Waste Heat Recovery Technology Assessment

Contents

1. Introduction to the Technology/System

1.1. Introduction to Waste Heat Recovery

Waste heat in manufacturing is generated from several industrial systems distributed throughout a 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 are not as apparent such as hot surfaces, steam leaks, and boiler blow-down water. Table 1 shows typical major waste heat sources along with the temperature range and characteristics of the source [1].

Table 1: Temperature Range and Characteristics for Industrial Waste Heat Sources [1]

Waste Heat Source	Temperature Range	Cleanliness
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	150 – 600	Clean
Compressor after-inter cooler 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

A number of reports prepared for the Department of Energy (DOE) and other organizations ([2], [3], [4], [7], [8], and [9]) studied sources of waste heat, primarily from industrial heating systems. The scope of these reports varied from estimating losses from various industrial heating systems in Btu per year to reviewing waste heat from various industries and identifying general R&D opportunities. Following is an overview of several waste heat reports that were used as references in this technology assessment.

Energy Use and Loss Analysis [2]

The "Energy Use and Loss Analysis" report [2], prepared by Energetics Incorporated, 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 Energy Information Agency. The MECS data was used to estimate major areas of energy use in a plant as well as losses from the subsystems, as shown in Figure 1.

The losses were based on estimated percentages of losses for the major areas of energy use. The loss factors for each area are shown in Table 2. Based on the loss factors and energy use, an estimate was made for the energy losses in various industrial sectors, as seen in Figure 2. The report did not attempt to identify specific areas of waste heat for the energy systems.

Figure 1: Major Areas of Energy Use in a Manufacturing Plant [2]

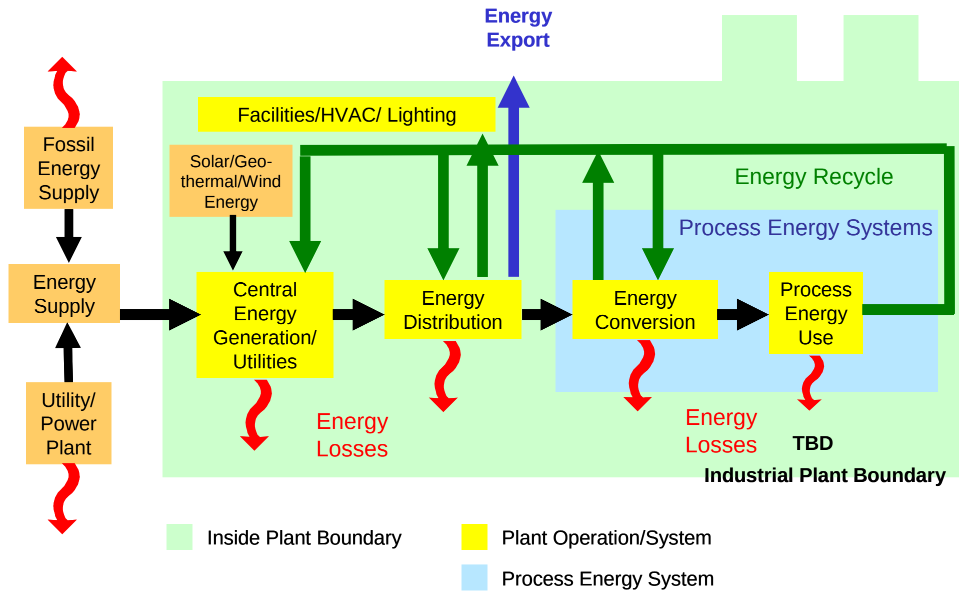
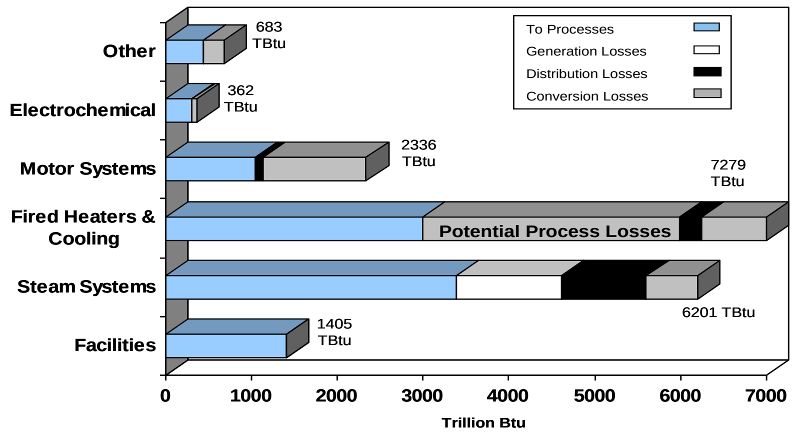


