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Estimation of and barriers to waste heat recovery from harsh environments in industrial processes

David Vance [a,*], Sachin Nimbalkar [a], Arvind Thekdi [b], Kristina Armstrong [a], Thomas Wenning [a], Joseph Cresko [c], Mingzhou Jin [d]

[a] Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN, 37831, USA
[b] E3M, Inc. 5206 Ivystone Court, Sugar Land, TX, 77479, USA
[c] U.S. Department of Energy, 1000 Independence Ave., SW, Washington, DC, 20585, USA
[d] Department of Industrial and Systems Engineering and Institute for a Secure and Sustainable Environment, University of Tennessee, 525D John Tickle Engineering Building, Knoxville, TN, 37996, USA

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A B S T R A C T

This paper discusses the industrial potential for waste heat recovery (WHR) in harsh environments – defined as a waste heat stream having either a temperature of at least 650 °C or containing reactive constituents that complicate heat recovery. The analysis covers five industries (steel, aluminum, glass, cement, and lime), chosen based on volume of production, discharge of exhaust gases containing components that present harsh environments, possibility of recovering considerably more heat than currently recovered, and current lack of acceptable WHR options. The total potential energy savings identified in harsh environment waste heat streams from these industries is equal to 15.4% (113.6 TWh) of the process heat energy lost in U.S. manufacturing. Existing technologies and materials for these industries are evaluated and the recoverable waste heat from harsh environment gas for each industrial sector is estimated. Finally, an in-depth summary of each waste heat source shows exactly where waste heat can be recovered and what specific issues must be addressed. The most potential lies within steel blast furnaces (46 TWh/year). Other waste heat streams considered include steel electric arc furnaces (14.1 TWh/year), flat glass (3.6 TWh/year), container glass (5.7 TWh/year), glass fiber (1.1 TWh/year), specialty glass (2.2 TWh/year), aluminum melting furnaces (4.7 TWh/year), cement (17.1 TWh/year), and lime (10.5 TWh/year). Although attempts to recover waste heat in harsh environments have been mostly unsuccessful, advances in research and technology could unlock an enormous potential for energy and cost savings.

1. Introduction

The manufacturing sector in the U.S. loses 747.6 TWh of energy annually through process heating systems (U.S Energy Information Administration, 2014). After equipment provides the process heat required, the stacks discharge the hot exhaust gases into the atmosphere. The waste heat contained in these exhaust gases from a fuel-fired or electrical heating system such as a furnace, oven, heater, or boiler is the single largest heat loss in manufacturing plants (Brueske et al., 2012). The total energy savings potential identified from exhaust gases containing either very high-temperature (greater than 650 °C) and/or reactive constituents studied in this paper is equal to 15.4% (113.6 TWh) of the process heat energy lost in U.S. manufacturing. Due to the large amount of energy and heat loss associated with these exhaust gases, it is important to consider these waste heat recovery (WHR) projects, despite the barriers and limitations that have hindered their effectiveness in the past. Advances in research and technology make it possible to realize the enormous potential for energy and cost savings from recovering heat in exhaust gases, historically thought of as unfavorable.

The temperature of hot exhaust gases discharged into the atmosphere from heating equipment depends on the process temperature and whether the system utilizes a WHR system to reduce

* Corresponding author.
E-mail addresses: vancedm@ornl.gov (D. Vance), nimbalkarsu@ornl.gov (S. Nimbalkar), athekdi@e3minc.com (A. Thekdi), armstrongko@ornl.gov (K. Armstrong), wenningtj@ornl.gov (T. Wenning), Joe.Cresko@ee.doe.gov (J. Cresko), jin@utk.edu (M. Jin).

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the temperature. The temperatures of discharged gases vary from as low as 93 °C to as high as 1650 °C. Several definitions have been used in the past, usually grouping temperatures into high, medium and low categories (Johnson et al., 2008). This paper uses five temperature regimes for classification of waste heat sources as illustrated in Fig. 1.

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 heated product and may pick up constituents such as reactive gases, liquid vapors, volatiles from low-melting-temperature solid materials, particulates, condensable materials, and the like. Particularly at high temperatures, some or all constituents may react with materials used in the construction of downstream heat WHR equipment and create significant problems.

A classification system of waste heat categories is outlined in Table 1. Waste heat characterization categories 3 to 6 fit within this paper's definition of harsh environment.

This paper specifically defines exhaust gases containing high-temperature (greater than 650 °C) or reactive constituents that complicate heat recovery (Category 3–6) as "harsh environments". Heat recovery from these harsh gases using commercially available WHR systems may result in excessive maintenance, short equipment life, and in some cases, safety risks. Often, existing equipment and technologies cannot adequately cope with the challenges harsh environments create. The presence of undesirable chemicals, high-temperature, and variability clearly pose considerable challenges for WHR systems. Currently, the manufacturing industry applies only partial or no heat recovery for managing exhaust gases in harsh environments according to Table 2.

The research questions this paper seeks to answer include: "What's the potential for industrial WHR from high-temperature harsh environments in the U.S.? What are the advanced and emerging technologies and materials available for recovering high temperature waste heat? What material and design issues limit the potential of WHR from high-temperature harsh environments? What are the research and development needs?" Existing technologies and the materials used with these systems are summarized. Then, significant waste heat sources are identified from five specific industries (steel, glass, aluminum, cement, and lime) and investigated in greater detail to determine where waste heat could be recovered and what specific issues must be addressed. Finally, the heat recovery potential for each industry is evaluated.

2. Background

There are many technologies and equipment available to recover waste heat in industrial heating systems. The selection among them is greatly influenced by the category of exhaust gas as specified in Table 1. Heat recovery from categories 1–3 are often cost-effective; however, equipment that offers long life, has justifiable cost, and recovers a large percentage (>50%) of the waste heat in harsh environment situations, is not readily available. Available WHR systems for harsh environments require high-temperature materials (alloys and in some cases ceramic or refractory materials), which have a high capital cost. Additionally, the harsh exhaust gases introduce operation and maintenance issues (such as deposition, fouling, and corrosion), requiring frequent attention and much expense. For category 4 and 5 exhaust gases, these issues are difficult to manage, thus, there is little or no WHR from exhaust gases in large energy use systems, such as EAFs, BOFs, and secondary aluminum melting furnaces.

