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Capturing the Invisible Resource: Analysis of Waste Heat Potential in Chinese Industry and Policy Options for Waste Heat to Power Generation

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List of Acronyms

BF	blast furnace
BFG	blast furnace gas
BOF	basic oxygen furnace
Btu	British thermal unit
CDQ	Coke Dry Quenching
CHP	combined heat and power
CO_2	carbon dioxide
DRI	direct reduction iron
EAF	electric arc furnace
ERI	Energy Research Institute of China
ESCOs	energy service companies
FYP	Five-Year Plan
GDP	gross domestic product
GJ	gigajoule
GW_e	gigawatt of electric energy
GW_{Th}	gigawatt of thermal energy
HRSG	heat recovery system generator
IPCC	Intergovernmental Panel on Climate Change
kgce	kilogram of coal equivalent
kWh	kilowatt hour
MEPS	minimum energy performance standard
MIIT	Ministry of Industry and Information Technology of China
Mt	million metric tons
Mtce	million metric tons of coal equivalent
MW_e	megawatt of electric energy
MW_{Th}	megawatt of thermal energy
NBS	National Bureau of Statistics of China
NO_x	nitrogen oxides
NSP	new suspension preheaters
ORC	Organic Rankine Cycle
PM	particulate matter
RD&D	research, development, and deployment
RMB	*renminbi* (Chinese currency)
SO_2	sulfur dioxide
SO_x	sulfur oxides
SRI	smelting reduction iron
tce	metric tons of coal equivalent
tpd	metric tons per day
TRT	Top Pressure Recovery Turbine
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency

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Executive Summary

Waste heat is an invisible energy resource. It can be used to provide electricity, steam, space heating, cooling, and hot water. Waste heat is a by-product of manufacturing processes, representing up to 50% of the sectoral fuel input. It is an invisible energy resource that requires careful management by following the “Reduce, Recycle, and Recover” principle.

China is the largest energy user and carbon dioxide (CO_2) emitter in the world. The industrial sector consumes about 70% of China’s energy where coal is the predominant fuel. As China sets its goal to peak CO_2 emissions around 2030 and plans to cap coal consumption, understanding, managing, and utilizing waste heat in China’s industrial sector will support China to achieve its energy, environment, 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 of the waste heat was 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.

This study analyzed the theoretical maximum potential and practical potential of waste heat in the cement, iron and steel, and glass sectors in China, based on thermal energy modeling, expert interviews, and literature reviews.

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, such as iron and steel, need to consider using waste heat as thermal energy rather than solely focusing on waste heat to power. Low temperature waste heat recovery has significant potential but key barriers exist in materials, technology designs, equipment, and costs.

This study finds that sectors such as glass and cement are favorable for implementing easily adopted and cross-sector waste heat to power technologies (such as Steam Rankine Cycle and Organic Rankine Cycle). They 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.

Glass sector, even though has a smaller energy profile compared to the cement and iron and steel sectors, has the highest waste heat to power generation potential on a per unit of production basis. However, the current penetration rate of waste heat to power generation technologies in the glass sector in China is very low, at about 10%. It is needed to understand the barriers to implementation of this technology in sectors that have high potential.

Key barriers to implementation of waste heat to power generation are identified in this study through surveys and interviews with industry experts and professionals. Economic hurdles, including long payback time, high first cost, and lack of access to capital, technical barriers to full utilization of the waste heat potential, and regulatory conditions such as low energy prices and lack of policy synergies are among the most important, in additional to organizational and behavioral barriers.

Therefore, to reduce these barriers and maximize the potential of waste heat, it is recommended to consider providing a rebate for electricity generated from industrial waste heat, at a level between 0.11 RMB/kWh ($0.02 USD/kWh) and 0.20 RMB/kWh ($0.03 USD/kWh). This range is determined through a benefit-cost analysis incorporating environmental benefits and the costs to adopt waste heat to power generation technologies. Technical assistance, such as formulating standards on waste heat assessments, developing software tools to quantify waste heat potential, providing technology guidebooks to screen domestic and international technologies, and conducting training workshops can be implemented quickly, to increase awareness, establish technical know-how, and reduce project uncertainties.

In the long term, it is recommended that the Chinese government to experiment with flexible financing schemes, incorporate waste heat into national energy or non-fossil targets, and integrate energy savings of waste heat projects explicitly with other policy schemes, such as the cap-and-trade program and the Top 10,000 program. Innovation, research, and development of new materials, innovative manufacturing processes, and advanced waste heat technologies need to be encouraged and accelerated through demonstration projects, pilot programs, awards, and competitions.

Introduction

What is waste heat and why it is important?

Many industrial processes generate unused or waste heat during manufacturing production processes. Depending on a number of factors, such as industry characteristics, fuel inputs, and operational practices, industrial waste heat accounts for 10-50% of total fuel consumption. 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 (CO_2) emitter in China, representing about 70% of China's total primary energy use and energy-related CO_2 emissions in 2012. Coal is the dominant fuel supply in the Chinese industry, accounting for about 71% of total fuel use in 2012. The industry sector is also one of the most important sectors to reduce air pollution, such as sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter in China. Improving waste heat utilization in China's industry sector not only can reduce coal consumption but also can provide significant environmental and public health benefits.