Table 2: Energy Loss Factors for Major Energy Systems in a Manufacturing Plant [2]

Energy System	Percent Energy Lost
Steam systems	Boilers – 20% Steam pipes and traps - 20% Steam delivery/heat exchangers – 15%
Power generation	Combined heat and power – 24% (4500 Btu/kWh) Conventional power – 45% (6200 Btu/kWh)
Energy distribution	Fuel and electricity distribution lines and pipes (not steam) – 3%
Energy conversion	Process heaters – 15% Cooling systems – 10% Onsite transport systems – 50% Electrolytic cells – 15% Other – 10%
Motor systems	Pumps – 40% Fans – 40% Compressed air – 80% Refrigeration – 5% Materials handling – 5% Materials processing – 90% Motor windings – 5%

Figure 2: Estimates of Energy Losses for Major Energy Use Areas in Manufacturing [2]



*Onsite generated power has been distributed among end-uses and is not included in the total.

Waste Heat Recovery: Technology and Opportunities in U.S. Industry [3]

AMO issued a detailed report prepared by BCS Incorporated titled "Waste Heat Recovery: Technology and Opportunities in U.S. Industry" that provides information on waste heat sources in major industrial sectors; the nature of waste heat; available waste heat recovery 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°–1,200°F), and low temperature (<450°F).

The BCS report provides a waste heat profile that describes the type of waste heat discharged from industrial plants, general observations related to waste heat sources, the nature of waste heat, and waste heat recovery practices. It outlines RD&D opportunities to extend the economic operating range of conventional technologies and conduct RD&D in emerging and novel technologies.

The report also identifies uncovered waste heat in different temperature ranges, concluding that the amount of heat wasted above 77°F reference temperature is 1,478 trillion Btu per year and lowers to 256 trillion Btu per year if the reference temperature is raised to 300°F. This indicates significant heat recovery opportunities in the 77°–300°F temperature range, which represents more than 80% of the total estimated waste heat and emphasizes the need for R&D in this range.

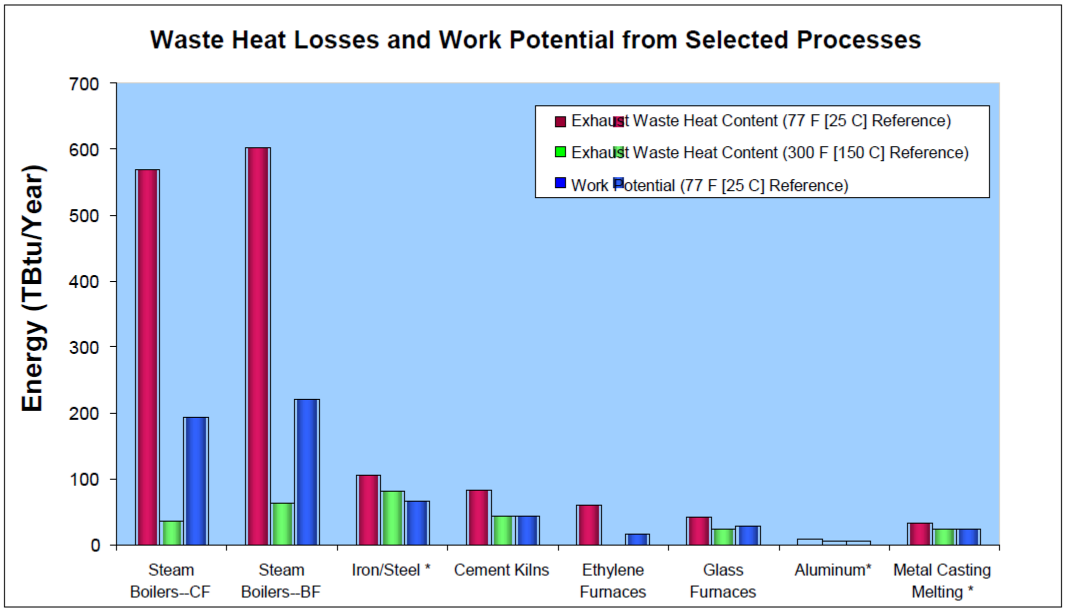
A summary of key RD&D opportunities identified in the BCS report cross-walked against barriers these opportunities address are shown in Table 3 [3].