Some of the most commonly used technologies for high to ultra-high temperature WHR include.

- recuperators,
- regenerators,
- waste heat boilers for steam generation,
- steam-based electrical power generation systems,
- cascade systems to recover heat from high-temperature gases for lower-temperature processes, and
- load or charge preheating.

There are other systems available, used only in very few cases for industrial applications. A detailed review of the listed devices is available in references (Goldstick and Thumann, 1986; Keiser et al., 2007; Thekdi and Nimbalkar, 2015).

Generally, industrial heating applications use the above equipment with clean gases and combustion products in the temperature range from 200 °C up to 870 °C. While good design and maintenance practices can help some equipment (e.g., radiation recuperators, steam generators, and water heaters) handle small amounts of combustibles and particulates, most attempts to use these types of equipment for high-temperature gases in harsh environments (i.e., containing contaminants) have resulted in a short life (less than one or two years) and more frequent maintenance.

For example, tubular metallic recuperators can preheat combustion air using heat from exhaust gases. However, an investigation of the use of recuperators at a large aluminum plant (Keiser et al., 2007) indicated that these recuperators have very short life due to corrosion of metals, localized high temperatures (resulting from the combustion of combustible gases in exhaust gases), deposits of dross and other flux material particles, and other issues. Even with frequent maintenance, the life expectancy has been less than two years.

The glass industry also uses radiation recuperators to preheat combustion air for glass melting furnaces in the glass fiber and

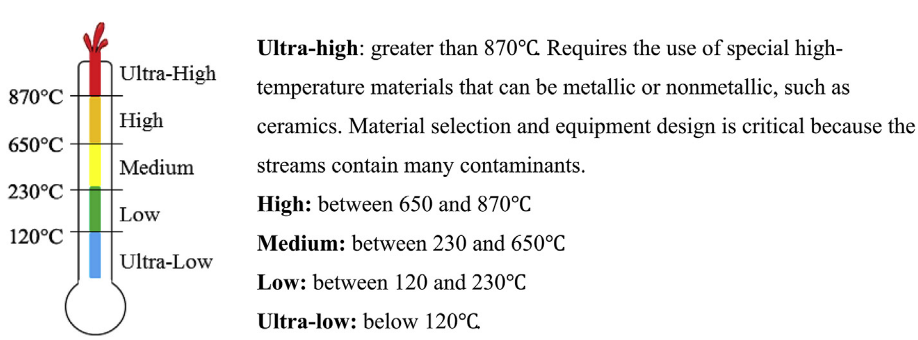

Fig. 1. Temperature regimes for classification of waste heat sources.

Table 1
Characteristics and descriptions of waste heat streams from process heating systems (Thekdi and Nimbalkar, 2015).

Category	Waste heat stream characteristic	Description and examples of sources
1	Clean combustion products [a]	Waste gases from natural gas–fired heating systems Examples: steam generators, furnaces, ovens, process heaters
2	Combustion products with presence of relatively large proportion (>1%) of combustible gases [b]	Waste gases from gas- or oil-fired heating systems in which the combustion process is not controlled properly, resulting in sub-stoichiometric combustion or reactions in selected areas of the heating system Examples: furnaces, ovens, process heaters
3	Combustion products containing fuel-based corrosive gases (e.g., SO_2, HCl)	Waste gases from heating systems fired byproduct gases (e.g., refinery gases, coke oven gas, blast furnace gas) Examples: heating systems including boilers used in chemical, petroleum refining, paper industry
4	Combustion products containing fuel-based ash, unburned carbon, soot, and so on	Waste gases from fuel-fired equipment using coal and other solid fuels, byproduct liquid fuels and some untreated gaseous streams. Examples: boilers, steel reheating furnaces; mostly used outside North America
5	Combustion products (categories 1–4) mixed with process- or product-generated solids, liquids volatiles, and vapors (contaminants)[c]	Waste gases from heating processes in which charge materials are in solid, liquid, sludge or slurry form and in direct contact with combustion products. These may use clean gaseous fuels such as natural gas or other types of fuels (mostly fuel oil) Examples: glass melting furnaces, secondary aluminum melting furnaces, cement and lime kilns
6	Other types of process equipment in which the process and/or fuels generate combustible material (gases, volatiles, using mostly solid fuels)	Waste gases from process equipment in which the "fuel" is a process reactant and produces waste gases containing combustible gases, solids, and condensable vapors Examples: blast furnaces, coke ovens, cokers, coke calciners

[a] Containing CO_2, H_2O, N_2, O_2 with very small (<0.1%) amount of combustibles (e.g., CO, H_2, CH_4).
[b] CO, H_2, CH_4 and gaseous hydrocarbons.
[c] Product-generated contaminants include solids, liquid vapors, or vapors of organic or inorganic materials generated or entrained from the product or process.

Table 2
Current practices for handling exhaust gases in harsh environments.

Practice	Examples
Partial WHR, because of materials limitations, design issues, and space considerations.	Using regenerators to preheat combustion air for a glass melting furnace
Partial WHR, because of other limitations such as safety, maintenance, lifetime.	Using scrap preheaters for electric arc furnaces (EAFs) and steam generation for basic oxygen furnace (BOF) installations.
Partial or no WHR, because of high capital cost, limited operating hours, or other operating and economic constraints.	Boilers, steel reheating furnaces
No WHR, but treating exhaust gases (scrubbing, cooling by blending with cold air or mist cooling) to meet regulatory requirements.	EAF and BOF exhaust gases.
No WHR, resulting in a 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.	Blast furnaces and coke ovens.

specialty glass sectors. Generally, stationary regenerators used for air-fuel combustion glass melting furnaces experience fouling or deposition-related issues (sodium sulfate and ash). A blast furnace stove (for preheating blast furnace combustion air) is a similar regenerator, but uses cleaner fuels, making degradation less of an issue.

