Capturing the Invisible Resource: Analysis of Waste Heat Potential in Chinese Industry

Hongyou LU ^{a1}, Lynn PRICE ^a, Qi ZHANG^b

^a Energy Technologies Area, Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

^b SEPA Key Laboratory on Eco-industry, Northeastern University, Shenyang, Liaoning, China

Abstract

Waste heat recovery and utilization represents a missed opportunity to reduce China's total energy use, decrease carbon dioxide emissions, and improve air quality. Currently, China does not have a standardized or transparent methodology to quantify the waste heat potential in the industrial sector, which accounts for more than two thirds of China's primary energy consumption. This paper presents the results of thermal energy modeling to quantify the technical maximum waste heat potential in three energy-intensive industrial sectors: cement, iron and steel, and glass. In addition, this paper identifies the practical potential for producing electricity from waste heat in these sectors. The analysis finds that the glass sector has the highest waste heat to power generation potential per unit of production basis among the studied sectors. This paper provides key principles for managing waste heat in the industrial sector and key sector characteristics for implementing waste heat to power generation technologies.

Key words: waste heat potential; waste heat to power generation; industry; China.

1. Introduction

Many industrial processes generate unused or waste heat during manufacturing. Depending upon a number of factors, such as industry characteristics, fuel inputs, and operational practices, industrial waste heat accounts for 10% to 50% of total fuel consumption in various industrial sectors. Waste heat can be a valuable energy source if it is managed well. Through waste heat utilization, waste heat can be used to provide electricity, steam, space heating, and hot water.

In China, the potential to improve industrial waste heat management is significant. The industrial sector is the largest energy consumer and carbon dioxide (CO₂) emitting end-use sector in China, representing about 70% of China's total primary energy use and energy-related

¹ Hongyou Lu: 1 Cyclotron Road, Mailstop 90R2121, Berkeley, CA 94702. Email: hylu@lbl.gov

CO₂ emissions in 2012 (NBS, 2013a; IPCC, 2006). In addition, coal is the dominant fuel supply in Chinese industry, accounting for about 71% of total fuel use in 2012 (NBS, 2013a). The industry sector is one of the most important sectors to address in order to reduce air pollutants, such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter, in China. Improving waste heat utilization in China's industry sector not only can reduce overall coal consumption but also can provide significant environmental and public health benefits.

Improving waste heat utilization supports China's targets related to energy and emissions. On November 12, 2014, in a joint statement with the United States, China announced its intention to peak CO₂ emissions around 2030 while striving to peak earlier (The White House, 2014). Achieving this goal will require China to install an additional 800 to 1,000 GW of zero-emission electricity generation capacity by 2030 (Podesta and Holdren, 2014). The growth of coal consumption is also targeted to decrease, as China set a goal of reducing the share of coal in total energy consumption to below 65% by 2017 (China State Council, 2013). In the 12th Five-Year Plan (FYP) for 2011-2015, China is expected to reduce the national energy intensity (energy use per unit of GDP) and carbon intensity (CO₂ emissions per unit of GDP) by 16% and 17%, respectively, from the 2010 level (China State Council, 2012).

1.1. Why this study is needed?

The concept of waste heat as a resource is similar to the concepts of oil reserves or wind power resources. However, the industrial waste heat resource is much more fragmented than other energy sources. The waste heat resource is dispersed geographically at the industrial plant level. Also, the supply and reliability of waste heat may fluctuate over time, mainly due to changes in industrial production or mismatches between supply and demand. In addition, the temperature and composition of the waste heat carrier streams varies from site to site.

There is a general consensus on the significance of the waste heat potential in industrial sectors. However, the literature on this topic reports minimal waste heat potential in only a few sectors in China, such as the cement sector. Technical analysis of waste heat potential of a full array of energy-intensive sectors in China does not exist at this time. More importantly, for those studies that have been conducted, the reported waste heat utilization potential is often presented without a clearly explained methodology. The use of vague and inconsistent methodologies across different sectors significantly impairs the ability of researchers, investors, or policymakers to accurately understand the reported waste heat potential.

This paper aims to fill the research gaps by identifying the available waste heat potential in key energy-intensive sectors in China through the use of a consistent and transparent methodology. Specifically, this paper focuses on waste heat to power generation and the primary objective is to analyze the technical potential of waste heat in three sectors: cement, iron and steel, and glass. In the sections below, the paper first summarizes the methods used for the technical potential analysis. Then, data, assumptions, and results are presented on the waste heat potential in the three sectors, including both the waste heat potential and the potential to produce electricity from waste heat. Lastly, this paper summarizes key technical findings, identifies research limitations, and describes needs for future research.

1.2. Review of international studies on waste heat potential

From a whole-society, whole-system perspective, in 1971, Earl Cook estimated that about 50% of the energy input to the U.S. society was lost as waste heat (Cook, 1971). This included energy losses from all sectors, such as power generation and industrial manufacturing. This study highlighted the need to understand the potential of waste heat. A later study conducted by the US Environmental Protection Agency (EPA) relied on EPA's National Emissions Data System, which collected stack temperatures from industrial sources, including boilers, internal combustion devices, and industrial processes (US EPA, 1984). The study found that about 30% of industrial input was lost as waste heat in 1974, and about 3% of the waste heat is available for recovery (at a temperature higher than 150° C (300° F)). However, this study used the stack temperature (from the emission database) instead of the exhaust gas temperature exiting the equipment. Stack temperature is normally much lower than exhaust temperature; thus, the findings of waste heat potential may very likely be underestimated.

Besides the studies conducted about 30-40 years ago (US EPA, 1984; Cooke, 1971), the United States Department of Energy (US DOE) and the Pacific Northwest National Laboratory (PNNL) conducted waste heat potential analyses in 2004, 2006, and 2008 (Energetics and E3M, 2004; PNNL, 2006; US DOE, 2008). The 2004 study identified key areas for improving energy efficiency and reducing energy losses in the US manufacturing sectors. Based on approximate assumptions on energy efficiency and improvement potential, it estimated about 20-50% of heat was lost (Energetics and E3M, 2004). The 2005 study conducted by PNNL focused on opportunities for recovering energy from chemical emissions and thermal emissions, such as the chemical energy in unburned carbon dioxide and methane (PNNL, 2006).

The latest waste heat potential study conducted by US DOE was in 2008. This study analyzed the technical potential based on an enthalpy analysis, taking into account energy inputs, temperatures, and heat recovery practices. The study found the waste heat practical potential in aluminum, iron and steel, glass, cement, metal casting, boilers, and ethylene furnaces to be 5%, 6%, 23%, 11%, 33%, 6%, and 5%, of the energy use of that sector, respectively (US DOE, 2008).

Most recently, Oluleye et al. (2015) developed a methodology to identify waste heat potential in industry. This study illustrated the methodology by using a case study from a refinery. It would be useful for policy makers and other researchers if this methodology could be applied to other industrial sectors, regions, or countries using actual industry, regional, or country data and information. Miró et al. (2015) collected industrial waste heat data from 33 countries and 6 sub-regions. The study identified that there is a lack of specification when reporting industrial waste heat data, which made data comparison of industrial waste heat potentials across countries difficult. This paper also recognized that there is a lack of data on industrial waste heat potential in Asian countries, especially China. While this paper's intention was not to estimate the industrial waste heat potential of a specific industry or country, it did provide recommendations on how the data should be reported, i.e., including the type of industrial waste heat potential, the methodology for calculating industrial waste heat potential, reference temperatures, year of data used, liquid or gas state of industrial waste heat, and boundaries

and scope of studies on industrial waste heat. Brückner et al. (2015) provided an overview of industrial waste heat potential, including definitions, main technologies, possible industrial waste heat sources, and temperatures of waste heat. This paper focused on an economic analysis of waste heat recovery technologies (including absorption chillers, electrical heat pumps, and absorption heat pumps) and estimated the maximum acceptable investment costs of each technology assessed. However, this analysis did not evaluate industry-specific potential or provide any discussion of the potential in China.