Improving waste heat utilization can support 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 CO_2 emissions around 2030 while striving to peak earlier. 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 (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 (CO_2 emissions per unit of GDP) by 16% and 17%, respectively, from the 2010 level.

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.

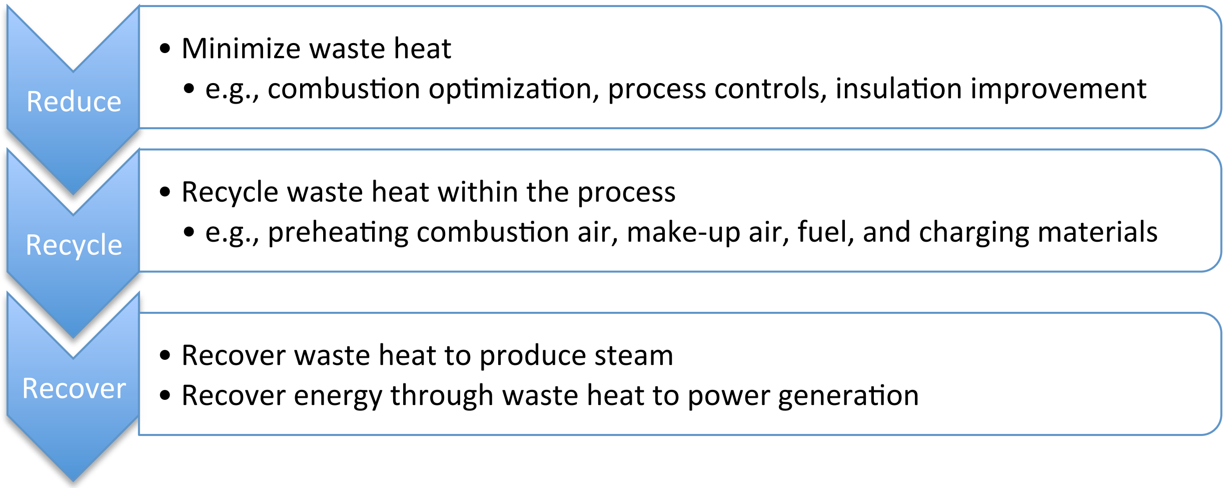

Figure 1. Waste Heat Management

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 it 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.

What are the current policies?

Legislative recognition

The Chinese government recognizes the importance of industrial waste heat. The 2008 amended *Energy Conservation Law of China* encourages the adoption of waste heat utilization in industrial companies (Article 31). China’s *Circular Economy Promotion Law* states that companies need to comprehensively utilize waste gas (and other waste materials) by following national requirements. In China’s 11th Five-Year Plan (FYP) (from 2006 to 2010) and 12th FYP (from 2011 to 2015), waste heat utilization is one of the Key Energy-Saving Projects, which promote improving thermal energy efficiency of industrial boilers and furnaces, as well as encouraging the adoption of waste heat to power generation technologies in energy-intensive industrial sectors (NDRC, 2006; State Council, 2011).

Direct and indirect incentives

Industrial waste heat utilization projects in theory can receive tax benefits in China. According to China's tax regulations, a waste heat utilization project can receive 100% refund of its value-added taxes after selling the produced electricity and/or steam (MOF and SAT, 2011). However, in practice, many industrial waste heat utilization projects cannot receive the tax exemption. If waste heat utilization projects are operated in island mode, i.e., offsetting electricity/steam purchases with the electricity/steam produced from waste heat, the 100% value-added tax refund policy does not apply, since no sales have occurred. For many industrial facilities, electricity produced from waste heat is a small percentage of total electricity use. Even if sales of electricity occur (such as sales to employees), the total amount of sales often does not meet the threshold for refundable value-added taxes. In some limited cases, industrial facilities produce excess electricity from waste heat and sell the excess electricity to the grid. In theory, these facilities can benefit from this policy. However, due to the current Chinese electricity policies, it is very difficult for industrial companies to sell electricity to the grid. Therefore, the 100% value-added tax refund policy does not apply to the majority of waste heat utilization projects.

In addition to specific incentives for waste heat, the Chinese government developed incentive policies that cover a number of sectors, systems, and technologies. During 2007-2010, energy-saving projects (including waste heat utilization projects) that saved more than 10,000 metric tons of coal equivalent (tce) can receive a one-time economic award of 200 *renmibi* (RMB)/tce in the east region or 250 RMB/tce in the middle and west region of China (MOF, 2007). In the 12th FYP (from 2011 to 2015), this incentive policy was expanded to cover relatively smaller projects (saving more than 5,000 tce) and the amount was expanded to 240 RMB/tce in the east region or 300 RMB/tce in the middle and west region (MOF, 2011).

Mandates and punitive measures

Mandates and punitive measures are also used to promote energy conservation and have an indirect impact on adopting waste heat utilization technologies. For example, the Top 10,000 Program in China, which covers 60% of total industrial energy use and includes more than 15,000 industrial companies, requires the targeted companies to sign individual energy-saving contracts, which collectively save 250 million tce (Mtce) by 2015.