Table 3: RD&D Opportunities and Barriers Addressed [3]

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

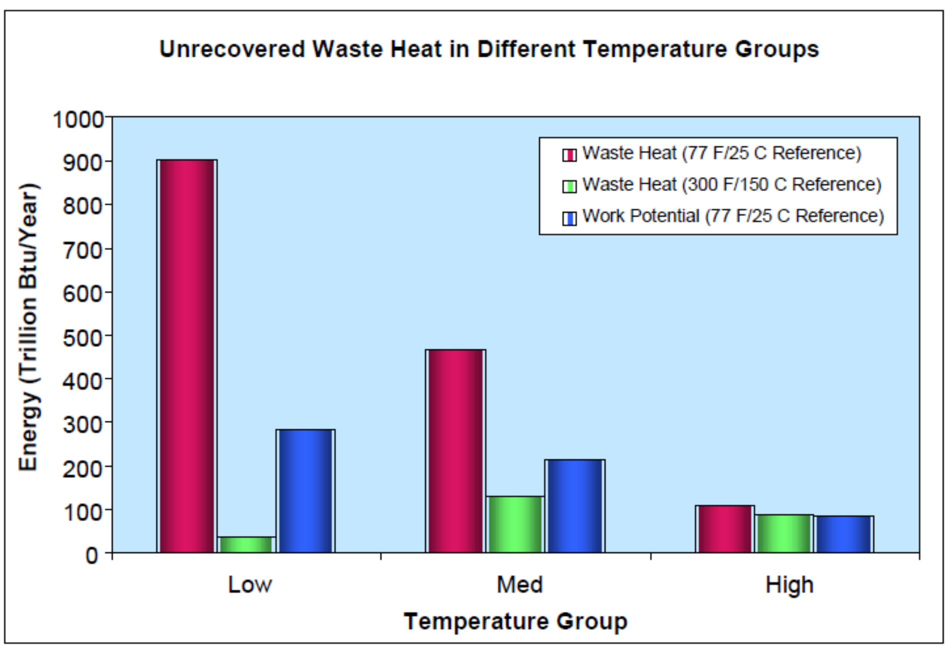
This study investigated several industrial processes, consuming a total of ~8,400 TBtu/yr, in order to estimate waste heat recovery opportunities. Estimates of unrecovered waste heat are shown in Figure 3 and 4. The Figure 4 indicates that the majority of waste heat losses (based on a 77°F [25°C] reference) are in the low temperature range. Though low temperature waste heat is a lower quality heat source, it is present in sufficiently large magnitudes that its work potential exceeds that of other waste heat sources.

Figure 3: Waste heat losses and work potential from selected process exhaust gases [3]



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

Figure 4: Unrecovered waste heat in different temperature groups [3]



Note: Figure 4 displays estimated waste heat losses in different temperature groups. 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.

Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions [4]

A Pacific Northwest National Laboratory (PNNL) report titled "Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions" discusses waste energy availability [4]. The report analyzes barriers and pathways to recovering chemical and thermal emissions from U.S. industry, with the goal of more effectively capitalizing on such opportunities.

A primary part of this study was characterizing the quantity and energy value of these emissions. The authors surveyed publicly available literature to determine the amount of energy embedded in the emissions and identify technology opportunities to capture and reuse this energy. The authors identify U.S. industry as having 2,180 petajoules (PJ), or 2 Quads (quadrillion Btu), of residual chemical fuel value. As landfills are not traditionally considered industrial organizations, the industry component of these emissions has a value of 1,480 PJ, or 1.4 Quads—approximately 4.3% of total energy use by U.S. industry.

The report discusses the advanced materials (e.g., thermoelectric, thermionic, and piezoelectric) and other technologies (e.g., solid oxide fuel cells) that, in the authors' opinion, are the most promising technologies for re-utilizing chemical and thermal emissions. The authors recommend additional research and development as well as industry education to make these technologies sufficiently cost effective and widely commercialized.