Besides governmental and research organizations, consulting companies also published estimations of waste heat potential. Frost & Sullivan (2010) estimated the potential of waste heat in the United States. This study showed a much higher percentage of heat being wasted in the studied sectors, on average about 20%, 49%, 40%, and 19% in aluminum (primary), oil refining, steel, and pulp and paper sectors, respectively (Frost & Sullivan, 2010). However, the methodology used to estimate the waste heat potential is not clearly described in the report.

The Norwegian utility Enova published a study in 2009 to assess the “usable waste heat potential” of the Norwegian industry by sending out questionnaires to 105 energy-intensive companies including the food processing, wood processing, cement and building block processing, chemistry, aluminum, and ferro alloy industries. Together, these companies represent about 63% of the Norwegian final energy consumption. The study received about 69% responses (72 companies out of 105 companies answered). The study reported that for metal production, basic chemistry, and processing of stone and earth, the waste heat (temperature at or above 140° C) potential of the final energy use is estimated to be 30%, 8%, and 40%, respectively (Sollesnes and Helgerud, 2009).

In Germany, two-thirds of final industrial energy use was used to produce process heat in 2007. Based on a Norwegian study’s findings of percentages of waste heat potential in certain industries (Sollesnes and Helgerud, 2009), researchers in Germany estimated that the techno-economic potential of waste heat (at a temperature above 140° C) in Germany is higher than 12% of the annual industrial energy use (Pehnt et al., 2011). The potential for medium-low temperature waste heat (60° C – 140° C) is estimated to be 6% of total industrial energy use in Germany (Pehnt et al., 2011).

These studies were conducted for different purposes and for different countries (e.g., the United States, Germany, Norway) but all found a significant industrial waste heat energy-savings potential. Depending on different manufacturing processes, fuel types, and technologies adopted, the waste heat potential could be as low as 3% to as much as 50% of total energy input (Table 1). This review of these studies highlights the need to establish a standardized methodology that can incorporate sector-level specifics, such as energy inputs, technology efficiency, and exhaust temperatures into the analysis.

1.3. Review of Chinese studies on waste heat potential in China

There are very few studies of industrial waste heat potential in China. The Energy Research Institute (ERI) of China conducted the most comprehensive study in 2011, which investigated

waste heat potential through questionnaires and field research. This study analyzed seven industrial products including cement, steel, glass, ammonia, caustic soda, calcium carbide, and sulfuric acid. It found that the waste heat potential ranged from 15% to 40% of the total fuel input, depending on the studied product/sector (ERI, 2011). Compared to many other reports and articles on China's waste heat potential, this study was one of the most comprehensive. However, it still relied heavily on self-reporting, assumed percentages for recovery rates, and assumed waste heat potential per unit of production.

Lu (2010) provided estimates of additional waste heat to power capacities in the cement, glass, iron and steel, chemicals, and non-ferrous metals sectors in China. Zhou (2012) provided information on estimated waste heat potential in seven sectors in China, but without a clearly explained methodology. Dong (2013) summarized the current status of waste heat utilization in industrial sectors based on a literature research, but did not provide analysis of the waste heat potential.

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Reviewed literature	Scope	Methods	Findings	Limitations
Cook (1971)	All sectors in the US, including energy production, transmission, distribution, and end-use sectors.	Comparing energy input of the whole society to end-use energy consumption	About 50% of energy inputs lost as waste heat	Lack of sector-specific details; conducted over 40 years ago
US EPA (1984)	Industrial sectors and power generation in the United States, such as boilers, internal combustion devices; industrial processes.	Based on US EPA emission database and stack temperature	About 30% of industrial inputs lost as waste heat; about 3% could be recovered at a temperature above 150°C (300°F)	Final exhaust temperature may be lower than furnace exit temperatures; conducted over 30 years ago
Energetics and E3M (2004)	Energy-intensive sectors in the US, including mining, chemicals, petroleum refining, forest products, iron and steel, food, and cement sectors.	Based on assumptions of thermal energy efficiency and improvement potential	About 20-50% of energy was lost in studied sectors	Lack of detailed waste heat analysis; based on assumptions of efficiency and improvement potential
PNNL (2006)	Focused on chemical and thermal emissions from industrial processes (such as chemical, glass, and cement) in the US	Survey of existing literature to determine the amount of energy embedded in the emissions	Non-CO2 greenhouse gas emissions in industry represented about 4.3% of total energy used in the US industry	Focused on chemical energy content in emissions; lack of detailed analysis of waste heat potential
US DOE (2008)	Aluminum, iron and steel, glass, cement, metal casting, boilers, and ethylene furnaces in the United States	Enthalpy analysis based on energy input and waste heat temperature	Practical potential of waste heat ranges from 5 to 33% of total energy input in industrial sectors	Lack of economic analysis; Lack of real-world assumptions on waste heat to power conversion
Sollesnes and Helgerud (2009)	Food processing, wood processing, cement and building block processing, chemistry, aluminum, and Ferro alloy industries in Norway	Questionnaires to 105 energy-intensive companies (response rate: 63%)	About 30%, 8%, and 40% of waste heat potential ($\geq 140^{\circ}\text{C}$ or 284°F) in metal production, basic chemistry, and processing of stone and earth sectors, respectively	Industry self-reporting; lack of standardized and transparent methodology
Frost & Sullivan (2010)	Aluminum, oil refining, steel, and pulp and paper sectors in the United States	Unclear	About 20-50% of energy input being wasted as heat in the studied sectors	Consulting report; Unclear methodologies; Lack of analysis on practical technical potential
Pehnt et al. (2011)	Energy-intensive sectors in Germany, such as metal production, basic chemicals, commercial paper, food processing, processing of stone and earth, and glass and ceramics.	Assigning percentages of waste heat potential based on previous studies and author opinions	Waste heat potential ranges from 3% to 40% depending on manufacturing sectors	Based on other country's studies; lack of in-country analysis; lack of standardized methodology
Brückner et al. (2015)	Overview of industrial waste heat potential; economic analysis of three waste heat recovery technologies	Economic analysis on payback time and return on investment	Estimated the maximum acceptable investment costs of each technology assessed	Did not evaluate industry-specific potential or provide any discussion of the potential in China
Miró et al. (2015)	Collected aggregated waste heat potential from 33 countries and six sub-regions	Data collection, literature review	Recommendations on industrial waste heat potential studies	Limited data for Asian countries, especially for China
Oluleye et al. (2015)	Modeling of four types of waste heat recovering technologies; and a case study from a refinery plant	Modeling of four waste heat recovering technologies	Identify ways to maximize site energy efficiency while recovering industrial waste heat	Limited application of the methodology in different sectors or different countries

Table 2. Chinese Studies on Waste Heat Potential

Reviewed literature	Scope	Methods	Findings	Limitations
Lu (2010)	Waste heat to power capacities in cement, glass, iron and steel, chemicals, and non-ferrous metals sectors.	Literature review and author estimation	Estimated additional waste heat to power capacities in selected sectors	Lack of analysis on waste heat potential
ERI (2011)	Energy intensive sectors in China, including iron and steel, cement, glass, ammonia, caustic soda, calcium carbide, and sulfuric acid.	Questionnaires and onsite field research	Waste heat potential is about 15-40% of total fuel input in the selected industries	Based on specific energy intensity and assume percentages of waste heat; did not consider waste heat to power penetration rates
Zhou (2012)	Seven energy-intensive sectors in China, such as cement, iron and steel, and ammonia.	Unclear	Waste heat potential is about 10-50% of total fuel input; 54% of waste heat is medium-low temperature (<400°C, or 752°F)	Unclear methodology; lack of sectoral detailed analysis
Dong (2013)	Iron and steel, non-ferrous metals, chemicals, buildings materials, and light industries in China	Literature review	Current waste heat utilization status in the studied sectors	Lack of analysis on waste heat potential