Industrial product minimum energy performance standards (MEPS) set the mandatory minimum energy efficiency levels (i.e., the maximum amount of energy could be used to produce one unit of product) for a number of energy-intensive products, including cement, crude steel, and flat glass. The standards include a minimum energy efficiency level for existing industrial plants, and a minimum energy efficiency level for newly constructed industrial plants. For example, under the cement standard, an existing rotary cement kiln with a capacity larger than 4,000 metric tons per day (tpd) needs to have a minimum energy efficiency of 120 kilogram of coal equivalent (kgce)/metric ton of clicker or better; a newly constructed rotary cement kiln with the same capacity needs to have a minimum energy efficiency of 105 kgce/metric ton of clinker or better.

The Chinese government piloted differential electricity tariffs in 2004. The policy applies different electricity tariffs to industrial companies based on their levels of efficiency categorized as “encouraged”, “permitted”, “restricted”, and “eliminated”. By the end of 2008, electricity tariffs for industrial companies in the category of “restricted” and “eliminated” were 7%-29% higher[1] than without the differential electricity pricing. Some provinces even implement stricter differential electricity pricing than the national policy. For example in 2015, Hebei Province implemented a differential electricity pricing policy in the iron and steel sector that is twice as much as the national “differential rate”.

Overall, the Chinese government encourages waste heat utilization and provides a tax refund on sales of electricity/steam from waste heat projects. However, actual take-up of the tax benefit is very limited due to the characteristics of waste heat projects. The Chinese government provides a “one-size-fits-all” incentive policy to cover all types of energy savings, including waste heat utilization. Mandates, such as energy-saving programs, energy-intensity targets, industrial energy performance standards, and differential electricity pricing are used to improve industrial energy efficiency.

Why this study is needed?

Need for technical analysis to understand potential

The concept of waste heat as a resource is similar to the concepts of oil reserves or wind power resources. But 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. The “supply” of waste heat may fluctuate and become less reliable 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.

A review of the existing studies on the Chinese waste heat potential shows that detailed technical analysis on waste heat potential in industrial sectors is lacking (see Summary 1: Literature review on waste heat potential). The U.S. Department of Energy provided one example of quantifying waste heat potential in the U.S. industrial sectors (US DOE, 2008). However, at present there is limited comprehensive research on waste heat potential in China’s key industrial sectors. The literature on this topic reports minimal waste heat potential in only a few sectors, such as the cement sector. 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 are 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.

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[1] Assuming the average electricity tariff for industry is 0.7 RMB/kWh ($0.11 USD/kWh based on the 2014 exchange

Need for policy analysis to identify barriers & solutions

Waste heat to power generation was significantly adopted by one sector in China: the cement industry. In 2005, the penetration of waste heat to power generation in the cement sector was close to zero. By 2012, 70% of the cement production capacity has installed this technology. The rapid uptake of waste heat to power generation in the cement sector not only demonstrates the viability of the technology but also indicates the possible scalability of waste heat to power generation in other industries. However, other energy-intensive sectors, such as the glass sector has only implemented waste heat to power generation to a limited degree in China to date, as illustrated in Figure 2.

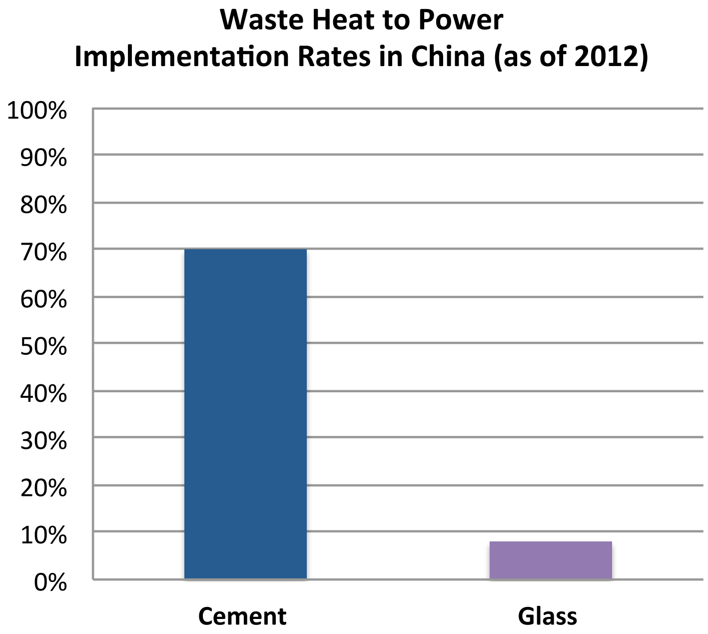

Figure 2. Penetration of Waste Heat to Power in China's Cement and Glass Sectors
Source: author estimates.

