glass batch drying and preheating systems using exhaust gases from the melting furnace or refining forehearth section exhaust gases. Previously developed systems have not been used by the industry due to a variety of issues related to operations and maintenance. A new approach or design is required.
- Hot gas cleanup systems for use by medium- to low-temperature gases prior to secondary heat recovery.
- Use of CHP systems for generating hot gases for use in annealing ovens. The system will deliver electricity as well as hot air with low oxygen for use as combustion air.
- Use of heat from annealed products. The heat is available at temperatures below 500°F.

Considerations for Coating Plants or Paint Shops

WHR related R&D consideration for the Coating Plants or Paint Shops include:

- Secondary heat recovery from regenerative thermal oxidizer (RTOs) exhaust gases that are available from 350°F – 400°F.
- Control system for ovens to regulate the amount of make-up air used. This will require development of a system that controls the amount of make-up air, and hence the amount of heat wasted from the oven.

Endnotes

1 Oak Ridge National Laboratory (ORNL), *Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities*, Arvind Thekdi (E3M Inc.) and Sachin Nimbalkar (ORNL), ORNL/TM-2014/622, January 2014. Available at: http://info.ornl.gov/sites/publications/files/Pub52987.pdf. This report provides a current, comprehensive assessment of WHR technologies, and sections of this report are excerpted in this Technology Assessment.

2 Large amounts of particles or condensable vapors can impede the performance of heat recovery technologies.

3 Energetics Incorporated and E3M, Incorporated, *Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing & Mining*, prepared for the U.S. Department of Energy, Industrial Technologies Program, December 2004. Available at: http://energy.gov/sites/prod/files/2013/11/f4/energy_use_loss_opportunities_analysis.pdf

4 BCS, Incorporated, *Waste Heat Recovery: Technology and Opportunities in U. S. Industry*, prepared for the U.S. Department of Energy, Industrial Technologies Program, March 2008. Available at: http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf

5 Pacific Northwest National Laboratory (PNNL), *Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions*, prepared for the U.S. Department of Energy, April 2006. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-15803.pdf

6 Lawrence Berkeley National Laboratory (LBNL), *Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries: An ENERGY STAR® Guide for Energy and Plant Managers*, prepared for the U.S. Environmental Protection Agency, February 2015. Available at: http://www.energystar.gov/sites/default/files/tools/ENERGY_STAR_Guide_Petroleum_Refineries_20150330.pdf

[7] Lawrence Berkeley National Laboratory (LBNL) and American Council for an Energy-Efficient Economy (ACEEE), *Emerging Energy-Efficient Industrial Technologies*, October 2000. Available at: http://escholarship.org/uc/item/5jr2m969

[8] McKinsey & Company, *Unlocking Energy Efficiency in the U.S. Economy*, July 2009. Available at: http://www.mckinsey.com/client_service/electric_power_and_natural_gas/latest_thinking/unlocking_energy_efficiency_in_the_us_economy

[9] U.S. DOE Office of Energy Efficiency & Renewable Energy, 2010 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions. Available at: http://energy.gov/sites/prod/files/2014/02/f7/AMO_footprints_definitions_and_assumptions_2014_update.pdf.

[10] U.S. DOE Office of Energy Efficiency & Renewable Energy, 2010 Manufacturing Energy and Carbon Footprints. Available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[11] U.S. DOE Office of Energy Efficiency & Renewable Energy, 2010 Manufacturing Energy and Carbon Footprint – All Manufacturing. Available at: http://energy.gov/sites/prod/files/2015/10/f27/manufacturing_energy_footprint-2010.pdf

[12] Energetics Incorporated for Oak Ridge National Laboratory, U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis, prepared for the U.S. Department of Energy, Industrial Technologies Program, 2012. Available at: http://www.energy.gov/eere/amo/downloads/us-manufacturing-energy-use-and-greenhouse-gas-emissions-analysis.

[13] Losses from process heating in the U.S. manufacturing sector total over 2.5 quads, as shown in the U.S. DOE Advanced Manufacturing Office (AMO) static Sankey diagram of process energy flows (http://www.energy.gov/eere/amo/static-sankey-diagram-process-energy-us-manufacturing-sector). Process heating losses in individual manufacturing subsectors can be explored using the AMO Dynamic Manufacturing Energy Sankey Tool (http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu). All these loss numbers are first law of thermodynamics estimates of losses.