2. Methods and Data Sources

2.1. Thermal energy modeling

A thermal energy-modeling tool was developed to estimate the technical potential for waste heat utilization. The method used in the model is thermal enthalpy analysis, as shown in Equation (1), which takes into account fuel inputs, combustion conditions, exhaust gas temperatures, reference temperatures, and types of technologies (US DOE, 2008).

$$E_{waste\ heat} = (m_{exhaust\ gas}) \times \sum_i (x_i \times h_i(t)) \quad (1)$$

where:

$E_{waste\ heat}$: thermal energy in waste heat

$m_{exhaust\ gas}$: mass flow of exhaust gas

i : species of gases in the exhaust gas

x_i : mass fraction of gas i in the exhaust gas

$h_i(t)$: enthalpy of gas i in the exhaust gas at temperature difference of t

t : temperature difference between the exhaust temperature and the reference temperature

Waste heat potential can be quantified by multiplying the mass flow rate of the exhaust gas with the enthalpy of the exhaust gas, as indicated in Equation (1). The mass flow rate of the exhaust gas can be determined by fuel consumption and combustion equations. The enthalpy can be determined by comparing the exhaust gas temperature to a reference temperature. This analysis used two reference temperatures; thus, two levels of waste heat potential are calculated: 1) a **theoretical maximum waste heat potential**, reducing the temperature of the waste heat to ambient temperature (25°C [77°F]) and capturing all possible thermal energy in the waste heat, and 2) a **practical waste heat potential**, reducing the temperature of the waste heat to 150°C (300°F) and capturing a significant portion of the thermal energy.

Based on the thermal energy potential of waste heat, this analysis also determined **three levels of waste heat to power generation potential**, varying in its efficiency of converting thermal energy into electricity: 1) “**power generation at current efficiency**”, representing the most practical amount of power that could be produced, based on the practical waste heat potential and current (real-world) power generation efficiency; 2) “**power generation approaching Carnot Efficiency**”, referring to a theoretical situation where the practical waste heat potential is converted to power at the rate of Carnot Efficiency (Carnot Efficiency determines the maximum amount of power that could be produced theoretically); and 3) “**power generation approaching Carnot Efficiency with max heat recovery**”, referring to a theoretical situation where the maximum waste heat potential is converted to power at the rate of Carnot Efficiency. Based on expert interviews and a 2004 report (Energetics and E3M, 2004), this study assumed in practice about 20% of the waste heat potential can be converted to electricity.

The predominant fuel input in Chinese industries is coal. Given the complexity in coal composition and coal types, this analysis assumed coal used in the studied industries has an average lower heating value of 5,500 kcal/kg (9,980 Btu/lb). This assumption is based on the most common purchased coal type in China and crossed check with the information found in Chinese cement plants (Price et al., 2009; LBNL and CBMA, 2012). Typical coal composition from China is used, i.e., 11% water content and 18% ash content (Wang and Li, 2001). In addition, this analysis also considered heavy fuel oil and used a typical lower heating value of 9,700 kcal/kg (17,470 Btu/lb). Lastly, this analysis assumed that there is about 3% oxygen remaining after the combustion process is completed.

2.2. Expert interviews

Expert interviews were conducted to cross check data inputs and key assumptions made in the modeling process. Key assumptions include exhaust gas temperatures and penetration levels of existing waste heat to power technologies in China. Interviewees were international energy experts, industry experts, professors, and researchers working in the field of cogeneration, the cement industry, the iron and steel sector, and in energy services consulting. Examples of interviewees are professors from Northeastern University in China and the University of Science and Technology - Beijing, cement experts from the China Cement Association, and U.S. experts specialized in cogeneration, steam systems, and process heating systems.

2.3. Cross-examination of data

Cross-examination methods were used to cross check the outputs from the thermal energy modeling. The methods used include comparing model outputs to reported Chinese data and comparing to the results from estimating the differences between the theoretical minimum energy intensity and the practical energy intensities of the various industries.

2.4. Data sources

Industrial energy use data in China mostly is provided in the *China Energy Statistical Yearbook* published by the National Bureau of Statistics (NBS) annually. Sectoral data, such as production by technology and by process, comes from sectoral yearbooks published by related industrial associations. Exhaust temperatures of current production processes as well as thermal efficiency and cost data for waste heat to power technologies are based on both literature review and interviews with industry experts in the U.S. and China. Penetration levels for current use of waste heat to power technologies relied on published government technology catalogues, industrial association surveys, interviews with experts, and literature research. Energy intensity levels for the studied sectors relied on the Chinese minimum energy efficiency standards (MEPS) for industrial products (AQSIQ and SAC, 2008; AQSIQ and SAC, 2012; AQSIQ and SAC, 2013).

3. How to Manage Waste Heat?

Similar to the general waste management principle of “Reduce, Recycle, and Reuse”, waste heat management should follow the principle of “Reduce, Recycle, and Recover” (Figure 1).

Sources of waste heat can be reduced through upgrading process equipment, reducing waste heat losses, and increasing system efficiency. Depending on the nature of the process and industry characteristics, industry can adopt measures such as combustion optimization, process controls, insulation improvement, minimizing openings, and implementing energy management systems. The goal is to reduce the release of waste heat as a by-product of manufacturing processes.

Waste heat can be recycled within the heating system for use in the manufacturing processes. Typically, waste heat can be used to preheat combustion air or make-up air, preheat fuel (in limited cases), and preheat charging materials. Due to its low investment cost and high energy-efficiency, it is commonly recommended to consider recycling waste heat for process use first.

Figure 1. Waste Heat Management

Recovering waste heat to produce steam is very common, as steam is a necessity for a number of manufacturing processes. A Heat Recovery Steam Generator (HRSG) is inexpensive and can be configured relatively easily with the process demands and existing operations. The properties of the waste heat, such as the temperature, volume, the availability of the waste heat, presence of any particulates in the waste heat, and chemical composition of the waste heat (such as corrosive gas compounds, condensable vapors, and combustible gases) are important when considering recovering waste heat for steam generation (Thekdi, 2011).

In addition, electricity can be produced from waste heat, through “waste heat to power generation” arrangements. One of the largest advantages of waste heat to power generation is that it produces a high quality energy product – electricity. Electricity can be used in all processes and different locations. However, waste heat to power generation is normally capital-intensive and much less energy efficient. Therefore, it is suggested that only when there are no other possible ways to utilize waste heat as heat (preheating, producing steam and/or hot water), waste heat to power generation can be considered.

The principle of “Reduce, Recycle, and Recover” is important for managing waste heat. This principle can improve the economic viability of waste heat utilization projects and tailor the

potential of waste heat to its best use. It serves as the foundation for waste heat potential analysis and implementation.

4. Waste Heat Potential Analysis

This analysis focused on three industrial sectors in China: cement, iron and steel, and glass. These three sectors were chosen because of their characteristics (see Table 3). Generally, sectors with high energy consumption have higher exhaust gas temperatures and, as a result, have more potential for capturing the waste heat. The complexity of the manufacturing process used within the sector may hinder the adoption of waste heat to power generation, so the current utilization rate of waste heat recovery plays an important role in determining the potential as well. Certainly, there are other manufacturing sectors such as chemicals, pulp and paper, and non-ferrous metals that could also be analyzed. However, this study focused on the cement, iron and steel, and flat glass sectors, each representing different waste heat utilization conditions.