A review of existing literature on the barriers to investment in energy efficiency projects in the industrial sector was conducted (see Summary 2: Literature review on barriers). The review shows that while energy efficiency measures are cost-effective, not all measures are implemented. In fact, the adoption rates of many energy efficiency measures are low. The academic community has recognized this "energy efficiency gap" since 1970s and studies have shown that it can be attributed to a number of factors, including economic, behavior, and organizational reasons. More specifically related to waste heat to power generation, the existing literature provides a long-list of barriers, ranging from physical, chemical properties of the exhaust gas to technical and financial capabilities of industrial facilities. However, so far there is very limited research on the development of waste heat to power generation in China. While some case studies have been identified, key barriers to waste heat to power generation implementation are not clear under the Chinese conditions.

Project objectives and structure

Waste heat utilization represents a missed opportunity to reduce China's total energy use, decrease carbon dioxide emissions, and improve air quality. This report focused on waste heat to power generation, and has three objectives:

1) Analyzing the technical potential of waste heat in three sectors, including cement, iron and steel, and glass;
2) Identifying key barriers to implementation of waste heat to power generation in China;
3) Developing policy solutions to promote greater use of waste heat to power generation in China's energy-intensive industry.

This analysis specifically focused on converting thermal energy to power, because compared to heat, electricity is easier to transport and can be used in all end-use sectors. The additional need for infrastructure building is much less for electricity compared to distribution of heat in China. The cost of transmission and distribution of electricity is also lower than transporting heat.

The sectors with different characteristics are chosen (see Table 1). Generally speaking, the more energy consumed in that sector and the higher exhaust gas temperature, there is more waste heat potential in that sector. The complexity of the process may hinder the adoption of waste heat to power generation, and the current utilization rate of waste heat recovery plays an important role in determining the potential as well. Certainly, other manufacturing sectors such as chemicals, pulp and paper, non-ferrous metals could also be analyzed. However, this study focused on the cement, iron and steel, and flat glass sectors, each representing a type of waste heat utilization condition.

Table 1. 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 report first summarizes the methods used for the technical potential analysis and the policy analysis. Then, the report presents key findings on waste heat potential, barriers to waste heat to power generation in China, and policy solutions to reduce the barriers. The report then provides recommendations to policymakers. Lastly, the report points to the limitations of the research and needs for future research.

Methods

Thermal energy modeling

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

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

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.

Key assumptions made for the technical analysis, include calorific heating values of coal and heavy oil, typical coal compositions, combustion control conditions, typical exhaust gas temperatures and reference temperatures for waste heat capture, type of technologies, as well as power generation equipment efficiency. Details of the assumptions used in the thermal modeling analysis can be found in Summary 3: Methodology and data sources.

Survey of key barriers

A survey was conducted to identify the largest barriers to implementation of waste heat to power generation projects in China. A list of 25 barriers categorized in six areas was developed (see Summary 4: Survey questionnaire). The survey requested recipients to rank the importance of barriers with a rating from 1 to 5, with 1 being the least important and 5 being the most important. Recipients of the survey could also rank the barriers with a rating of “0”, indicating the barrier is not important at all for China. In addition, recipients could add other barriers they regard as important.

Expert interviews

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

During the interviews, barriers to implementing energy efficiency projects in industrial companies and barriers to investing in waste heat to power projects were also discussed. Opinions of industrial experts were documented and used as an important source for identifying the most important barriers, in parallel to the survey results.

Cross-examination of data

Cross-examination methods are used to cross check the outputs from the thermal energy modeling. The methods 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. Data sources used in the report can be found in Summary 3: Methodology and data sources.

Benefit-cost analysis

Benefit-cost analysis is used to estimate the potential benefits and costs resulting from implementing a hypothetical incentive policy. In this step, items of direct benefits and co-benefits (such as reduced coal use, carbon emissions and pollutants, and improved health impacts) and costs are identified. The impacts are monetized over a studied period of 10 years with a social discount rate of 8%. Detailed assumptions of the benefit-cost analysis can be found in Summary 5: Assumptions of the benefit-cost analysis.

Key Findings

Waste heat potential in industry

The purpose of this analysis is to determine the technical potential and identify industry characteristics for implementation of easily-adopted and cross-sector waste heat to power generation technologies in energy-intensive sectors in China. Therefore, this analysis focused on already commercialized technologies, such as Steam Rankine Cycle and 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 the Top Pressure Recovery Turbines for blast furnaces in iron-making), technologies that have not achieved wide adoption (such as Kalina Cycle or supercritical CO_2 cycle), or other emerging technologies (such as thermoelectric generation and piezoelectric power generation) are not within the scope of this analysis. However, a general discussion on the characteristics of these technologies can be found in Summary 9: Overview of waste heat to power generation technologies.

This analysis focused on three industrial sectors: cement, iron and steel, and glass. In the cement sector, waste heat from cement kiln exhaust gas and from the clinker cooler is the main source for waste heat recycle and recovery. In the iron and steel sector, this analysis focused on the most energy-intensive process of an integrated iron and steel-making plant, the blast furnace (BF) iron-making process. The main source of waste heat considered in this analysis is the exhaust from the blast furnace hot stove.[2] In the glass sector, the analysis focused on the melting and refining process.