The use of exhaust gas waste heat for load or charge preheating is another area of interest for high-temperature industrial heating systems. This heat recovery method offers several advantages to a process heating system, such as reduced energy use (electricity and fuel), reduced melting or processing times, increased productivity, and in some cases, reduced emissions. Unfortunately, several issues (such as high installation cost, production equipment downtime, maintenance costs, safety issues, and low process controllability) have prevented wide use of this WHR method (Association for Iron and Steel Technology, 2014a).

The selection of materials for recovering waste heat in harsh environments must consider temperature, strength, and oxidation stability, all while meeting specific application requirements. WHR equipment must be strong and resilient against the unique stresses imposed on them, especially those arising from significant temperature changes and thermal gradients in many high-temperature applications. WHR from streams above 870 °C requires the use of special high-temperature materials. The selection of material and design is very critical in these cases as such streams contain many contaminants.

Choosing appropriate materials requires knowing what materials are available and the extent to which they suit the specific application. The user or designer must properly understand that the off-gas environment dictates the materials selection approach at all stages of the process or application. For optimum performance, a supplier must be aware of the application, and the user must be aware of the range of available materials, the limitations of the design or operating conditions, and the mechanical limits of the selected material (Bullock et al., 2012).

A major concern when selecting materials for harsh environments is limiting the effects of corrosion. Corrosion is a chemical attack upon solid functional or structural materials that results in degradation of the desired properties and forms undesirable reaction products. (Lai et al., 1983). There are certain distinguishing features of high-temperature corrosion that aid in determining the cause of damage, such as thick scales, grossly thinned metal, burnt (blackened) or charred surfaces, molten phases, deposits of various colors, distortion and cracking, and magnetism in what was a nonmagnetic (e.g., austenitic) matrix.

The most common high-temperature corrosion reaction is oxidation (Lai, 2007); other examples include sulfidation, halogenation, carburization, nitriding, and molten product corrosion. Damage varies based upon the environment and is most severe when an alloy sustains breakaway attack by oxygen/sulfur, halogen/oxygen, oxidant/low-melting fluxing salts, molten glasses, or molten metals. An example of breakaway attack is sulfidation (a reaction of a metal or alloy with some form of sulfur, producing a sulfur compound that forms on or under the surface of a metal or alloy (Bhattacharyya et al., 2008)); this reaction can be very damaging, since metal sulfides form at faster rates than metal oxides, have low melting points and can result in scale spallation.

3. Methods

There are five major industries in which large amounts of waste heat from harsh environments are available but are not being utilized due to harsh environments and their associated difficulty with using WHR equipment. Selected industries include 1) Iron and Steel, 2) Aluminum, 3) Glass, 4) Cement, and 5) Lime.

Various waste heat sources were selected from these industries based on quantity of recoverable heat, possibilities for recovering considerably more heat than is recovered currently, and lack of availability of acceptable WHR options (Nimbalkar et al., 2014b). Each of these sources has different characteristic considerations (e.g., particulate matter, combustibles, corrosive contaminants) and temperature ranges, resulting in different WHR equipment that can be used as shown in Table 3.

Based on various sources identified, estimations of recoverable waste heat from harsh environment gases were updated from (Nimbalkar et al., 2014b) for each of the five industrial sectors. The following is an example of the calculation procedure used to estimate recoverable waste heat for EAF operations in the steel industry.

Temperature of off-gases from an EAF: 1500 to 1700 °C (Kirschen et al., 2001).

Steel production in the U.S. (2015): 78.8 MMtons (United States Geological Survey, 2017a).

EAF steel production as percentage of total U.S. steel production: 63% (United States Geological Survey, 2017a).

Energy input: 742 kWh/tonne of billet (or molten steel).

Sensible heat: 16.7% (Evenson et al., 2001).

Chemical heat: 21.4% (Evenson et al., 2001).

Total recoverable heat for U.S. EAF industry:

$$(16.7\% + 21.4\%) \times 742\ \frac{kWh}{tonne} \times 78,800,000\ \frac{tonne}{year} \times 63\% = 14.05\frac{TWh}{year}.$$

4. Results and discussion

The following sections will analyze these five industries in detail to show where the heat recovery potential exists, provide examples of waste heat source heat balance, and discuss specific issues that must be addressed for further development.

4.1. Steel industry

The steel industry has the highest potential for utilization of harsh environment WHF (68.2 TWh/year), most of this as chemical heat (84%). Within the steel industry there are two major waste heat streams with harsh environments: blast furnaces (BF), and electric arc furnaces (EAFs) (the basic oxygen process fits the requirements but has much lower potential for WHR).

A BF converts iron oxides into liquid iron through a series of chemical reactions. Hot liquid metal production in BFs is one of the most energy-consuming processes. In the U.S., the iron and steel

Table 3
Currently used waste heat recovery equipment for identified potential waste heat sources.

Industry	Waste heat source	Temp. range (°C)	Characteristics	WHR Related equipment
Steel	Blast furnace gases	200–320	Dust, sulfur, cyanide compounds, and other contaminants	Scrubbers, top gas pressure recovery turbines, and recuperator hot blast stoves
	EAF exhaust gases	1500 –1700	Combustibles, particulates, etc.	Consteel scrap preheaters, Bucket types scrap preheaters, Twin-shell furnaces, Fuchs shaft furnaces, and Evaporative Cooling (ECS) technology
	Basic oxygen process	1250 –1700	Combustibles, particulates, etc.	Boiler or HRSGs, BOF gas cooling devices, dedusting devices, etc.
Glass	Regenerative system	400–600	Particulates; HCl, GH, boron vapors can be expected	Stationary regenerators, cullet preheaters, HRSGs, Organic Rankine Cycle (ORC) equipment
	Oxy-fuel system	1450 –1550	Particulates, condensable vapors, etc.	Batch/Cullet preheaters, HRSGs, ORC equipment
	Nonregenerative + other	1450 –1550	Particulates, condensable vapors, etc.	N/A
Aluminum	Al melting furnaces (fuel fired)	750–950	Combustibles, particulates, polycyclic organic matter, fluxing agents (chlorine, fluorine, etc.).	Conventional recuperators, regenerative burners, charge preheaters, HRSGs
	Anode baking	300–500	Particulates, fuel combustion products, etc.	Thermoelectric generators, sidewall heat exchangers, combustion air preheaters
	Calcining	300–500	Particulates, fuel combustion products, etc.	Cyclones and fluidized bed alumina coolers
Cement (Clinker)	Cement kiln exhaust gases from modern clinker making operation	200–400	Particulates, combustibles, NO_x and SO_2. Relatively easy to handle	Waste heat recovery boilers, shaft type charge preheaters
Lime	Lime kiln exhaust gases based on commonly used rotary kiln type operation	200–600	Particulates, combustibles, NO_x and SO_2. Relatively easy to handle	Waste heat recovery boilers, shaft type charge preheaters