Table 3. Characterization of Selected Sectors

Sector	Sectoral Total Energy Use	Exhaust Gas Temperature	Process Complexity	Heat Recovery Utilization Rate
Cement	High	High	Low	High
Iron and Steel	High	Medium-High	High	Low
Glass	Medium	Medium	Low	Low

The purposes of this analysis are to determine the technical potential of waste heat as well as to identify industry characteristics for implementation of easily-adopted and cross-sector waste heat to power generation technologies in China. Therefore, this analysis focused on already commercialized technologies, such as the Steam Rankine Cycle and the Organic Rankine Cycle, which can be applied to a number of energy systems and sectors. In other words, power generation technologies that are tailored to certain manufacturing processes such as Top Pressure Recovery Turbines for blast furnaces in iron-making, technologies that have not achieved wide adoption such as the Kalina Cycle or supercritical CO₂ cycle, or other emerging technologies such as thermoelectric generation and piezoelectric power generation, are not within the scope of this analysis.

The sections below discuss the analysis and findings for the three studied sectors, with a focus on data and assumptions used in the cement sector analysis. Details of data and assumptions used in the other two sectors can be found in the author's thesis (Lu, 2015).

4.1. Cement sector

4.1.1 Industry background

China has been the world's largest cement producer since 1986 (LBNL and CBMA, 2012). In 2012, China produced 2.2 billion metric tons of cement, represented 60% of global production

(USGS, 2014a). The cement industry is the third largest energy-consuming manufacturing sector in China, representing 12% of China's total manufacturing energy use, or about 5% of China's total energy use in 2012 (NBS, 2013a). In addition, China's cement industry is very fuel-intensive. From 2008 to 2012, about 90% of energy input was fuel while around 10% was from electricity (CCA, 2008-2014). Coal is the predominant fuel source in the Chinese cement industry, contributing around 97% of the fuel input.

There are two main sources of waste heat in cement manufacturing. The first one is the exhaust gas from the cement kiln, where clinker calcination takes place. The clinker making process is the most energy-intensive process in which the kiln feed is combusted at a high temperature, about 982 °C (1,800°F) in the calcination stage and the oxides react to form clinker at a temperature of 1,510°C (2,750°F) (US EPA, 1995). The exhaust temperature from the cement kiln can vary from 449°C (840°F) to 204°C (400°F), depending on the waste heat recovery technologies used (US DOE, 2008). The second main source of waste heat is from the clinker cooler. In this step, red-hot clinker is discharged from the kiln to the clinker cooler. It is then rapidly cooled from 1,093°C to less than 93°C (2,000°F to 200°F) by ambient air. The heated air not only cools the clinker but also recovers portions of the heat.

Energy contained in the exhaust gases from the kiln and the clinker cooler can be recovered and reused to provide valuable energy services, such as use for drying and preheating the kiln feed in preheaters, preheating secondary air in the kiln's combustion system, or preheating tertiary air for the precalciner. This analysis focuses on the waste heat from the kiln exhaust and the clinker cooler.

4.1.2 Data and key assumptions

As of 2012, a large majority of China's cement kilns are dry process rotary kilns, referred to as "New Suspension Preheater" (NSP) kilns in China. This technology includes rotary kilns with preheaters only, and rotary kilns with preheaters and precalciners. In 2012, NSP kilns represented 92% of total clinker production in China (CCA, 2014). As shown Table 4, about 37% of clinker was produced from NSP kilns larger than 4,000 metric tons of clinker per day (tpd). NSPs that produce 1,000-2,000 tpd accounted for another 36%. Small NSP kilns (<1,000 tpd) contributed to 15% of total clinker production.

Table 4. Clinker Production by Kiln Size in China (2012)

	% of total clinker production	Clinker Production (Mt)
Cement Sector	100%	1,328
NSP <1,000 tpd	15%	194
NSP 1,000 – 2,000 tpd	36%	473
NSP 2,000 – 4,000 tpd	5%	69
NSP > 4,000 tpd	37%	485
Non-NSP	8%	106

Source: CCA, 2014.

The General Administration of Quality Supervision, Inspection and Quarantine of China (AQSIQ) and the Standardization Administration of China (SAC) publish minimum energy performance standards (MEPS) for industrial products, which are updated periodically. The latest MEPS standard (GB 16780-2012) for cement was published in December 31st, 2012 and took effective on October 1st, 2013 (AQSIQ and SAC, 2012). This standard prescribed minimum energy performance levels (i.e., the maximum amount of energy could be used to produce one unit of production) for existing cement plants, minimum energy performance levels for newly constructed cement plants, as well as advanced international values. The minimum energy performance levels are provided for NSP kilns and broken down by kiln size.

As a mandatory standard, all existing cement plants are required to meet the minimum performance requirements, at least in theory. This study recognizes that the compliance rate of the MEPS standard may not be 100%; however, this study also found some cement plants (typically large and newer plants) report and/or have lower energy intensity levels than required by the MEPS. For these reasons, this study used minimum energy performance levels of the existing cement plants in the MEPS standard as an average energy intensity level for existing NSP kilns in 2012 (see Table 5). The energy intensities of non-NSP kilns (such as wet kilns and dry hollow kilns) used in this study are based on the investigation conducted by Lawrence Berkeley National Laboratory and the World Bank in 16 cement plants in Shandong Province, China in 2008 (Price et al., 2009).

Table 5. Energy Intensity of Cement Production by Size in China

Kiln type/ size	Fuel Intensity	Electricity Intensity
	(kgce/t clinker)	(kWh/t cement)
NSP < 1,000 tpd ^a	135	120
NSP 1,000 – 2,000 tpd ^a	130	115
NSP 2,000 – 4,000 tpd ^a	125	110
NSP > 4,000 tpd ^a	120	105
Non-NSP ^b	141	119

Source: a – AQSIQ and SAC, 2012; b—Price et al., 2009.

Note: NSP kiln intensity values based on the Chinese MEPS; non-NSP values based on field surveys.

Exhaust gas temperatures may vary, depending on a number of factors, such as types of kiln used, combustion controls, handling of materials, and the length of the kiln. This analysis assumed two exhaust temperatures for NSP kilns and non-NSP kilns, respectively. Based on expert interviews of international and Chinese experts in the field and literature research, it is assumed that the exhaust gas temperature for NSP kilns is around 338°C (640°F) and the exhaust gas temperature for non-NSP kilns is approximately 490°C (840°F) (US DOE, 2008; ERI, 2011; Harrell, 2014). Table 6 shows the estimated energy use and typical exhaust gas temperature by cement kiln.

Table 6. Fuel Use and Exhaust Temperature by Kiln Size (2012)

Cement Sector	Fuel Use (Mtce/yr)	Typical Average Exhaust Temperature	
		°F	°C
	170		
NSP < 1,000 tpd	26	640	338
NSP 1,000 – 2,000 tpd	62	640	338
NSP 2,000 – 4,000 tpd	9	640	338
NSP > 4,000 tpd	58	640	338
Non-NSP	15	840	449

4.1.3 Results

Based on the 2012 historical production data, more than a quarter (26%) of the fuel used in China's cement sector is released as waste heat and could be captured, at least theoretically. Medium to high temperature waste heat (>150°C [300°F]) represents about 13% of the fuel input, while low-temperature waste heat (below 150°C [300°F]) accounts for nearly another 13%, as illustrated in Figure 2.