Industrial waste heat potential as well as the potential to produce electricity from waste heat are determined through a thermal energy modeling analysis. 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 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. Three levels of waste heat to power generation potential are determined: 1) a practical waste heat to power generation potential, considering "real-world" power equipment efficiency, 2) waste heat to power generation potential when improving efficiency to approaching the Carnot Efficiency, and 3) a maximum power generation potential based on the Carnot Efficiency and maximum heat recovery. Sections below provide the key findings in the studied sectors.

Cement sector

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, 2014). 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, 2013b). 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. 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. In 2012, NSP kilns represented 92% of total clinker production in China (CCA, 2014).

Based on the Chinese government minimum energy performance standard (MEPS) for cement production, as well as expert interviews on typical exhaust temperatures, this analysis conducted the thermal modeling and determined thermal energy available in waste heat as well as the waste heat to power generation potential. Details of the modeling assumptions and data sources for the cement sector can be found in Summary 6: Waste heat potential in the cement sector.

Using the 2012 historical production data, more than a quarter (26%) of the fuel use 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 3.

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[2] Blast furnace gas, a by-product of the blast furnace, is recovered and reused as a fuel in the iron and steel making process in China.

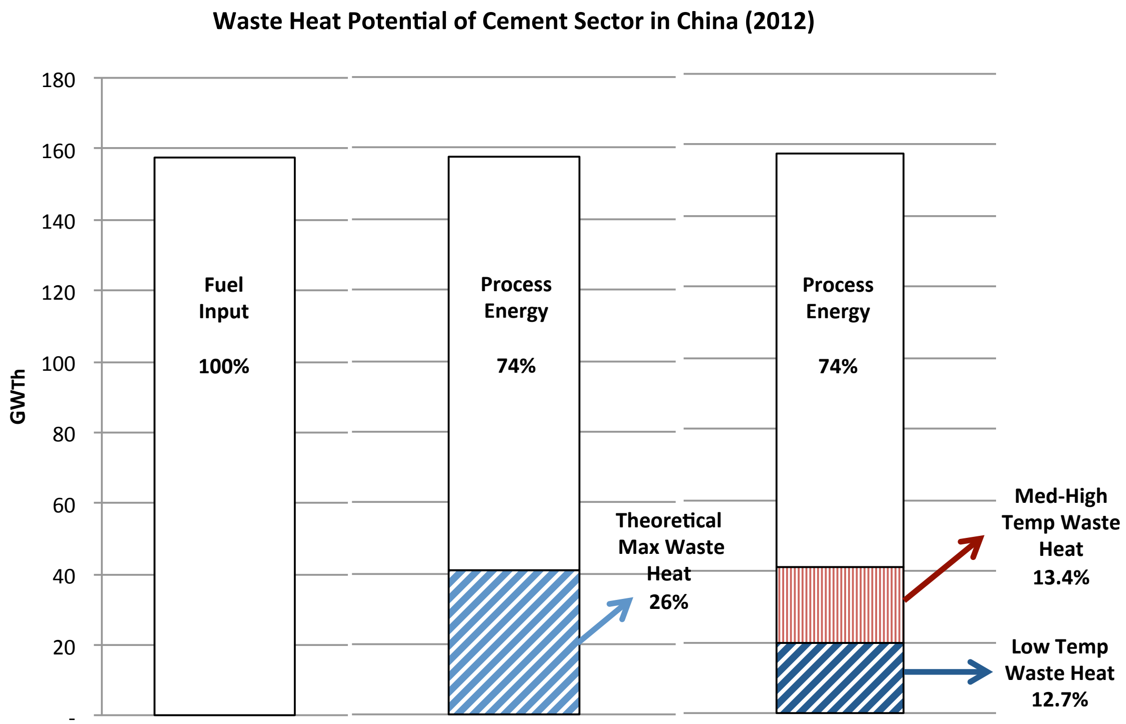

Figure 3. Waste Heat Potential of the Cement Sector in China (2012)

China's cement industry has a theoretical maximum waste heat 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 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 GW_e 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 4).