Engineering Scoping Study of Thermoelectric Generator (TEG) Systems for Industrial Waste Heat Recovery [5]

PNNL and BCS, Incorporated prepared a report titled "Engineering Scoping Study of Thermoelectric Generator (TEG) Systems for Industrial Waste Heat Recovery" that was issued in November 2006 [5]. This report evaluated the TEG system with the intent to accomplish the following:

- Examine industrial processes in order to identify and quantify industrial waste heat sources that could potentially use TEGs.
- Describe the operating environment that a TEG would encounter in selected industrial processes and quantify the anticipated TEG system performance.
- Identify cost, design, and engineering performance requirements needed for TEGs to operate in the selected industrial processes.
- Identify the research, development, and deployment needed to overcome limitations that discourage the development and use of TEGs for recovery of industrial waste heat.

Three industrial waste heat processes were selected to investigate applicability of TEGs: glass furnaces (485°–1,400°C), aluminum Hall-Hèroult cells (~960°C), and reverberatory furnaces (~760°C). Based on the analysis of opportunities, the report concludes that TEG application in glass furnaces would generate more than $25 million in annual sales, assuming that higher efficiency TEGs with a dimensionless figure of merit ZT ~2 could be built for $5/watt and assuming that 5% of the market buys TEGs per year.

The report suggests pursuing R&D work in thermal transfer technologies and engineering studies to interface TEG systems with existing process equipment, as well as studies of possible exhaust system modifications (e.g., duct length and residence times) that could lead to greater opportunities for integrating TEG systems in more industrial applications.

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. The BCS report identifies three temperature ranges to classify waste heat sources and opportunities; however, there is no general agreement on or basis for this definition of the temperature range. In this report, the temperature ranges have been expanded on both sides (high and low) of the spectrum. This expansion allows for the exploration and identification of R&D opportunities in the temperature ranges below 250°F (ultra-low temperature) and higher than 1,600°F (ultra-high temperature), in which it is difficult to identify cost-effective waste heat recovery methods or equipment. Hence, this report recognizes the following five temperature ranges:

- Ultra low temperature: below 250°F. The lower temperature for this range is usually the ambient temperature or the temperature of a cooling medium such as cooling tower water or other water used for cooling systems. The upper limit is based on several considerations, 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 waste heat recovery systems such as heat pumps.
- Low temperature: 250°–450°F, as defined in the BCS report.
- Medium temperature: 450°–1,200°F, as defined in the BCS report.
- High temperature: >1,200°F, as defined in the BCS report. However, based on contacts with the industry and waste heat recovery equipment suppliers, it is suggested that this range be divided in two temperature ranges. The normal definition of the "high" temperature range, based on availability of equipment and material, is 1,200°–1,600°F.
- Ultra high temperature: >1,600°F. Waste heat recovery from streams above 1,600°F requires use of special high-temperature materials that can be metallic or nonmetallic, such as ceramics. Selection of material and equipment design becomes very critical in many cases, as such streams contain a large amount of contaminants.

Technologies and Materials for Recovering Waste Heat in Harsh Environments [6]

The temperature of the exhaust gases discharged into the atmosphere from heating equipment depends on the process temperature and whether a waste heat recovery (WHR) system is used to reduce the exhaust gas temperature. The temperature of discharged gases varies 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 heat 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; deposit 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 report prepared by Oak Ridge National Laboratory and E3M Inc. identifies industries and industrial heating processes in which the exhaust gases are at high temperature (>1200°F), contain all of the types of reactive constituents described, and can be considered as harsh or contaminated. The report also identifies specific issues related to WHR for each of these processes or waste heat streams.

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

1. High gas temperature (>1,600°F): Although the process temperature might be less than 1,600°F, the presence of combustible components such as CO, H_2, or hydrocarbons in flue gases, and their combustion in the presence of air that could leak into the flue gas ducts or into a WHR system such as a recuperator, could increase the localized temperature that may exceed temperature limit of the heat recovery system component temperature. Examples include EAF and 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 materials in WHR equipment. 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 or exotic materials that would extend the recuperator life is 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 soot blowing, but this is not possible for all types of heat recovery systems.
4. Presence of combustibles (e.g., CO, H_2, hydrocarbons): 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 still presents 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: Most heating equipment using a large amount of energy, such as EAFs, BOFs, and many aluminum melting furnaces, operates 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 heat recovery 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 heat recovery 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 4 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 4.