[14] Pacific Northwest National Laboratory (PNNL) and BCS, Incorporated, *Engineering Scoping Study of Thermoelectric Generator (TEG) Systems for Industrial Waste Heat Recovery*, prepared for the U.S. Department of Energy, Industrial Technologies Program, November 2006. Available at: https://www1.eere.energy.gov/manufacturing/industries_technologies/imf/pdfs/teg_final_report_13.pdf

[15] A thermoelectric material's efficiency of converting heat to electricity is characterized by the dimensionless figure of merit $ZT = (\sigma S^2 T)/k$ where σ is the electrical conductivity, S is the Seebeck coefficient, T is the temperature, and k is the thermal conductivity. Thermoelectric materials with a ZT of ~1 are widely available. Advanced materials have now been demonstrated with a ZT of 2 and higher.

[16] Oak Ridge National Laboratory (ORNL) and E3M Inc., *Technologies and Materials for Recovering Waste Heat in Harsh Environments*, Sachin Nimbalkar, Arvind Thekdi, et.al., ORNL/TM-2014/619. Available at: http://info.ornl.gov/sites/publications/files/Pub52939.pdf

[17] U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available at: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu. Note that sources of waste heat losses include high temperature exhaust gases, in addition to hot surfaces, hot liquids, and hot products. The Recoverable Potential column in this table only examines the recoverable potential for WHR from high temperature exhaust gases. The process heating losses column shows the total process heating losses in each sector, irrespective of recovery potential.

[18] Drew Robb, "Supercritical CO2 – The Next Big Step? Special Report, *Turbomachinery International* 53, No. 5, pp. 22-28, September/October 2012.

[19] The barrier categories are described in the *Waste Heat Recovery: Technology and Opportunities in U.S. Industry* report as follows:

- Long payback periods: Costs of heat recovery equipment, auxiliary systems, and design services lead to long payback periods in certain applications.
- Material Constraints and Costs: Certain applications require advanced and more costly materials. These materials are required for high-temperature streams, streams with high chemical activity, and exhaust streams cooled below condensation temperatures. Overall material costs per energy unit recovered increase as larger surface areas are required for more efficient, lower temperature heat recovery systems
- Maintenance Costs: Corrosion, scaling, and fouling of heat exchange materials lead to higher maintenance costs and lost productivity.
- Economies of Scale: Equipment costs favor large-scale heat recovery systems and create challenges for small-scale operations
- Lack of End-Use: Many industrial facilities do not have an on site use for low-temperature heat. In addition, technologies that create end use options (e.g., low temperature power generation) are currently less developed and more costly.
- Heat Transfer Rates: Small temperature differences between the heat source and heat sink lead to reduced heat transfer rates and require larger surface areas.
- Environmental concerns: WHR from exhaust streams may complicate or alter the performance of environmental control and abatement equipment.
- Process Control and Product Quality: Chemically active exhaust streams may require additional efforts to prevent cross contamination between streams.
- Process-Specific Constraints: Equipment designs are process specific and must be adapted to the needs of a given process. For example, feed preheat systems vary significantly between glass furnaces, blast furnaces, and cement kilns.
- Inaccessibility: It is difficult to access and recover heat from unconventional sources such as hot solid product streams (e.g., ingots) and hot equipment surfaces (e.g., sidewalls of primary aluminum cells).

[20] TMS, *Linking Transformational Materials and Processing for an Energy-Efficient and Low-Carbon Economy—Innovation Impact Report*, 2011, The Minerals, Metals, & Materials Society: Warrendale, Pennsylvania, USA. Available from: http://energy.tms.org/docs/pdfs/InnovationImpactReport2011.pdf

[21] P. A. Pilavachi, *Energy Efficiency in Process Technology*, Elsevier Applied Science, 1993.

[22] National Energy Technology Laboratory, "Particulate Removal." Web page. Available at: http://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/particulate-removal.

[23] U.S. DOE Office of Energy Efficiency and Renewable Energy, "Advanced Membrane Separation Technologies for Energy Recovery." DOE Fact Sheet DOE/EE-0507, May 2011. Available at: https://www1.eere.energy.gov/manufacturing/industries_technologies/imf/pdfs/advanced_membrane_separation.pdf.

[24] Tom McGowan, "VOC and Odor Control Options for Industry and Manufacturing," presented at the Air & Waste Management Association Conference, Atlanta, GA, 2013.