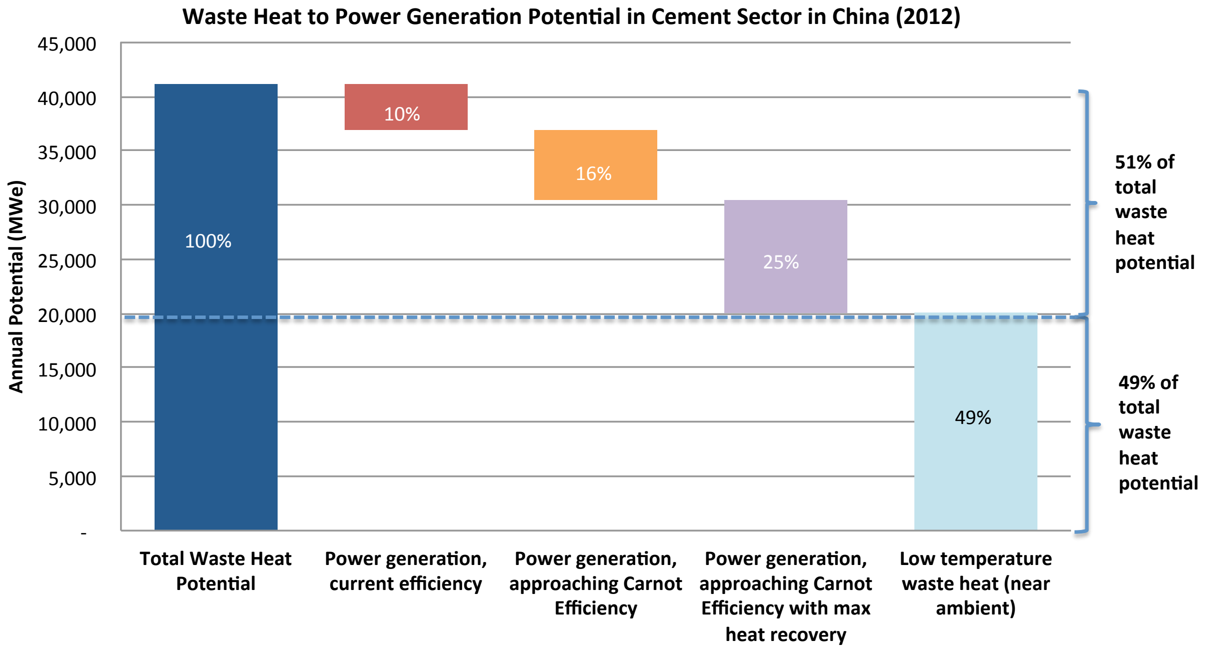

Figure 4. Waste Heat to Power Generation Potential of the Cement Sector in China (2012)

As of 2012, the reported penetration of waste heat to power in cement sector reached more than 70% (China Environment News, 2013). This means the currently available, untapped potential is much less, about 1 GW_e 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 energy-efficiency technologies.

Iron and steel sector

China is the world's largest iron and steel producer. In 2012, China produced 60% of global pig iron production and 46% of global crude steel production (USGS, 2014b). Iron and steel production is one of the largest energy sectors in China, with energy consumption accounting for 10-15% of the total energy use and 15-20% of the total industrial energy use (Ma et al., 2012). In addition, 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, 2013). Overcapacity directly affects the prices of products as production increases 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. China became a net steel exporter in 2005. 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 ton in 2012, which is higher than the total steel production of Germany in 2012. Product quality is a weakness of the iron and steel sector. According to the Chinese Ministry of Industry and Information Technology (MIIT), only about 30% of the Chinese steel production achieves international advanced quality levels (MIIT, 2011c).

This paper focused on the most energy-intensive process in the iron and steel sector, the blast furnace process. The paper identified waste heat from the blast-stove is the potential area to recover waste heat to produce power. 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 shows that a maximum technical waste heat potential of 2.9 GW_{Th} is available, with a practical waste heat potential of 1 GW_{Th}. Details of the key assumptions and data sources can be found in Summary 7: Waste heat potential in the iron and steel sector.

The waste heat to power generation potential of the blast-stove exhaust is relatively low. As illustrated in Figure 5, 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 to 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.