Figure 2. Waste Heat Potential of the Cement Sector in China (2012)

The results showed that China's cement industry has a theoretical maximum waste heat potential of 41 GW_{Th}. About 10% of this potential, or 4 GW_e, can be converted to produce power, using today's commercialized technologies and real-world power generation efficiency. However, power generation potential could be doubled to 10 GW_e if the efficiency can be improved to be close to the Carnot Efficiency through advances in technologies, materials, and chemical properties. The theoretical maximum power generation potential could be increased

to more than 20 GWe if both the Carnot Efficiency and the maximum heat recovery are achieved. The remaining 49% of the waste heat potential is in the form of low-temperature (near ambient) waste heat (Figure 3).

Figure 3. Waste Heat to Power Generation Potential of the Cement Sector in China (2012)

China has been promoting waste heat to power generation in the cement sector since the 11th Five-Year Plan (2005-2010) through its “Ten Key Projects”, which includes “waste heat and waste heat utilization projects” as one of the ten government promoted energy-saving projects. By the end of 2010, 55% of China’s NSP kilns were equipped with waste heat to power generation, according to the central government’s planning report (MIIT, 2011b). It is reported that as of 2012, the penetration of waste heat to power generation reached to more than 70% (China Environment News, 2013). The current target for waste heat to power penetration in the cement sector is 75% by the end of the 12th Five-Year (2011-2015) (MIIT, 2011b). This means the currently available, untapped potential is much less, about 1 GWe, of practical electricity generation potential. However, the widespread adoption of waste heat to power technologies in the cement sector not only demonstrates the viability of the technology but also indicates the scalability of the application. Energy-intensive sectors that are similar to the cement industry may be able to replicate the successful example of adopting this energy-recovery approach. Table 7 summarizes the results of waste heat potential in the cement sector.

439 **Table 7. Waste Heat Potential in China's Cement Sector (2012)**

Cement Sector	Thermal Energy Potential (in the form of heat)		Electricity Potential (in the form of power)			
	Theoretical Waste Heat Potential	Practical Waste Heat Potential	Theoretical Power Generation Potential	Practical Power Generation Potential	Practical Power Generation Potential	Untapped Power Generation Potential
	[T _{ref} =25°C (77°F)]	[T _{ref} =150°C (300°F)]	[Theoretical Thermal Potential × Carnot Efficiency]	[Practical Thermal Potential × Carnot Efficiency]	[Practical Thermal Potential × Practical Efficiency]	[Practical Thermal Potential × Practical Efficiency × (1-Penetration Rate)]
	MW _{Th}	MW _{Th}	MW _e	MW _e	MW _e	MW _e
Potential	41,117	21,108	21,037	10,654	4,222	1,266

440

4.2. Iron and steel sector

4.2.1 Industry background

China is the world's largest iron and steel producer. In 2012, China produced 60% of global pig iron and 46% of global crude steel (USGS, 2014b). Iron and steel production is one of the largest energy sectors in China, with energy consumption accounting for 10-15% of total energy use and 15-20% of total industrial energy use (Ma et al., 2012). More than 96% of energy input in China's iron and steel sector comes from fuel, including coke, washed coal, and raw coal. The energy efficiency of China's iron and steel sector has improved over the last ten years while production has increased at a rapid rate, but the specific energy consumption of iron and steel sector is still 20% higher than international advanced levels (Ma et al., 2012).

China's current steel-making capacity has exceeded 1 billion metric tons, with a utilization rate of 70% in 2013 (MIIT, 2014). Overcapacity directly affects the prices of products as production has increased much faster than demand. This has led to low profit margins for small steel producers domestically and low-cost and low-quality products in the global steel market. Compared to domestic steel consumption, the net export of steel is still small (about 6% of total finished steel production was exported in 2012). However, given China's large production volume, a small percentage translates into a large absolute number, e.g., China's steel export was about 56 million metric tons in 2012, which is higher than the total steel production of Germany that year. Product quality is a weakness of China's iron and steel sector. According to the Chinese Ministry of Industry and Information Technology (MIIT), only 30% of the Chinese steel production achieved international advanced quality levels (MIIT, 2011c).

4.2.2 Data and key assumptions

Specific energy intensities by process and production data for China's iron and steel sector in 2012 were obtained from the 2013 *China Iron and Steel Yearbook* (Editorial Board of China Steel Yearbook, 2013). The *China Energy Statistical Yearbook* (NBS, 2013a) reported the recovered amount of coke oven gas, blast furnace gas, and basic oxygen furnace gas. In addition, this analysis took into account the current adoption rates of waste heat recovery technologies in this sector. Based on the estimated implementation rates and typical energy recovery rates, this analysis estimated the amount of recovered energy in Coke Dry Quenching (CDQ), sintering machines, Top Pressure Recovery Turbine (TRT), recovered steam from basic oxygen furnace (BOF), as well as waste heat recovery in electric arc furnace (EAF). The shares of electricity in each process are based on reported data from the China Iron and Steel Association (Huang, 2013). **Table 8** presents the estimated energy use by process in this sector.

In 2012, the blast furnace accounted for more than 60% of the total energy use in China's iron and steel sector (Table 8). The analysis focused on easily adopted and cross-sector waste heat to power generation technologies. Thus, the analysis further identified waste heat from the blast stove of the blast furnace process as the potential area to recover waste heat to produce power.

482 **Table 8. Energy Use of China's Iron and Steel Sector by Process (2012)**

Iron and Steel Making Process	Reported Energy Intensity	Production	Final Energy Use	Recovered Energy	Total Energy Input	Share of Electricity	Total Fuel Use
	kgce/t	Mt	Mtce	Mtce	Mtce	%	Mtce
Coke ovens	105	442	46	23	70	1%	69
Sintering	50	810	41	2	42	10%	38
Pelletizing	29	136	4			10%	4
Blast Furnace	402	670	270	15	285	1%	282
Basic Oxygen Furnace	-6	666	-4	7	3	15%	3
Electric Arc Furnace	67	65	4	1	5	40%	3
Continuous Casting, Rolling, and Refining	N/A	N/A	46	N/A	46	15%	39
Total	604	731	407	48	455	N/A	437

483 Note: "Recovered Energy" refers to energy that is recovered and reused in the processes.

484 Source: Editorial Board of China Steel Yearbook, 2013; Huang, 2013; NBS, 2013a.

4.2.3 Results

The blast stove is used to preheat air for use in the blast furnace for iron making. The potential for recovering waste heat from the blast stove exhaust of the blast furnace is relatively small compared to the total energy input of the blast furnace. This is mostly due to the fact that there are other waste heat recovery opportunities, such as recovering blast furnace gas and recovering waste pressure from the blast furnace.

The analysis showed that a maximum technical waste heat potential of 2.9 GW_{Th} is available, with a practical waste heat potential of 1 GW_{Th}. The waste heat to power generation potential of the blast stove exhaust is relatively low. As illustrated in Figure 4, the practical power generation potential is about 7% of the total waste heat potential, about 215 MW_e. If the energy efficiency of power generation equipment could be improved to approach the Carnot Efficiency, electricity production could be doubled. If the maximum heat recovery could be achieved while power equipment efficiency approached the Carnot Efficiency, a maximum of 40% of waste heat potential could be converted to power. However, even with all the potential technical improvements, at least 60% of the waste heat potential would remain as low-temperature (near ambient) heat.

Figure 4. Waste Heat to Power Generation Potential of Blast Stoves in China (2012)

Recovered energy from blast stove exhaust can be used to preheat combustion air and fuel in the blast stoves. In China, this method has not been widely implemented and it is estimated that the current penetration level is about 5% (Huang, 2013).