[25] U.S. DOE Office of Energy Efficiency and Renewable Energy, "Continuous Processing of High Thermal Conductivity Polyethylene Fibers and Sheets: A Lightweight Material for Heat Exchange Applications." DOE Fact Sheet DOE/EE-0869. Available at: http://energy.gov/sites/prod/files/2015/03/f20/Polyethylene%2520Fibers%2520and%2520Sheets.pdf

[26] Van Long Le, Michel Feidt, Abdelhamid Kheiri, and Sandrine Pelloux-Prayer, "Performance optimization of low-temperature power generation by supercritical ORCs (organic Rankine cycles) using low GWP (global warming potential) working fluids." *Energy* 67 (2014) 513-526.

[27] P.E. Hufford, "Direct Refrigeration from heat recovery using 2-stage Absorption Chillers," Proceedings from the Fifth Industrial Energy Technology Conference Volume II, Houston, TX, April 17-20, 1983.

[28] Balaji, K., Ramkumar, R., "Study of Waste Heat Recovery from Steam Turbine Xhaust for Vapour Absorption System in Sugar Industry." *Procedia Engineering* 38 (2012) 1352-1356.

[29] Examples include ash from coal or solid waste fired boilers, slag from steel melting operations, dross from aluminum melters, bottom waste from reactors, and sludge

[30] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Chemicals Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/sites/prod/files/2014/02/f7/2014_chemicals_energy_carbon_footprint.pdf. This data is also accessible via the U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available at: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

[31] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Petroleum Refining Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/sites/prod/files/2014/02/f7/2014_petroleum_refining_energy_carbon_footprint.pdf. This data is also accessible via the U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available at: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

[32] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[33] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Forest Products Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/sites/prod/files/2014/02/f7/2014_forest_products_energy_carbon_footprint.pdf. This data is also accessible via the U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available from: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

[34] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[35] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Food and Beverage Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/sites/prod/files/2014/02/f7/2014_food_beverage_energy_carbon_footprint.pdf. This data is also accessible via the U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available from: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

[36] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[37] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Iron and Steel Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/sites/prod/files/2014/02/f7/2014_iron_steel_energy_carbon_footprint.pdf. This data is also accessible via the U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available from: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

[38] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[39] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Alumina and Aluminum Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/sites/prod/files/2014/02/f7/2014_alumina_%20aluminum_energy_carbon_footprint.pdf. This data is also accessible via the U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available at: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

[40] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[41] EPA Combined Heat and Power Partnership, *Waste Heat to Power Systems*, 2012. Available at http://www.epa.gov/chp/documents/waste_heat_power.pdf.

[42] J. Zhu, et al., "Experimental study of a thermoelectric generation system," *Journal of Electronic Materials* 40(5), 744–752, 2011.

[43] S. LeBlanc, S. Yee, M. Scullin, D. Dames, and K. Goodson, "Material and manufacturing cost considerations for thermoelectrics," *Renewable and Sustainable Energy Reviews*, pp. 313–327, 2014.

[44] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Cement Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/sites/prod/files/2014/02/f7/2014_cement_energy_carbon_footprint.pdf. This data is also accessible via the U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available at: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

[45] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs.

[46] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Glass and Glass Products Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/sites/prod/files/2014/02/f7/2014_glass_energy_carbon_footprint.pdf. This data is also accessible via the U.S. DOE Advanced Manufacturing Office Dynamic Manufacturing Energy Sankey Tool, available at: http://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu.

[47] U.S. DOE Office of Energy Efficiency & Renewable Energy, *Manufacturing Energy and Carbon Footprints* (2010 MECS), available at: http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs

Acronyms

BF	By-product fuel
BOF	Basic oxygen furnace
DTEC	Direct Thermal Energy Conversion
DOE	Department of Energy
EAF	Electric arc furnace
EIA	Energy Information Administration
EPA	Environmental Protection Agency
HRSG	Heat recovery steam generator
HVAC	Heating, ventilation, and air-conditioning
MECS	Manufacturing Energy Consumption Survey
MMBtu	Million Btu
ORC	Organic Rankine cycle
RC	Rankine cycle
SRC	Steam Rankine cycle
rpm	Revolutions per minute
R/R	Regenerative & recuperative
scf	Standard cubic foot
TEG	Thermoelectric generators
tonne	Metric ton (1,000 kilogram)
US	United States