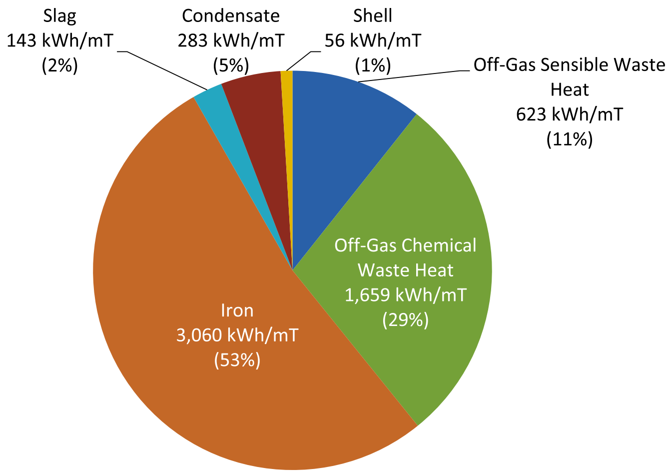

Fig. 2. Example heat balance of a BF (mT = tonne) (Johnson, 2012).

industry account for 34% of industrial energy use (Worrell et al., 2011). As of 2014, there were 22 BFs installed in the U.S. with rated capacities varying between 1.2 and 2.8 million metric ton (tonne) per year (Association for Iron and Steel Technology, 2014b). The heat balance in Fig. 2 shows that about 40% of the total heat input of a BF may be discharged as sensible and chemical heat in off-gases. In this example, chemical heat is 29% of the discharged heat, indicating a large amount of combustible gases.

The huge amount of heat waste from BFs represents significant potential for heat recovery: the use of BF off-gas heat to preheat combustion air, generate electricity, or recover chemical heat can save energy, reduce emissions, and save money. However, there are several issues and barriers to consider, depending on the WHR method used and the size of the BF.

Top-gas recovery can recover chemical heat, which represents over 90% of the potential WHR for BF. After removing particulates with a scrubber, the resulting gas, containing approximately 10% of the energy content of natural gas, can be mixed with other fuels to heat another part of the process or used to generate electricity. Top-gas pressure recovery expands the higher-pressure gas in a turbine and generates electricity. The gas must be cooled and cleaned before use, but top pressure recovery systems have high reliability and are abrasive resistant. Both systems will likely have a long payback period (approximately 30 years), but as a long-term investment, they will have significant environmental benefits.

Recuperator systems recover sensible heat from flue gases from the blast stove or the top gases of the blast furnace to preheat the combustion fuel or air. These two systems are similar, but have different advantages and disadvantages (e.g., the use of top gases may cause corrosion of working surfaces but can have a lower payback period than gases from the blast stove). Additionally, particulates and gases can increase the resistance to heat transfer and corrode the system. The major issues for applying WHR to BFs are the following:

- In each WHR method available, only a portion of the waste heat is recoverable. Although a significant amount of chemical energy can be recovered, a great deal of the sensible heat is often lost to the atmosphere.
- Top Gas recovery
  - o U.S. BFs do not operate at extremely high pressures, making top gas recovery somewhat difficult and uneconomical unless there is a large quantity of exhaust gas or installation in a new system (Institute for Industrial Productivity, 2013).
  - o Retrofit may be difficult for some recovery methods (Association for Iron and Steel Technology, 2014b)
  - o It may be challenging to dispose of scrubber waste water (Trinkel et al., 2015).
- Recuperators
  - o Lack of suitable technology in U.S. makes the recovery of sensible heat difficult (Sharma et al., 2014).
  - o High temperatures and articulates cause corrosion in recuperators not made of appropriate materials (American Iron and Steel Institute; Lawrence Berkeley National Laboratory, 2010).

The other major waste heat stream with harsh environments in the U.S. steel industry, the electric arc furnace, has experienced significant growth in the production of liquid steel from recycled scrap, accounting for 63% of U.S. steel production in 2015 (United States Geological Survey, 2017a). This process uses electricity and fossil fuels, primarily natural gas and some carbon, to supply process energy requirements. According to an EAF roundup (Association for Iron and Steel Technology, 2014a), there are approximately 173 EAFs in the U.S., resulting in a WHR potential of about 14 TWh/year. Of these 173, a clear majority (>90%) collect EAF exhaust gases, mix them with ambient air to oxidize the combustible materials, and then reduce the temperature of the gases to less than 204 °C before discharging to the atmosphere, without using any WHR technology (Nimbalkar et al., 2015). In a typical EAF, off-gas wasted chemical heat makes up a large percentage (21.4%) of the energy balance, indicating the presence of a large amount of combustible gas (Fig. 3).

In rare cases (less than 10% of the EAFs in the U.S.), the process recovers the waste heat from EAF off-gases for scrap preheating or steam generation. Some of these systems can recover a considerable fraction of the waste heat (e.g., charging bucket, Fuchs shaft preheater, CONSTEEL technology) and others can heat almost 100% of the scrap (i.e. Fuchs finger shaft furnace). Use of EAF off-gas heat to preheat scrap in EAFs offers several benefits, including continuous charging, lower use of energy in the EAF, and increased productivity per MW. However, only a part of the off-gas heat transfers to the charge material, most of heat is left in the exhaust gases that leave the scrap preheater (Nimbalkar et al., 2014a).

Despite the advantages attributed to scrap preheating, the use of these technologies has the following limitations in the U.S. and in the rest of the world.