The analysis of waste heat potential in the iron and steel sector revealed several important points. First, waste heat to power generation is a valuable option and could be developed in the future. Second, other ways to recycle and recover waste heat, such as Coke Dry Quenching

(CDQ), Top Pressure Recovery Turbine (TRT), and recovering sensible heat from slag are equally important as waste heat to power generation. Lastly, the potential of waste heat to power generation may not be as large as waste heat recycling and reuse. In other words, this analysis found that the iron and steel sector has the potential to develop waste heat to power generation, but the industry characteristics are more suitable or favorable for utilization of waste heat as thermal energy.

4.3. Glass sector

4.3.1 Industry background

Flat glass is the main glass product in China, representing about 70% of total glass production nationally. As of 2011, China produced about 740 billion weight cases of flat glass (equivalent to 37 million metric tons), and 14 million metric tons of container glass (Sina News, 2012). From 2000 to 2012, China's flat glass production grew at an average rate of 13% per year (NBS, 2013b).

The dominance of flat glass in China is quite different from developed countries. In the U.S., container glass is the largest glass industry segment, accounting for 50% of total glass production. In the European Union (EU-25), container glass represented 53% of total production in 2005. Domestically, China's glass manufacturers are quite dispersed but a majority of companies use the floating process to produce flat glass. By 2010, China had around 280 flat glass production lines, and about 240 of them were floating glass processes (ERI, 2011). In comparison, EU-27 countries have less than 60 flat glass production lines. Globally, although China accounted more than half of the world's flat glass production in 2011, none of the Chinese glass companies are among the top four glass companies (European Commission, 2013a). It is estimated that about 37% of the global flat glass production is low quality and mainly comes from China (IIP, 2014).

The glass sector in China consumed about 12 Mtce in 2012, accounting for about 1% of total industrial energy use, or 0.4% of China's national energy consumption (NBS, 2013a). The flat glass industry in China mainly relies on coal (63%) and fuel oil as energy inputs (Wang, 2011). As of 2006, electricity consumption accounted for 5% of the total energy consumption in this sector (China Economic Net, 2007). A typical energy distribution of a float glass process shows that the melting and refining process consumes about 83% of total energy inputs (Worrell et al., 2008; European Commission, 2013a). The main source of waste heat in the float glass process is the exhaust from the glass furnace in the melting and refining process.

4.3.2 Data and key assumptions

This analysis categorized the sizes of the glass furnaces into those that are smaller than or equal to 500 metric tons per day (tpd), those that are larger than 500 but smaller than 800 metric tons per day, and furnaces larger than or equal to 800 metric tons per day. The General Administration of Quality Supervision, Inspection and Quarantine of China (AQSIQ) and the Standardization Administration of China (SAC) published two minimum energy performance standards (MEPS) for glass furnaces in 2008 and 2013. Considering 2012 is the base year of this

analysis, the average values of the energy intensity between the two standards are used for this study (Table 9).

Table 9. Energy Intensity of Flat Glass Production in China (2012)

Furnace size	Energy Intensity	Energy Intensity	Fuel Intensity
	(kgce/weight case)	(kgce/kg)	(kJ/kg)
≤500 tpd	14	0.28	6,700
500 tpd – 800 tpd	13.5	0.27	6,400
>800 tpd	12	0.24	5,650

Source: based on AQSIQ and SAC, 2008 and AQSIQ and SAC, 2013.

China's National Bureau of Statistics (NBS) reports flat glass production annually. However, production by furnace sizes is not available. This study assumed that 5% of the production was produced by smaller furnaces (≤500 tpd), given the Chinese government's push to close down small facilities and phase out small and old production units. Based on the 12th Five-Year Plan for flat glass development in China, this analysis assumed 25% of flat glass production in 2012 came from furnaces larger than or equal to 800 tpd (MIIT, 2011a). Table 10 shows the production of flat glass by furnace sizes in 2012.

Table 10. Flat Glass Production by Furnace Size in China (2012)

Flat Glass Sector	Production	Share of Total Production
	Mt	%
Sector-wide	40	100%
≤500 tpd	2	5%
500 tpd – 800 tpd	28	70%
≥800 tpd	10	25%

Source: NBS, 2013b; MIIT, 2011a; and author calculations.

Energy use by manufacturing subsector is only available at an aggregated level in China. The energy use in the glass sector is reported with cement manufacturing, ceramic manufacturing, and other building materials under the "Non-Metallic Mineral Products". NBS reported that in 2012 the non-metallic mineral products sector consumed about 241 Mtce. Based on China's goals for the flat glass industry development, it is assumed the flat glass industry in China accounted for about 5% of energy use in the manufacturing of non-metallic mineral products, with a total energy use close to 12 Mtce in 2012 (Table 11). The result is in agreement with China's *Implementation Guide on the Energy Management System of Flat Glass Industry* (CNIS, 2013), and the MEPS standards (AQSIQ and SAC, 2008; AQSIQ and SAC, 2013).

Table 11. Energy Use by Furnace Size in China's Glass Sector (2012)

Flat Glass Sector	Total Energy Use
	Mtce/year
Sector-wide	11.9
≤500 tpd	0.7

500 tpd – 800 tpd	8.9
≥800 tpd	2.4

Source: CNIS, 2013; AQSIQ and SAC, 2008; AQSIQ and SAC, 2013; and author calculations.

Exhaust temperature varies depending on technologies used. As shown in Table 12, an oxy-fuel furnace (i.e., use pure oxygen as combustion air) has the highest exhaust temperature. This is because it can increase the combustion temperature to a much higher degree by using pure oxygen. However, this does not directly translate into higher waste heat potential, as the mass of exhaust is reduced (saving energy as well). Regenerative and electric-boosted furnaces have the lowest exhaust gas temperature, due to high energy utilization rates (for regenerative furnaces) and high energy conversion efficiency (for electric-boosted furnaces). A recuperative furnace recovers a portion of the waste heat potential through a heat exchanger, but its exhaust temperature is still relatively high.

Table 12. Typical Exhaust Temperatures by Furnace Type in Glass Sector

Furnace Type	Typical Exhaust Temperature	
	°F	°C
Regenerative	800	427
Electric-Boosted	800	427
Recuperative	1,800	982
Oxy-Fuel	2,600	1,427

Source: US DOE, 2008.

China currently has very few oxy-fuel furnaces and the share of electric-boosted furnaces is still low even though it is increasing. The main types of furnaces in China are regenerative and recuperative. China has been implementing a national policy to close down small plants and phase out obsolete capacity in Chinese energy-intensive industries since 2005. Now the existing facilities are relatively new, have newer designs, and employ relatively larger and more efficient furnaces. In addition, considering that many glass facilities are already recovering a portion of the waste heat potential from the exhaust to preheat combustion air and/or the charging materials, this analysis assumed the typical average exhaust temperature of the Chinese glass furnaces to be around 427°C (800°F). This value is the low-end estimate compared to the reported exhaust temperature in China, which is in the range of 400°C to 600°C (752°F to 1,112°F) (ERI, 2011). This indicates that the total estimated waste heat potential of the Chinese glass sector in this analysis may be lower than the actual potential.

There is very limited reporting on the current penetration of waste heat to power generation technologies in China's flat glass sector. However, based on government think tank reports and the Chinese government's 12th Five-Year Plan for the glass sector, the Ministry of Industry and Information Technology (MIIT) estimated that there are 20 units of waste heat to power generation in the glass sector (MIIT, 2011a). The government think tank Energy Research Institute (ERI) reported that there are around 240 production lines in flat glass sector (ERI, 2011). Based on this, this analysis assumed the current penetration of waste heat to power generation technologies in the flat glass sector is about 8%.

4.3.3 Results

The theoretical maximum waste heat technical potential in China's flat glass industry is about 1.8 GW_{Th} based on 2012 data. The practical waste heat potential is determined to be around 1 GW_{Th}. This shows the total waste heat potential is about 16% of the industry's fuel input. The practical waste heat potential is about 9% of the total fuel input (Figure 5).