Table 4 - Recoverable waste heat from selected harsh environment waste gas streams [6]

Criteria: Exhaust gases considered either >650°C and/or containing combustibles and contaminants

Industry	Waste heat source	Temp. range (°C)	Characteristics	WHR technology/system status	Production (MM tons/year)	Recoverable—potential TBtu/year [a]			Exhaust gas flow
						Sensible	Chemical	Total	
Steel	Blast furnace gases	400 to 600	Contain combustibles, particulates, etc.	Available and widely used–partial WHR	30	15.49	172.69	188.2	Constant
	EAF exhaust gases	1,500 to 1,600	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	64.32	27.21	34.86	62.1	Varying
	Basic oxygen process	1,250 to 1,700	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	31.68	4.47	25.22	29.7	Varying
Glass	Flat glass	430 to 1430	Contain particulates, etc.	Available for air-fuel combustion only and widely used–partial WHR	5.00	12.38	Negligible	12.4	Constant
	Container glass	430 to 1430	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and widely used–partial WHR	10.00	19.30	Negligible	19.3	Constant
	Glass fiber (all types)	980 to 1430	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and partially used–partial WHR	3.00	3.65	Negligible	3.7	Constant
	Specialty glass	480 to 1430	Contain particulates, condensable vapors, etc.	Available for partial heat recovery but rarely used.	2.00	7.60	Negligible	7.6	Constant
Aluminum	Al melting furnaces (fuel fired)	750 to 950	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	10.00	15.88	Small - site specific	15.9	Constant
	Anode baking	300 to 500	Contain combustibles, particulates, polycyclic organic matter, etc.	Available but NOT demonstrated	2.22	1.88	Small/site specific (unknown)	1.9	Constant
	Calcining	300 to 500	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	200 to 400	Contain particulates, etc. Relatively easy to handle	Available, not widely used–partial WHR	69.3	53.02	Negligible	53.0	Constant
Lime	Lime kiln exhaust gases based on commonly used rotary kiln type operation	200 to 600	Contain particulates, etc. Relatively easy to handle	Available, not widely used–partial WHR	20.9	40.7	Negligible	40.7	Constant
							Total	**434.4**	

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

Other Reports

The Lawrence Berkeley National Laboratory Industrial Energy Study group has prepared several reports ([7] and [8]) that describe energy use and energy efficiency improvement opportunities such as the "Energy Efficiency Improvement and Cost Savings Opportunities for Petroleum Refineries: An ENERGY STAR Guide for Energy and Plant Managers." These reports were published for several industries, including steel, cement, and food processing, and include discussion of waste heat recovery and suggestions on using certain technologies to recover waste energy for industrial processes.

A July 2009 report prepared by McKinsey & Company [9], "Unlocking Energy Efficiency in the U.S. Economy," examines, in detail, the potential for greater efficiency in non-transportation energy uses and assesses the barriers to this goal. The report suggests formulating an overarching strategy that includes recognizing energy efficiency as an important energy resource, as well as formulating and launching approaches to foster innovation in the development and deployment of next-generation energy efficiency technologies. The report does not provide specific suggestions regarding R&D program areas.

In September 2009, an industry-government forum on Energy Intensive Processes was held at the ITP-sponsored "Energy Intensive Processes Workshop." The goal of the workshop was to collect feedback on ITP's Energy-Intensive Processes R&D portfolio and strategy, as well as obtain guidance on future efforts. The workshop included a session on waste heat minimization and recovery and discussion on reducing fuel demands of steam boilers and furnaces by utilizing waste heat recovery. Workshop participants were asked to evaluate platforms, R&D focus areas, and project selections, and to provide recommendations on future topic areas. Participants were interested in the following areas of waste heat minimization and recovery:

- Ultra-high efficiency steam generation, with one project including the "super boiler"
- High-efficiency process heating equipment, with priority R&D opportunities including the following:
  - Ultra-high efficiency combustion
  - Insulation and refractory systems
- Waste energy recovery, with top R&D opportunities including the following:
  - Low-temperature heat utilization
  - Advanced energy conversion (e.g., solid-state and mechanical)
  - Heat recovery from high-temperature contaminated flue gases
  - Deployment of novel, waste-heat-to-electricity in a series of industrial demonstrations
- Waste energy minimization, with top R&D opportunities including the following:
  - Develop high-efficiency compressors, motors, and variable speed drives
  - Implement heat transfer improvements, such as coatings, and other ways to resist corrosion
- Process intensification and integration, with top R&D opportunities including the following:
  - Integrate industrial control system components (e.g., valves, actuators, and sensors)
  - Replace batch operations with continuous ones
  - Develop predictive modeling and simulation for combustion

Findings from Previous Reports

Analysis of previous studies along with direct contact with industry and equipment suppliers have shown that a large amount of waste heat is not recovered 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.