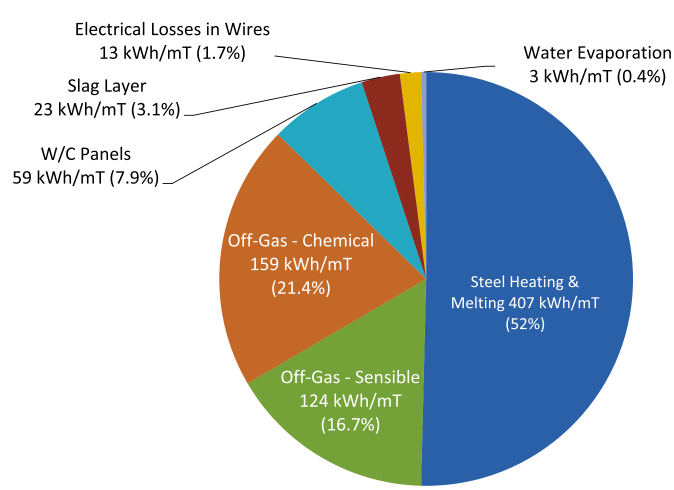

Fig. 3. Example heat balance on an EAF (Evenson et al., 2001).

- Use of currently available scrap preheating systems can recover only a portion of the heat recovery potential from the total heat of off-gases
- Many systems experience operating issues related to safety, maintenance, and localized melting
- Oil and other flammable contaminants present in the scrap emit a lot of heat while burning out
- At temperatures higher than 800–900 °C, the fine scrap is oxidized intensely because of its very large surface area
- When scrap is preheated, it is likely that highly toxic compounds of halogens with hydrocarbons of varying composition, dioxins, may form
- The Consteel technology, a major scrap preheating method, conveyes scrap though a tunnel, exposing it to radiated heat (and a negligible amount of convection on the scrap top layer), however, it only significantly heats the top layer of scrap on a conveyor (Argenta and Bianchi Ferri, 2005)

These limitations cause the need for frequent maintenance and may result in uneven heating of scrap and localized melting of steel, creating operational problems. These are caused by the varying gas temperatures and the presence of combustibles, together with unpredictable air flow patterns may result in uncontrolled burning of combustible gases. These issues must be more fully explored and overcome to practically realize the potential of waste heat recovery for scrap preheating.

4.2. Glass industry

The U.S. glass industry can be classified in four major subsectors: flat glass (25% of total annual tonnage), container glass (50%), specialty glass (10%), and glass fiber products (15%) (Johnson et al., 2008). Between the four subsectors, there is a waste heat recovery potential of about 43 TBtu/year. WHR is already common in the glass industry, over half of the glass producing furnaces (59.1% (Johnson et al., 2008)) are regenerative and recuperative (R/R) furnaces. In an average furnace, about 45% of the total overall energy input is used to melt the charge material (consisting of fresh batch and cullet), and 27% is lost in exhaust gases (Johnson et al., 2008; Khoshmanesh et al., 2007). The three primary contributors to waste heat losses are convective and radiative losses from the furnace walls, radiative losses from open ports and gaps, and flue/exhaust gas losses (Kozlov et al., 1985; Plodinec et al., 2005; Sardeshpande et al., 2007). Fig. 4 illustrates R/R heat use in an example furnace; here, only 27% of the energy input is expended in the exhaust gases, and 18% is lost through the walls. While the profusion of R/R furnaces helps the glass industry reduce the heat wasted in exhaust gases, they only capture a portion of the waste heat, leaving some potential for improvement.

While already common, R/R furnace efficiency can improve with advanced materials and better material design choices. Regenerators (for heating combustion gases) must have both high and low thermal conductivity materials (to maximize heat transferred to incoming gases and minimize heat transfer through the walls). Also, they must be able to resist chemical attack from exhaust gases, resist creep deformation and have low thermal expansion. Recuperators are lower cost than regenerators (not requiring ceramic materials) but have a lower heat recovery. Further R&D into high-temperature and corrosive resistant alloys or thin films could help increase thermal efficiency.

The use of regenerative systems is specifically limited by availability and the ability of the designer to accommodate changes in the system design parameters (e.g., system size, cost, life, and maintenance (Beerkens, 2009; Ross et al., 2004; Rue et al., 2007; Sardeshpande et al., 2011; Worrell et al., 2002)) as installation of these systems requires a furnace rebuild (Kobayashi et al., 2007). Current regenerator designs can suffer from blockages: the exiting flue gas contains a substantial amount of dust, which deposits along the exhaust gas path. Additionally, air leaks limit regenerator efficiency, reducing the exhaust gas temperature and altering the chemical composition. Like with all harsh environment WHR systems, the material used in the WHR system is key (Sardeshpande et al., 2011). It must have a high heat capacity and heat transfer coefficients. Moreover, it must be resistant to extreme temperatures, abrasion, inhibit dust accumulation, and resist the actions of alkaline gases and volatiles within the exhaust gases. Ceramic materials in regenerator checkers and walls could increase regenerator efficiencies, reduce problems with blockages, reduce maintenance requirements, and increase life expectancy.

Material concerns are also the primary limitation for recuperator system design. Recuperators, like regenerative systems, use exhaust gases to heat combustion air, cannot be installed after furnace installation and are limited by design materials. They require advanced materials, with good convective and radiative heat transfer properties, to operate effectively at high temperatures. Development of better temperature and corrosion-resistant metallic materials would enable high-efficiency devices, permitting a larger temperature drop in the exhaust gases, enabling more extraction of sensible heat. Developing such devices requires extensive research; and, once they are commercially available, they will likely have high production and machining costs (Maziasz et al., 2007; Sharma et al., 2014).

Batch and cullet preheating can directly (moving the charge material though counter-flow exhaust gases) or indirectly (using a parallel plate heat exchanger) heat glass charge materials. As with other preheating systems, this saves fuel by reducing the heat required to reach the process temperature. In addition to the WHR limitations of high capital and maintenance costs, glass heating introduces additional design issues (i.e., batch to cullet ratio, cullet composition, dry batch trapping) and the technology has not been proven for all glass compositions. Finally, like all high temperature process heating systems, exhaust gas can generate steam or electricity. This has a high potential in the glass industry due to the relatively high heat, but they are not often employed due to poor economics. Steam or electricity generation can also use exhaust gases from a regenerator, but it still has a high cost and is unproven for glass production exhaust gases containing particulates.