Figure 5. Waste Heat Potential in the Glass Sector in China (2012)

The practical power generation potential for China's flat glass sector is about 207 MW_e. This considers the real world efficiency of converting thermal energy to power, as well as the practical amount of thermal energy that could be recovered. This represents about 13% of the total theoretical maximum waste heat potential. Power generation potential could be more than doubled if power equipment efficiency could approach to the Carnot Efficiency. If waste heat recovery could be maximized as well, a total of 57% of the waste heat could be converted to power (Figure 6).

Figure 6. Waste Heat to Power Generation Potential of the Glass Sector in China (2012)

Given that the current penetration of waste heat to power generation in China's flat glass sector is estimated to be around 8%, this indicates that an untapped practical power generation potential of 190 MW_e is available. This may be an underestimate, as this analysis uses conservative assumptions related to exhaust gas temperatures and waste heat to power efficiency. However, this provides a lower bound of the actual potential in the flat glass industry.

4.4. Key Findings

The identified technical potential of waste heat to power generation of the studied sectors is summarized in Table 13. The analysis found that the cement sector has significant waste heat to power generation potential in China. Even with a high penetration level of waste heat to power technologies, the cement sector still has the highest untapped power generation potential compared to other sectors studied in the analysis. The technical characteristics of the cement sector can be used as a helpful case to identify favorable sectors for adopting waste heat to power generation technologies.

The iron and steel sector in China has a significant energy profile. By focusing on the largest energy-using process of the sector (blast furnace) this analysis identified more waste heat to power generation potential than the whole sector of the glass industry in China. However, the process and nature of the iron and steel industry is complex and requires steam for process use. The process delivers various products and often releases waste heat with contaminants. This is an industry that is best for optimizing waste heat potential as thermal energy, through waste heat reduction, reuse, and recycling. Pursuing waste heat to power generation is possible; however, the potential is much smaller than thermal waste heat utilization. Technologies for waste heat to power generation in the iron and steel sector could be further developed and implemented. However, the possibility of applying technologies that are tailored to the iron and steel sector to other sectors seems to be limited and needs to be further researched.

Table 13. Waste Heat to Power Generation Potential in Selected Sectors in China (2012)

Sector	Untapped Power Generation Potential <i>[Practical Thermal Potential × Practical Efficiency × (1-Penetration Rate)]</i>	Practical Power Generation Potential <i>[Practical Thermal Potential × Practical Efficiency]</i>	Practical Power Generation Potential <i>[Practical Thermal Potential × Carnot Efficiency]</i>	Theoretical Power Generation Potential <i>[Theoretical Thermal Potential × Carnot Efficiency]</i>	Waste Heat to Power Generation <i>[Practical Potential]</i>
	MWe	MWe	MWe	MWe	kWh/t
Cement	1,266	4,222	10,654	21,037	28 (per ton of clinker)
Iron and Steel (Blast Furnace Stove*)	205	215	594	1,160	3 (per ton of iron)
Glass	190	207	427	1,027	46 (per ton of glass)

* This analysis only considers using blast furnace hot stove exhaust gas for power generation.

The glass sector has a much smaller energy profile than the cement or iron and steel sectors in China. However, the glass sector has the highest waste heat to power generation potential per unit of production, as shown in Table 13. Based on practical waste heat to power generation potential, the glass sector could produce 46 kWh of electricity per metric ton of glass produced.

The glass sector shares some similar characteristics with the cement sector. Both the cement and glass sectors produce a homogenous product (clinker or glass) and both have a relatively short and simple manufacturing process, with normally one key energy-using process. Exhaust gas temperatures of these two sectors are in the medium-high range, even after waste heat has been recycled and reused as thermal energy. The exhaust gas is relatively clean, i.e., does not contain many contaminants, which makes waste heat recovery easier and less costly to implement. These characteristics are presented in Table 14. From a technical perspective and based on the successful example of the cement sector, it is possible that waste heat to power generation technologies could be implemented widely in the glass sector, especially considering the current low technology penetration rate.

Table 14. Industry Characteristics for Adopting Waste Heat to Power Generation

Category	Characteristics
Product	Producing a homogenous product
Process	Relatively short and simple process
Temperature	Medium-high exhaust gas temperature
Contaminants	Fewer contaminants to avoid issues such as corrosion
System components	Relatively small number of system components
Penetration	Low penetration rate of waste heat to power technologies

5. Waste Heat to Power Generation Technologies

The Steam Rankine Cycle is the most commonly used technology for producing power from thermal energy in China. It is not just used for waste heat to power generation, but also widely used for power generation from coal, biomass, and nuclear. The Steam Rankine Cycle uses heat to produce steam, which then drives a turbine to produce power. The most suitable waste heat temperature range for the Steam Rankine Cycle is medium-high temperature, at about 340 to 370 °C [650 to 700 °F] (US DOE, 2008). Lower temperatures are also acceptable; however, they are much less cost-effective and require bulkier equipment. Lower temperatures may also lead to potential condensation and corrosion issues.

Instead of using water as the working fluid, the Organic Rankine Cycle (ORC) uses hydrochlorofluorocarbon (HCFC) or hydrocarbons, which have a lower boiling point and higher vapor pressure. Suitable waste heat temperature for the ORC is 150 to 300°C ([302 to 572°F]). The ORC has higher efficiency compared to the Steam Rankin Cycle in using the same temperature range of waste heat.

The Kalina Cycle uses a mixture of ammonia and water as the working fluid. Different from the single working fluid cycles, the bi-working fluid's temperature increases during evaporation,

which allows it to extract more thermal energy from the waste heat source. Its acceptable temperature ranges from 100°C to 450°C (212 to 842°F). The Supercritical CO₂ Power Cycle uses supercritical CO₂ as working fluid. Without having a phase change (from liquid to gas), the working fluid “undergoes drastic density change over small ranges of temperature and pressure” (NETL, 2013). Table 15 summarizes the temperature ranges, working fluids, conversion efficiencies, and reported costs of these four types of commercialized waste heat to power generation technologies.

Table 15. Waste Heat to Power Generation Technologies

	Steam Rankine	Organic Rankine (ORC)	Kalina Cycle Ammonia (NH₃) - Water	Supercritical CO₂ Power Cycle
Temperature Range	340 to 370°C [644 to 700°F]	150 to 300°C [302 to 572°F]	100 to 450°C [212 to 842°F]	225 to 650°C [437 to 1,202°F]
Working Fluid	Treated water	HCFCs or hydrocarbons	Ammonia - water mixture	Carbon dioxide
Working Fluid Attributes	Requires treatment to reduce corrosion and mineral deposition	Limited temperature range, flammability, thermally unstable at higher temperature	Limited temperature range, corrosive, ammonia leaks	Non-corrosive, non-toxic, non-flammable, thermally stable
Conversion Efficiency (%)	10% to 20%	8% to 12%	8% to 15%	13% to 17%
Reported Cost (\$/kW)	>\$600	>\$2500	>\$2500	>\$2000

Sources: Thekdi 2011 and Harrell 2014.

Other technologies, such as thermoelectric generation, piezoelectric power generation, and thermionic generation, convert thermal energy directly to electricity (US DOE, 2008; EPRI, 2010). However, these technologies are still emerging and have not yet reached full commercialization for application in large-scale industrial plants.

The application of waste heat to power generation technologies will depend on a number of factors, such as the physical and chemical characteristics of the waste heat (e.g., temperature and chemical composition), cost-effectiveness, and physical space limitations.