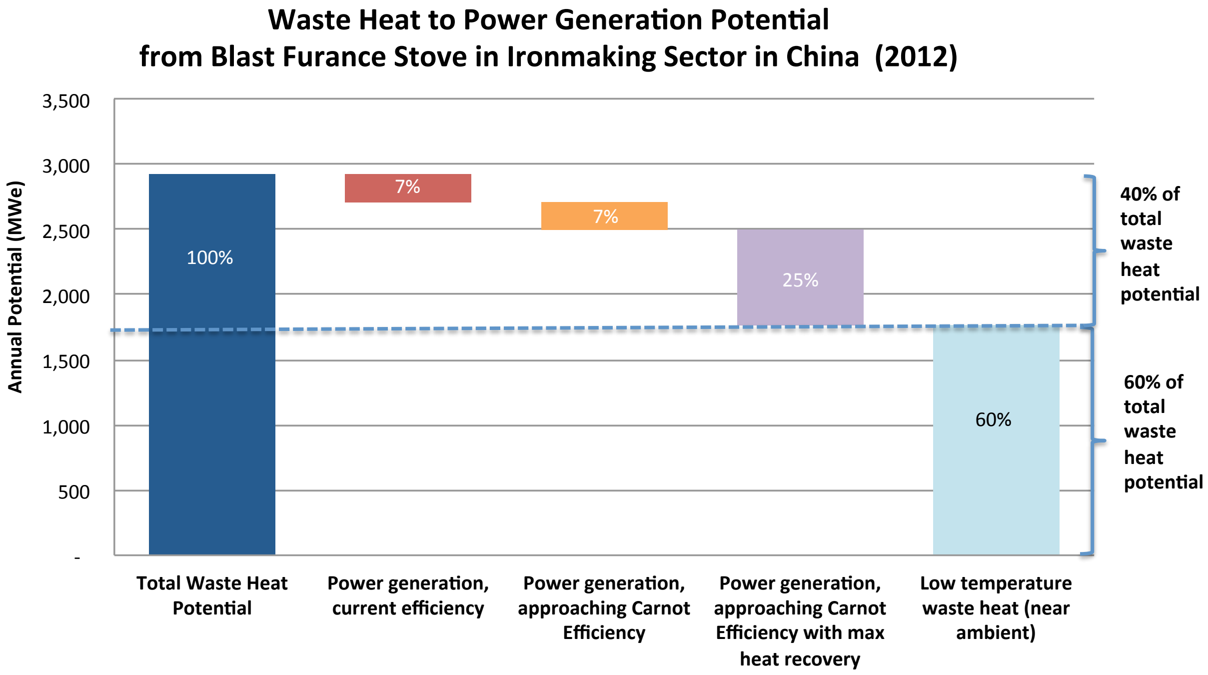

Figure 5. Waste Heat to Power Generation Potential of Blast Stoves in China (2012)

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 reveals 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 recycle and reuse. In other words, this analysis finds 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.

Glass sector

Flat glass is the main glass product in China, representing about 70% of total glass production nationally. The dominance of flat glass in China is quite different from developed countries. In the United States, 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).

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, 2013b). The flat glass industry in China mainly relies on coal and fuel oil as energy inputs. 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.

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 6).

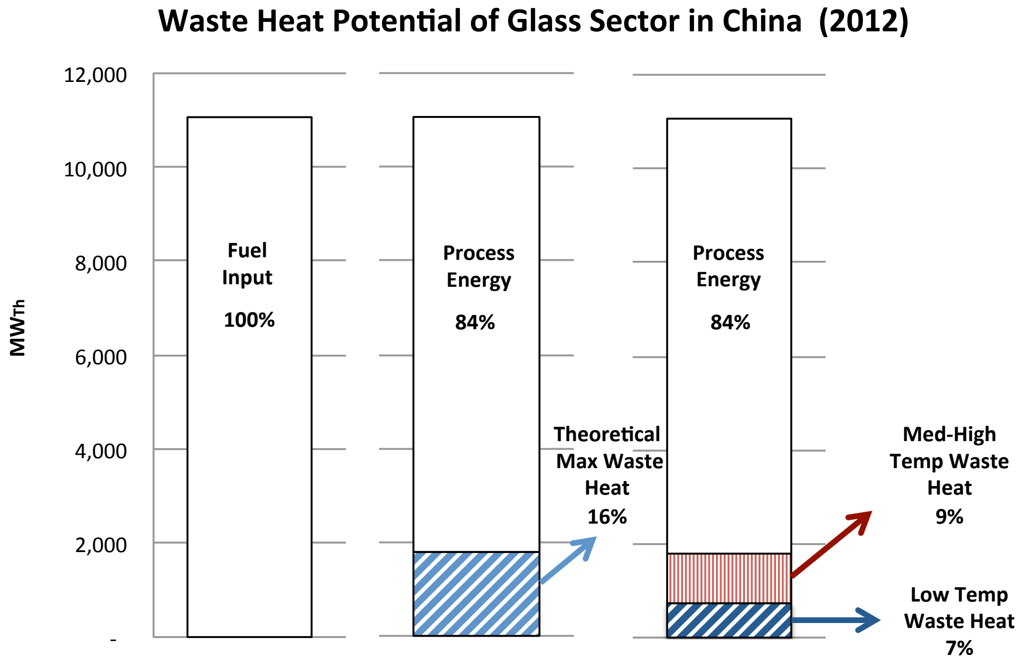

Figure 6. Waste Heat Potential in the Glass Sector in China (2012)

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 7). Assumptions and data sources used in analyzing glass sector potential can be found in Summary 8: Waste heat potential in the glass sector.