1.2. Challenges and Barriers for Waste Heat Recovery

The following section summarizes the barriers/challenges to waste heat recovery in the major industries. These barriers are presented by type of waste heat stream and by industry.

The following is a summary of waste heat by type and associated barriers:

- 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%) O2 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 MM Btu/hr) 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 use of 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.
- 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 use of low-grade heat within the plant or economically justifiable energy conversion systems.
- Hot water or liquids containing dissolved perceptible solids, dissolved gases (e.g., CO2 and SO2) or liquids.
    - No major technical barriers for filtering the water (removing the solids).
    - The presence of SO2, CO2, and other dissolved gases presents problems of high PH values for water use within a plant. There is no simple method of neutralizing the water.
    - Lack of use of 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 use of 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 use of 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 reefing or the chemical, food, mining, or paper industries.
    - No major technical barriers for recovering heat if there is sufficient temperature "head."
    - Lack of use of 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. 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.
    - 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 kiln 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 cost for advanced surface-mounted energy conversion technologies such as thermoelectric systems.

1.3. Public and Private Activities

To date: What is each sector doing on the system/technology and associated R&D? What is needed?

1.4. Public/Private Roles Going Forward

Why should DOE support R&D on this technology? What is the public value?

2. Technology Assessment and Potential

2.1. Current Status of Waste Heat Recovery Technologies

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

2.1.1. Commonly Used Waste Heat Recovery Systems

A summary of conventional or commonly used waste heat recovery technologies for various temperature ranges is found in Table 5.

Table 5: Commonly Used Waste Heat Recovery Systems by Temperature Range

Ultra-High Temperature (>1600° F)	High Temperature (1200° F to 1600° F)	Medium Temperature (600° F to 1200° F)	Low Temperature (250° F to 600° F)	Ultra-Low Temperature (< 250° F)

• Refractory (ceramic) regenerators • Heat recovery boilers • Regenerative burners • Radiation recuperator • Waste heat boilers including steam turbine-generator based power generation • Load or charge preheating	• Convection recuperator (metallic) – mostly tubular • Radiation recuperator • Regenerative burners • Heat recovery boilers • Waste heat boilers including steam turbine-generator based power generation • Metallic heat wheels (regenerative system) • Load or charge preheating	• 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 • Heat pipe exchanger • Metallic heat wheel	• Convection recuperator (metallic) of many different designs • Finned tube heat exchanger (economizers) • Shell and tube heat exchangers for water and liquid heating • Heat pumps • Metallic heat wheel • Condensing water heaters or heat exchangers • Heat pipe exchanger • Direct contact water heaters	• 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

The commonly used systems listed in this table are available from several suppliers and are used on industrial waste heat sources. In most cases, the systems are proven; however, they are continuously being improved in one of the following areas to offer better performance:

- Design changes to offer higher thermal efficiency in smaller footprint or size
- Cost reduction through use of better design and manufacturing techniques
- Improved seals to reduce maintenance or extend the life of the seals
- Use of different materials to improve heat transfer performance or maintenance cost
- Design changes to meet customer demands for different or previously untested applications

2.1.2. Emerging or Developing Waste Heat Recovery Technologies

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

Table 6: Emerging or Developing Waste Heat Recovery Technologies by Temperature Range

Ultra-High Temperature (>1600° F)	High Temperature (1200° F to 1600° F)	Medium Temperature (600° F to 1200° F)	Low Temperature (250° F to 600° F)	Ultra-Low Temperature (< 250° F)
• Regenerative burners • Systems with phase change material • Advanced regenerative systems • Advanced load or charge preheating 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	• 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	• Convection recuperator (metallic) of many different designs • Advanced heat pipe exchanger • Advanced heat pumps • Membrane type systems for latent heat recovery from water vapor • Low temperature power generation (i.e., ORC, Kalina cycle, etc.) • Thermally activated absorption systems for cooling and refrigeration • Systems with phase change material • Thermoelectric electricity generation systems • Condensing water heaters or heat exchangers	• 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

Emerging or developing technologies are being developed and tested at the laboratory or pilot scale. Development work is being carried out in many countries. The current status of the technology or product development depends on the local energy situation (cost and availability) and support from the local governments or funding agencies. In general, the following areas are getting 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 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

All of these areas of development are discussed in the R&D opportunities section of this report.