4.3. Aluminum industry

There are currently more than 300 aluminum production plants in the U.S., which consume about 226 TWh, of which, 5.3 TWh can be recovered from waste heat per year (Johnson et al., 2008). Aluminum production utilizes two different methods: refining from bauxite and recycling. The primary production method, refining aluminum from bauxite, relies on electrolytic cells that are very energy-intensive. Recycling aluminum scrap and aluminum metal received from primary productions plants, the secondary aluminum production method and focus of this section, requires only one-sixth of the energy that the primary method requires. Aluminum scrap includes new scrap (created in aluminum processing steps) and old scrap (disposed of at the end of life). Scrap is first preheated to dry and remove any contaminants and then sent to an aluminum melting furnace, in which it is melted and impurities are removed through fluxing (Johnson et al., 2008). As seen in Fig. 5, while there are three major sources of heat loss, the majority (nearly 65%) is lost as heat in the flue gas.

Like with steel melting furnaces, recuperators can transfer heat from the flue gases to preheat combustion air. This reduces the fuel needed to heat the air, saving energy, increasing the efficiency by

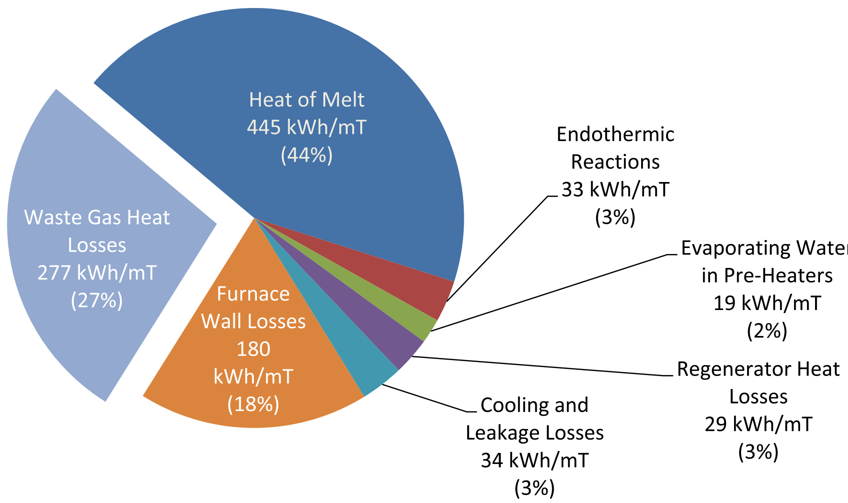

Fig. 4. Example heat analysis for a R/R glass furnace (Beerkens, 2009).

20–30%. This widely used method also has very high maintenance costs due to corrosion and overheating. A less common, but more efficient method uses a regenerative burner – a more complex recuperator system utilizing two burners, that alternate between firing and exhausting gases to the preheat the others' inlet air. This system is more expensive and very difficult to retrofit, but still can have a short payback period. Systems can also use flue gases to preheat charge materials, reducing moisture and volatile organic compounds before entering the furnace and reducing energy use by 20–35%. Again, this type of system is difficult to retrofit and has a high capital cost. Additionally, it is best suited for low variability, continuous furnaces and can result in difficulties with product quality control.

Finally, waste heat can generate steam in a boiler; this method is easy to retrofit, but only useful in facilities that need hot water, steam or to generate electricity. Electricity generation can yield significant amount of electricity, but only when the facility is melting aluminum and has significant capital and maintenance costs.

Dirty gases and very high temperatures associated with aluminum melting furnaces hinder the ability to add waste heat recovery and further complicate the aluminum production process.

Capital and maintenance costs of WHR methods used in aluminum melting are often very high. Particle remnants from dirty gases also add potentially significant cleaning costs (Das, 2007; Johnson et al., 2008).

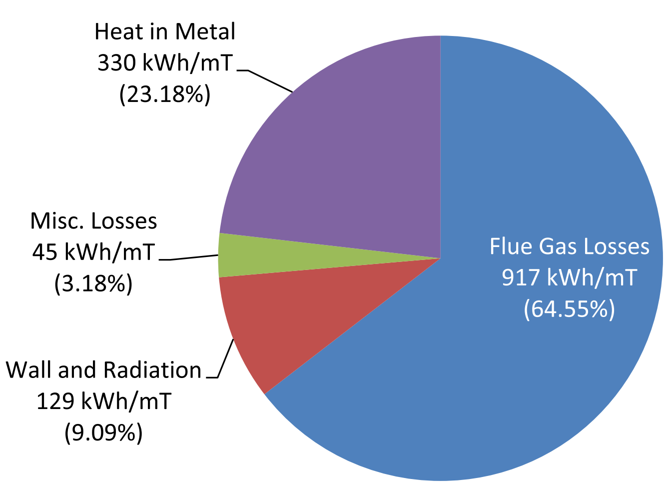

Fig. 5. Example heat analysis for an aluminum melting furnace (Keiser et al., 2007).

Economic feasibility is application-specific: some recovery methods work well with specific furnaces, but not with others (Das, 2007).

Most WHR methods only recover a portion of the waste heat for process use. In many cases, such as preheating combustion air, less than half of the sensible heat is recovered (Das, 2007; Johnson et al., 2008).

It is difficult to retrofit heat recovery systems onto existing installations (Johnson et al., 2008).

It may not be possible to use reliable and long-life (>2 year) systems in situations where the scrap quality, size, and composition vary considerably (Johnson et al., 2008).

4.4. Cement-lime industry

The U.S. produced about 77.8 million tonne (metric ton) of cement and about 19.0 million tonne of lime in 2013 (United States Geological Survey, 2017b; 2017c). The cement and lime production processes are similar: both use fuel-fired kilns to process raw materials at high temperatures, and both are energy-intensive, continuous-production industrial processes. The specific energy use of cement and lime kilns varies depending upon the type of kiln, reactants, and fuel; energy use for cement kilns is between 798 kWh/tonne of clinker for a dry kiln with preheater and precalciner, and 2843 kWh/tonne of clinker for a wet kiln without preheater (Worrell et al., 2013). The kiln's energy use is approximately 74% of the total energy required to produce cement. (Das, 2007; Madlool et al., 2013). With such substantial energy expenditures, the possible reduction and recovery of the energy lost (potentially 95 TBtu/year) within such processes is an appealing prospect.