6. Conclusions

China is the largest energy user and CO₂ emitter in the world. The industrial sector consumes about 70% of China’s energy where coal is the predominant fuel. As China strives to peak CO₂ emissions around 2030 or earlier and plans to cap coal consumption, understanding, managing, and utilizing waste heat in China’s industrial sector will support China in achieving its energy, environmental, and climate goals both domestically and internationally.

A review of existing studies on the waste heat potential in China shows that detailed technical analysis is lacking. Often, waste heat potential was reported without a transparent or

standardized methodology. As a result, China's technical and practical potential for waste heat utilization is not clear. In addition, except for successful adoption in the cement sector, waste heat to power generation technologies have not been implemented widely in other energy-intensive sectors in China.

By adopting two levels of temperature set points (25°C [77°F] and 150°C [300°F]) and two levels of power generation equipment efficiency (practical efficiency and the Carnot Efficiency), this study analyzed the theoretical maximum potential and practical potential of waste heat in the cement, iron and steel, and glass sectors in China through a standardized thermal modeling method in addition to data collection, cross-examination of data, and expert interviews.

The results showed that as of 2012, the untapped practical potential to produce electricity from waste heat in the China's cement sector is about 1.3 GW_e. With today's technologies, the cement industry can produce 28 kWh of electricity per ton of clinker. The cement sector experience demonstrates the viability of waste heat to power generation technologies and also indicates the scalability in other sectors.

However, sectors with complex processes and various products, such as iron and steel, need to consider using waste heat as thermal energy rather than solely focusing on waste heat to power. This analysis focused on the waste heat potential of the blast furnace stove in the iron-making process, and found the untapped waste heat to power generation potential in this process is about 205 MW_e, which is about 3 kWh of electricity per ton of iron based on 2012 production levels in China.

In addition, this analysis found that sectors such as glass and cement are favorable for implementing easily adopted and cross-sector waste heat to power technologies such as the Steam Rankine Cycle and the Organic Rankine Cycle. These sectors share similar characteristics, include producing a homogenous product, relatively short and simple processes, medium-high exhaust gas temperatures, fewer contaminants in the heat stream, and low penetration of waste heat to power generation technologies.

The glass sector, even though it has a smaller energy profile compared to the cement and iron and steel sectors, showed the highest waste heat to power generation potential on a per unit of production basis - 46 kWh of electricity per ton of glass. The total untapped practical potential to produce electricity from waste heat in glass sector is 190 MW_e. However, the current penetration rate of waste heat to power generation technologies in the glass sector in China is very low, at about 10%. In order for the glass sector to realize its high potential, identifying and understanding the barriers to implementation of the technology in this sector is critical.

7. Limitations and Future Research

7.1. Limited research scope

This research was limited in scope to three industrial sectors, to waste heat from exhaust gases, and to utilization of waste heat to produce power.

This research estimated the technical potential of waste heat in three selected industries, with an emphasis on waste heat potential from exhaust gas, because exhaust gas is the largest potential area of waste heat recovery. There are other sources of waste heat that exist in industrial facilities, such as heat loss through furnace walls, conveyor belts, poor insulation, unusual leakages, and openings. Sensible heat from slag and manufactured industrial products is another area of emerging waste heat recovery. However, this analysis focused solely on exhaust gas waste heat.

This research chose to focus on waste heat to power generation, because electricity can be used in all sectors and can be relatively easily and inexpensively transported in China. However, a significant amount of the waste heat potential will remain in the form of heat. How to make best use of the low temperature waste heat is an important energy and policy question that deserves more research and policy attention. More work is needed to understand the barriers and opportunities in utilizing medium to low temperature industrial waste heat.

7.2. Lack of plant-level details

This research aimed to provide a bottom-up analysis of the waste heat potential of Chinese industry. However, it is almost impossible to conduct such an analysis at the plant level given the lack of publically available information. This posed limitations in understanding location specific conditions. This research reduced this limitation by disaggregating the sector as much as possible by waste heat temperature, technology, project size, and efficiency levels.

7.3. Potential biases in assumptions

To determine fuel use by industry, this research used minimum energy performance standards (MEPS) published by the Chinese government. This research used the average values between the 2008 and 2013 standards for the baseline values in 2012. However, the enforcement rate of the minimum energy performance standards may not be 100% and could vary by industry. Using the prescribed minimum energy efficiency levels for existing plants provides a lower-bound estimate of the total available waste heat potential.

This research analyzed waste heat potential by technology type. For example, both NSP kilns and non-NSP kilns were considered in the cement sector. However, when a technology penetration breakdown was not available (as in the glass sector), this research assumed that the Chinese plants use a better technology (e.g., regenerative furnaces in the glass sector). This assumption is based on the fact that the Chinese “phasing out” program has been closing down small and old furnaces and equipment since 2006 and most of the Chinese furnaces are relatively new (built or retrofitted in the last 10-15 years). But a better technology does lead to a lower estimate of the available potential waste heat. This means the research results are conservative.

A key parameter used in the analysis is exhaust temperature, which varies by sector, technology, energy and material inputs, and technical operations. It is very difficult to use only one exhaust temperature to represent the whole industry. Exhaust temperatures used in this analysis are based on previous reports published by the U.S. Department of Energy and expert interviews. These sources tend to provide a better than average condition, which means lower exhaust gas temperatures. This may lead the results to reflect a lower-bound estimate of total available waste heat potential.

7.4. Future research

This study analyzed the waste heat potential of three industrial sectors in China using a standardized methodology. In the future, this method can be applied to assess other energy-intensive sectors such as ammonia, caustic soda, non-ferrous metals, and sulfuric acid.

Previous studies have found significant waste heat potential in the three Chinese industries analyzed in the research described in this paper. ERI (2011) estimated that in 2010 there was about 29 million tonnes of coal equivalent (Mtce) [850 PJ] waste heat potential in the Chinese ammonia industry, 16 Mtce (469 TJ) waste heat potential in the Chinese sulfuric acid industry, 12 Mtce (352 PJ) waste heat potential in the Chinese calcium carbide industry, and 3.9 Mtce (114 PJ) waste heat potential in the Chinese caustic soda industry. Dong (2013) estimated that about 60% of total energy use in the refining process of China's non-ferrous industry is converted to waste heat. By focusing on waste heat to power generation, Lu (2010) and Dong (2013) also estimated that the market potential of coke dry quenching technologies (the main means of waste heat recovery in the coke industry) could reach 1 GW.

In addition, the methodology described in this paper can be used in countries other than China, such as Brazil and India, to better understand the international potential for use of waste heat. Applying a transparent and consistent methodology across sectors can help researchers and policy makers to compare results across industries to identify gaps and action priorities.

Future research can also focus on assessment of the waste heat potential analysis at a deeper level. For example, sampling of industrial companies to collect detailed plant-level data would provide more accurate information related to a number of assumptions, such as exhaust gas temperatures and technology adoptions. This type of industry-level deep analysis can provide higher resolution results, such as identifying waste heat potential by exhaust gas grades and providing tailored recommendations to the studied industry.

Analysis related to low-temperature waste heat utilization potential in China is needed. This study provides a first assessment of the total aggregated energy potential of the low-temperature waste heat. Future research on technologies, materials, and system designs to utilize low-temperature waste heat is needed.

Cross-sector (between the industrial sector and building, urban systems) analysis, such as industrial park system optimization, cascading use of energy in urban cities, and optimal

locations of industrial facilities, is also needed to help China achieve low-carbon, sustainable urbanization development.

Finally, policy analysis is needed on how to integrate waste heat utilization in China's energy and climate goals. Such efforts could include formulating industry or national standards on quantifying waste heat potential and savings from implementing waste heat to power generation projects or designing policy mechanisms to recognize waste heat potential as "non-fossil equivalent" in order to incorporate waste heat savings into China's non-fossil targets.

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