2.1.3. Limitations of Currently Available Technologies

Table 7 and 8 depict limitations and barriers of currently available waste heat recovery technologies for ultra-high, high, and medium temperature ranges.

Table 7: Limitations of Currently Available Waste Heat Recovery Technologies, High and Ultra High Temperature Ranges

Equipment	Limitations and Barriers
Metallic recuperators	• Upper temperature limit of 1,600°F • Economically justifiable heat recovery efficiency – 40%–60% • High maintenance for use with gases containing particulates, condensable vapors, or combustible material • Life expectancy in applications where the mass flow and temperature of the fluids vary or are cyclic • Fouling and corrosion of heat transfer surfaces • In some cases, difficulty in maintaining or cleaning the heat transfer surfaces
Ceramic recuperators	• Life expectancy due to thermal cycling and possibility of leaks from high-pressure side • 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 footprint • Declining performance over the lifetime • 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	• Seals 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 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	• Can be used for large size systems (usually higher than 25 MM Btu/hr) • Can be used only for clean, particulate free, exhaust gases • Need to identify use of steam in the plant • Initial cost is very high compared to other options such as recuperators

Table 8: Limitations of Currently Available Waste Heat Recovery Technologies, Medium Temperature Ranges

Equipment	Limitations and Barriers
Metallic recuperators	• Economic justification for exhaust gas temperature below about 1,000°F • Economically justifiable heat recovery efficiency – 40%–60% • High maintenance for use with gases containing particulates, condensable vapors, or combustible material • Fouling of heat transfer surfaces • In some cases, 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	• Seals 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 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

Another approach would be to develop a matrix according to the type of equipment available in the market. Considerations would include its application range, in terms of temperatures and heat source characteristics; performance level; and limitations with respect to industrial applications.

2.2. R&D Opportunities

R&D opportunities are presented in three formats: by temperature range, by major industry, and by research category.

2.2.1. R&D Opportunities for Various Temperature Ranges

The following are lists of R&D opportunities categorized in temperature regimes at which waste heat is available.

2.2.1.1. Opportunities for High-Temperature Waste Heat Sources

This section includes two different categories of high temperatures: 1,200°–1,600°F, and >1,600°F.

- Heat recovery systems that can handle high-temperature gases with solids and condensable contaminants. These systems can also have internal cleaning systems that allow 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.
- Development of 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.
- Development and testing of 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 installation as a retrofit for existing systems, which are usually located in limited space in the 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 to remove particulates from high-temperature gases.
- 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.

2.2.1.2. Opportunities for Medium-Temperature Waste Heat Sources

This section includes temperatures from 600°–1,200°F.

- Compact heat exchangers or micro-channel heat exchangers for clean gases that reduce the size or footprint of the heat recovery system.
- 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.

2.2.1.3. Opportunities for Low-Temperature Waste Heat Sources

This section includes two different categories of low temperatures: <250°F and 250°–600°F.

- Innovative condensing heat exchangers for gases containing high moisture levels with particulates, as discharged from paper machines, food drying ovens, or other sources.
- Nonmetallic materials (polymers) that can withstand condensed water from combustion products containing acid gases. These must be cost competitive and used for low-temperature condensing heat exchangers.
- 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.
- Dry coolers for cooling liquids that reduce or eliminate water use in heat exchangers.

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 waste heat recovery. R&D needs for this category of waste heat recovery 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.

2.2.2. R&D Opportunities by Major Industry

The following opportunities have been identified where R&D could impact waste heat recovery in the major industries analyzed in this report.

2.2.2.1. Opportunities for the Aluminum Industry

- Cleaning high-temperature contaminated gases without cooling them to lower (<300°C) 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.
- 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 reliability and longer life for submerged heating devices for corrosive surroundings, such as molten aluminum or molten glass.

2.2.2.2. Opportunities for Food (Snack) Manufacturing

- Development of 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 amount of oil vapors.
- Development of heat recovery from low-temperature water (<100°F) for plant use.
- Development of efficient heater systems to reduce energy intensity.

2.2.2.3. Opportunities for Integrated Steel Industry

- 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. The industry has not considered this notion, perhaps due to its nature (low- to medium-grade) and difficulty in recovering and using the heat.
- Recovery and use of waste heat from highly contaminated hot gases such as hot COG 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 area.
- Recovery or utilization of radiation—convection heat from furnace walls or openings, or 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.