As with many process heating systems, exhaust gas losses compose a significant fraction of the energy input. Fig. 6 shows an example energy distribution for a 6364 tonne/year capacity, 5.5 m diameter, 66 m long rotary cement kiln (Ari, 2011). A similar heat distribution of a 24 tonne/day shaft lime kiln (Gutiérrez et al., 2013) is shown in Fig. 7. These two figures together illustrate the similarities between the cement and lime processes, with most of the heat being lost in the formation of either clinker or quicklime and from the kiln exhaust gas.

Nearly all dry process cement and lime kilns preheat the charge material with exhaust gas via a series of suspension preheaters, called cyclones, that drop the incoming solids through the exhaust gases before they enter the kiln (Hasanbeigi et al., 2012). The primary barrier for preheaters is capital expense, although charge material preheating reduces the operating cost of a kiln, the initial cost has been estimated at $25–155/ton annually, depending upon the kiln setup before installation (Worrell et al., 2013). Also, as with other harsh environments, the environment in which preheaters operate is abrasive and the exhaust gases likely contain corrosive species (primarily sulfur). Thus, the temperature drop must avoid condensation of these chemicals, limiting the potential heat recovery. Exhaust gas heat can also remove moisture from fuel coal, improving the heating value and available heat. However, these systems are uncommon, can be difficult to design, and may not be economically viable.

Beyond preheating the charge material, hot clinker from cement kilns can also be used to preheat combustion air or air for the precalcinators, improving thermal efficiency and throughput. For lower temperature lime kilns, regenerators or recuperators can preheat the combustion air or fuel; these are more expensive, cannot create some types of lime (i.e., hard burnt), and may increase dust accumulation within the kiln. Additionally, these systems can suffer from excessive fouling, poor quality product, or require a new furnace or furnace rebuild to install.

Lastly, the heat from exhaust gases can generate steam (or electricity). As with the other industries explored, this has a high potential for heat recovery but incurs high capital and maintenance costs and will only generate low pressure steam.

Many common barriers exist among WHR technologies used in the cement and lime industries, with several problematic technologies shared among the various possible WHR methods. For example, nearly all WHR use a heat exchanger, and fundamental material and design challenges limit the effectiveness of these devices in such harsh environments. Material limitations include surface degradation from chemical wear and ablation, high temperatures, and fouling concerns. Designs must consider structural and infrastructural challenges, such as siting, size, feed material, kiln type, and fuel type. Additionally, the large amounts of particulates in cement and lime kiln exhaust gases tend to inhibit heat exchangers and reduce efficiency. Finally, the low payback of these systems would be a challenge for any novel project, especially ones that require the materials and design considerations of these systems.

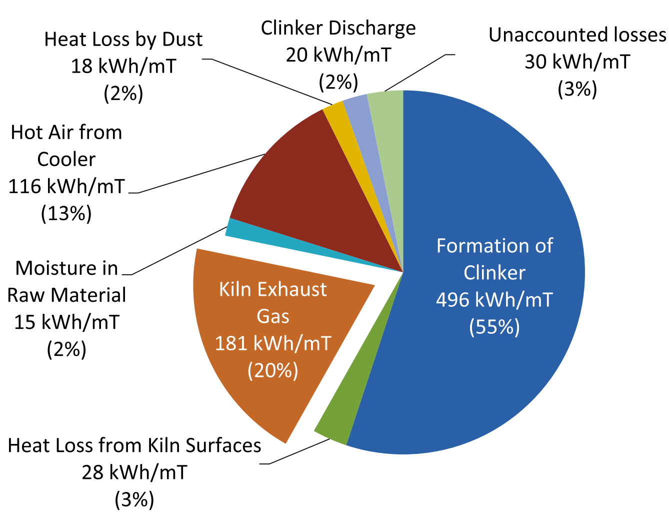

Fig. 6. Example heat distribution of a rotary cement kiln (Ari, 2011).

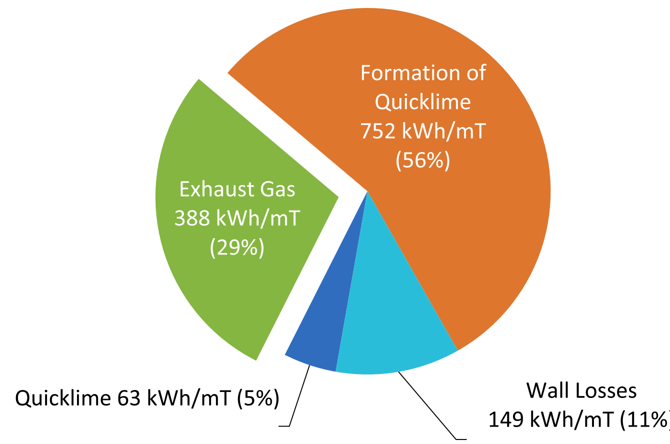

Fig. 7. Example heat distribution of a rotary lime kiln (Gutiérrez et al., 2013).

4.5. Summary

The results from estimating the recoverable waste heat from harsh environments are given in Table 4 and a summary of the advantages and disadvantages of WHR systems and their applicable industries is given in Table 5.

6. Conclusions

This paper estimates the potential for WHR and outlines the barriers to WHR installation in harsh environments for five major industries. Attempts to recover heat from gases in harsh industrial environments have largely been unsuccessful due to the limitations of available equipment and technologies. The research questions that this paper answers include: "What's the potential for industrial WHR from high-temperature harsh environments in the U.S.? What are the advanced and emerging technologies and materials available for recovering high temperature waste heat? What material and design issues limit the potential of WHR from high-temperature harsh environments? What are the research and development needs?"

This work has shown that the most potential lies within steel blast furnaces (46 TWh/year). Other waste heat streams considered include steel EAF (14.1 TWh/year), flat glass (3.6 TWh/year), container glass (5.7 TWh/year), glass fiber (1.1 TWh/year), specialty glass (2.2 TWh/year), aluminum melting furnaces (4.7 TWh/year), cement (17.1 TWh/year), and lime (10.5 TWh/year).