USGS	US Geological Survey
WHP	Waste heat to power
WHR	Waste heat recovery

Glossary

Air to fuel ratio	In a combustion process, the ratio of the air supply flow rate to the fuel supply flow rate when measured under the same conditions.
Absorption chiller	A type of air cooling device that uses absorption cooling to cool interior spaces.
Available heat	The gross quantity of heat released within a combustion chamber minus both the dry flue gas loss and the moisture loss. It represents the quantity of heat remaining for useful purposes (and to balance losses to walls, openings, and conveyors).
Blow-down	Water intentionally ejected from a boiler to avoid the precipitation of impurities on the boiler heat exchange surfaces during continuing evaporation of steam. The water is blown out of the boiler by steam pressure within the boiler.
Blower	The device in an HVAC system that distributes the filtered air from the return duct over the cooling coil/heat exchanger. This circulated air is cooled/heated and then sent through the supply duct, past dampers, and through supply diffusers to the living/working space.
Burner Capacity	The maximum heat output (in Btu per hour) released by a burner with a stable flame and satisfactory combustion.
By-product fuel	Materials having calorific value, which are generated as a by-product in manufacturing and production processes. For example – black liquor, wood chips, bio-gas, etc.
Cleanliness of exhaust gases	The quality of exhaust gases from industrial heating processes. It depends on many factors related to the operation and design of heating equipment. For example, the presence of highly corrosive fluxing agents (e.g., chlorides, fluorides, etc.), particulates (e.g., metal oxides, carbon or soot particles, fluxing materials, slag, aluminum oxide, magnesium oxide, manganese), and combustibles (e.g., CO, H_2, hydrocarbons) affect the cleanliness of exhaust gases.
Combustion air	All of the air supplied through a burner other than that used for atomization.
Dew point	The temperature at which a vapor condenses when it is cooled at constant pressure.
Electrolysis	A chemical change in a substance that results from the passage of an electric current through an electrolyte.

Excess air	The air remaining after a fuel has been completely burned, or that air supplied in addition to the quantity required for complete stoichiometric combustion. A lean fuel/air ratio contains excess air.
Flue gas	All gases—combustion gases, products of combustion (e.g. water vapor), excess oxygen, nitrogen, etc.—that leave a furnace, recuperator, or regenerator, by way of the flue.
Heat source	A medium or process from which heat may be extracted. For heat transfer to occur between a source and recipient, the source must always be at a temperature higher than the recipient.
Heat waste	Energy in the form of heat rejected or lost from a process, which may be recovered or reused in another process providing it is of sufficient quality (i.e., hot enough and there is a use for it).
Higher heating value (hhv)	The total heat obtained from combustion of a specified amount of fuel and its stoichiometrically correct amount of air, both being at 60°F when combustion starts, and after the combustion products are cooled, hence includes the latent heat of vaporization of water vapor produced by the combustion process. See lower heating value.
Latent heat	Heat absorbed or given off by a substance without changing its temperature, as when melting, solidifying, evaporating, condensing, or changing crystalline structure.
Lower heating value (lhv)	The gross heating value minus the latent heat of vaporization of the water vapor formed by the combustion of hydrogen in the fuel.
Phase change	The process of changing from one physical state (solid, liquid, or gas) to another, with a necessary or coincidental input or release of energy.
Rankine cycle	An idealized thermodynamic cycle that converts sensible heat into mechanical work. The Rankine cycle that is an ideal standard for comparing performance of heat-engines, steam power plants, steam turbines, and heat pump systems that use a condensable vapor as the working fluid; efficiency is measured as work done divided by sensible heat supplied.
Recuperator	Equipment that uses hot flue gases to preheat air for combustion. The flue gases and airflow are in adjacent passageways so that heat is transferred from the hot gases, through the separating wall, to the cold air.
Regenerator	A cyclic heat interchanger, which alternately receives heat from gaseous combustion products and then transfers heat to air before combustion.
Regenerative heating	The process of using heat that is rejected in one part of a cycle for another function or in another part of the cycle.
Reverberatory furnace	A reverberatory furnace is a metallurgical or process furnace that isolates the material being processed from contact with the fuel, but not from contact with combustion gases.
Sensible heat	Heat exchanged by a body or system that results in a temperature change, (as opposed to latent heat).

Smelting The chemical reduction of a metal from its ore. Smelting separates impurities, allowing for their removal from the metal.

Specific heat The amount of heat required to raise a unit of mass of a substance by one degree in temperature, under a specified temperature and pressure.

Thermal efficiency A measure of the efficiency of converting a fuel to energy and useful work; useful work and energy output divided by higher heating value of input fuel times 100 (for percent).