2.2.2.4. Opportunities for the Glass Industry (Fiberglass and others)

- 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.
- Rapid quenching methods of hot gases to eliminate generation of sticky solids, and subsequent use of these gases in conventional boilers or air heaters.
- Electricity generation through direct contact or radiation from moderate temperature (300°–900°F) surfaces with economically justifiable paybacks. Possible methods are thermoelectric and photovoltaic 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 such as producing hot water or steam for the evaporators as well as the need for cooling towers for the condenser. This 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 from 800°–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.

2.2.2.5. Opportunities for the Paper Industry

- 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 amount of fibers or duct.
- A system for dehumidifying high-temperature (≥140°F) air containing fibers or dust.
- 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.

2.2.2.6. Opportunities for Steel Mini-mills (EAF Furnaces and Rolling Mill)

- 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.
- Recovery of heat from surfaces of hot ladles. The heat is in the form of radiation and convection and the ladles are moved from one location to another during the day.
- 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.

2.2.2.7. Opportunities for Coating Plants

- Secondary heat recovery from regenerative thermal oxidizers (RTOs) exhaust gases that are available from 350°–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.

2.2.2.8. Opportunities for Aluminum Recycling Operations

- 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°–800°F.

2.2.2.9. Opportunities for the Cement Industry

- Heat recovery from hot surfaces or kiln shell surfaces.
- Cleaning (particulate removal) of heated clinker cooling air prior to its use 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.

2.2.2.10. Opportunities for the Chemicals and Petroleum Refining Industries

- Heat recovery from low-temperature (200°F and higher) 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 use mediums that use no or minimal water are needed.
- Treatment of high-temperature gases containing corrosive gases such as HCL from TO gases that 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 and associated energy use.
- Economically justifiable energy recovery from flared gases.

2.2.3. R&D Opportunities by Research Category

The industry requirement-based R&D lists have been consolidated to identify 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. While there are many ways the R&D areas could be presented, the following employs the method of dividing R&D activities into specific programs that can be pursued by equipment suppliers to advance the technology or performance of the currently offered systems:

2.2.3.1. Opportunities in Basic Research

- **Heat transfer**
  - 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.
  - 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.
- **Particulate removal or gas cleaning**
  - Particulates filtering for particulate laden gases in all temperature ranges through innovative methods of increasing filtering efficiency with minimized pressure drop. 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.
  - 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**
  - 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.
  - 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.

2.2.3.2. Opportunities in Advanced Materials

- 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).
- Cost-effective thermoelectric or thermo-ionic materials capable of producing electricity from heat with 15%–20% thermal efficiency.
- Working fluids for low-temperature power generation cycles that can withstand broader temperature ranges for use in ovens and furnaces.
- 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.

2.2.3.3. Opportunities in Advanced Concepts and Designs

- Innovative heat transfer methods and heat exchanger geometries to reduce heat exchanger size (see the Basic Research section).
- 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 Basic Research section 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 size 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.
- Waste heat "boilers" in condensers thermally driven lower temperature (≥100°F) high pressure condensing thermally-activated refrigeration and heat pump systems driven by waste heat 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 use direct gas – air heating for the evaporators and air for condensers.
- 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.

2.2.3.4. Opportunities in Sensors and Controls

- 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 recycling of exhaust gases and reduce the amount of make-up air.
- Systems for monitoring heat exchanger performance to detect performance degradation and alarms for maintenance.
- A low cost reliable system for monitoring O2 and CO in small applications (<5 MM Btu/hr fired systems).

- Continuous monitoring of energy intensity (Btu or kWh per unit of production) to identify performance problems.

2.2.3.5. Opportunities in Advanced High Efficiency Power Generation Systems

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

3. Risk and Uncertainty, and other Considerations

Identify and describe issues related to the following

- **Risk and Uncertainty Issues**: As described above, identify risk and uncertainty issues to queue them up for EPSA/QER. Where appropriate, identify how these impacts and need to be taken into account in the R&D work.
- **Technology characteristics impact policy:** Identify where technology characteristics impact policy design, and set this up for EPSA/QER. Also describe how policy factors may drive technology considerations and choices. In both cases, don't explore policies in detail; leave that for EPSA.
- **Other considerations TBD**

4. Sidebars; Case Studies

Prepare 2-3 short case studies or vignettes to illustrate key aspects of DOE R&D, including cross-cut activities, enabling science, or other issues, where possible, these should have a clear outcome or conclusion and a strong graphic is desirable. These should be in the form of self-standing boxes or side-bars.

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