The following cost, material and operating issues significantly hinder industry's ability to utilize the heat in exhaust gases in harsh environments:

- Only a portion of the waste heat is recoverable.
- Retrofitting is often difficult or not possible.
- Safety issues arise from chemical reactions in harsh environment (e.g., toxic compound formation).
- Maintenance issues caused by particulate build up and corrosion add to operational costs.
- Efficiency and reliability degrade from harsh environment.
- Improving materials to resist the unique stresses of harsh environments, including large temperature swings and chemical corrosion requires further R&D.
- High capital cost of WHR systems limits practical installation potential

The technologies used for high-temperature and ultra-high

Table 4
Recoverable waste heat from various sources with harsh environment in five major industries.

Industry	Waste heat source	WHR technology/system status	Production[b] (MM tons/year)	Waste heat recovery potential TWh/year[a]			Exhaust gas flow
				Sensible	Chemical	Total	
Steel	Blast furnace gases	Available and widely used–partial WHR	25.4	3.8	42.31	46.1	Constant
	EAF exhaust gases	Available, not widely used–partial WHR	49.64	6.15	7.89	14.05	Varying
	Basic oxygen process	Available, not widely used–partial WHR	29.16	1.2	6.83	8.03	Varying
Glass	Flat glass	Available for air-fuel combustion only and widely used–partial WHR[c]	5.00	3.63	Negligible	3.63	Constant
	Container glass	Available for air-fuel combustion only and widely used–partial WHR[c]	10.00	5.7	Negligible	5.7	Constant
	Glass fiber (all types)	Available for air-fuel combustion only and partially used–partial WHR[c]	3.00	1.07	Negligible	1.07	Constant
	Specialty glass	Available for partial WHR but rarely used	2.00	2.23	Negligible	2.23	Constant
Aluminum	Al melting furnaces (fuel fired)	Available, not widely used–partial WHR	10.00	4.7	Small - site specific	4.7	Constant
	Anode baking	Available but NOT demonstrated	2.22	0.55	Small - site specific	0.55	Constant
	Calcining	Available but NOT demonstrated	Data not currently available				
Cement (Clinker)	Cement kiln exhaust gases from modern clinker making operation	Available, not widely used–partial WHR	76	17.15	Negligible	17.15	Constant
Lime	Lime kiln exhaust gases based on commonly used rotary kiln type operation	Available, not widely used–partial WHR	18.3	10.45	Negligible	10.45	Constant
Total (TWh/year) = 113.6							

[a] For a few waste heat sources (particularly in steel, aluminum, and glass industries), a small quantity of waste heat is already being recovered.
[b] Production data for steel industry are from 2016, glass industry 2002, aluminum industry 2012, and cement and lime industry 2016.
[c] WHR technologies currently not available/used for oxy-fuel fired systems.

Table 5
Advantages and disadvantages of WHR systems for various industries.

Equipment	Explanation	Applicable Industries						Advantages	Disadvantages
		S-BF	S-EAF	Al	G	C	L		
Recuperator	Heating combustion gases (air or fuel)	X		X	X		X	• Less maintenance costs (than glass regenerator) • Lower capital cost than other WHR systems	• Increased maintenance costs • Buildup/fouling • Corrosion • Overheating • Requires selective feed
Regenerator	Heating combustion gases (air or fuel)				X		X	• Work well with large process heating systems like glass melting furnaces	• Requires high temp materials • High capital costs • High maintenance costs (fouling) • Difficult to retrofit/must rebuild
Preheating	Preheating charge material		X	X	X	X	X	• Increase productivity • Can reduce dust (EAF) • Can be added with other WHR systems • Can reduce emissions (Glass)	• Requires selective feed • High capital costs • Safety issues • Physically large system • Difficult to retrofit/must rebuild • High maintenance costs (fouling) • Works best for static systems • Product quality issues
Steam Generation	Steam Generation for process steam or electricity			X	X	X	X	• Provides steam or electricity • Easy to retrofit • Can be added with other WHR systems • Can use exhaust gas from other WHR systems	• High capital costs • High maintenance costs (fouling) • Process must be on • Produces low-pressure steam

(*continued on next page*)

Table 5 (*continued*)

Equipment	Explanation	Applicable Industries						Advantages	Disadvantages
		S-BF	S-EAF	Al	G	C	L		
Top Gas Recovery	Use exhaust gas as a fuel and power turbine using pressure of exhaust gas	**X**						• High reliability • Abrasive resistant	• High maintenance costs • Scrubber wastewater
Regenerative Burners	Two burners that alternate firing and venting exhaust gas to heat other			**X**				• Relatively higher thermal efficiency compared to recuperators	• High capital costs • High maintenance costs (fouling) • Difficult to retrofit/must rebuild
Fuel Drying/ Preheating	Pass exhaust gases over coal fuel					**X**			• Only used for coal • High costs • Difficult to design & operate
Clinker Cooling	Cool clinker by heating combustion air					**X**		• Increase productivity	• May alter product quality and kiln emissions

*S–BF =Steel- Blast Furnace, S-EAF =Steal- Electric Arc Furnace, Al = Aluminum, G = Glass, C = Concrete, L = Lime.

temperature ranges need significant improvement to offer better performance and longer lives. Recommended improvements include:

- Use of advanced materials to improve heat transfer performance, increase performance life, and/or reduce maintenance cost
- Design changes to enable survival in harsh conditions for different or previously untested applications
- Design changes to offer higher thermal efficiency with a smaller physical footprint or size
- Cost reduction through better design and manufacturing techniques
- Improved seals to reduce maintenance and/or extend seal life

Despite the existing barriers, it is essential that industry advance its WHR technologies to exploit the large amounts of lost energy associated with these gases. Advanced WHR research and technology development has enormous potential to reduce energy and costs by making use of the energy in gases that are currently a problem. However, more work must be conducted to firmly establish which WHR technologies and advancements could result in the highest WHR potential realized, to give a direction to advanced materials and design research and development.

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Appendix A. Supplementary data

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