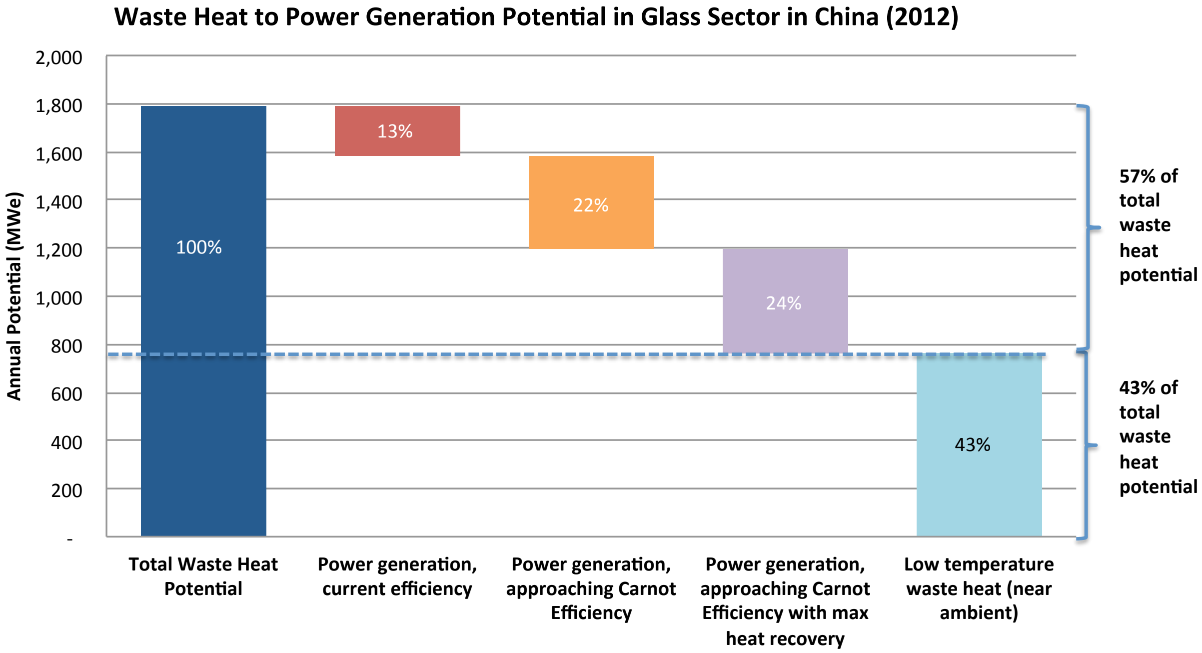

Figure 7. Waste Heat to Power Generation Potential of the Glass Sector in China (2012)

Given 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.

Technical analysis summary

The identified technical potential of waste heat to power generation of the studied sectors is summarized in Table 2. The analysis confirmed 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 report. 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 – the 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 energy. The process delivers various products and often releases waste heat with contaminants. This is an industry that is best for maximization the potential of waste heat as thermal energy, through waste heat reduction, reuse and recycling. Applying 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 2. Waste Heat to Power Generation Potential in Selected Sectors in China (2012)

	Untapped Power Generation Potential *[Practical Thermal Potential × Practical Efficiency × (1-Penetration Rate)]*	**Practical Power Generation Potential** *[Practical Thermal Potential × Practical Efficiency]*	**Practical Power Generation Potential** *[Practical Thermal Potential × Carnot Efficiency]*	**Theoretical Power Generation Potential** *[Theoretical Thermal Potential × Carnot Efficiency]*	**Waste Heat to Power Generation** *[Practical Potential]*
Sector	**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. However, the glass sector has the highest waste heat to power generation potential per unit of production, as shown in Table 2. 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 cement and glass sector produce a homogenous product (clinker or glass). 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 3. 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 with the current low technology penetration rate.

Table 3. 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 rates of waste heat to power technologies

Policy options and implications

Barriers to implementation of waste heat to power generation

Based on the survey results and expert interviews, a list of the key barriers to waste heat to power generation in China is identified (Table 4). The largest barriers are economic and technical barriers. Waste heat to power generation projects usually requires significant capital investment with high first cost for companies. Industrial companies often have an internal criterion to screen and select investment projects. Waste heat to power generation projects often do not meet the investment payback time criterion. For smaller companies, lack of access to (cost-effective) capital is another issue pointed out by the survey responders. Technically, it is very expensive to utilize low-medium temperature waste heat to produce power, which greatly reduces the potential benefits of implementing the energy-saving measure.

Table 4. Key Barriers to Waste Heat to Power Generation in the Chinese Industry

Economic	Long payback time High first cost Lack of capital
Technical	Unable to fully utilize low-medium temperature waste heat Mismatches between heat supply and demand
Regulatory	Low and/or subsidized energy prices Difficulty for grid interconnection Lack of mechanisms to connect waste heat utilization to other policies
Organizational	Lack of top leadership commitment Lack of internal technical expertise Lack of high quality external expertise
Behavioral	Uncertainty of savings

The relatively low energy price in China is another barrier that significantly reduces the economic attractiveness of waste heat to power generation. Survey responders also pointed out that in China it is very difficult for industrial companies to sell power to the grid, or sometimes they face a long and burdensome process in order to be connected to the grid. In addition, the survey results show that in China waste heat to power generation projects are not integrated into other on-going policy schemes, such as the CO_2 emissions cap-and-trade pilots in China. Other key barriers to implementing waste heat to power generation in China, such as lack of top leadership commitment, lack of technical expertise, and uncertainty of energy and cost-savings, were also identified during the survey.

Recommended policy options

To reduce or minimize the identified barriers, policy options are developed aimed at attracting investment in waste heat to power generation projects, reducing project risks, increasing research, development, and deployment (RD&D), and leveraging local motivations at the provincial and city level.

Policy options are developed in two packages. A short-term package (2015-2016) includes policies that can be implemented quickly, drive tangible investments, and lay the groundwork for future development. A long-term package (2017-2020) includes policies that require longer time to prepare (e.g., drafting policies and political discussions among stakeholders) and longer time to achieve results. The long-term package can also benefit from the already-implemented short-term policy solutions in terms of technical assistance, information dissemination, and awareness in waste heat to power generation projects. Identified policy options for both the short-term and the long-term are presented in Table 5. The sections below explain each of the policy options, including its purpose, the targeted sector, and the potential impact.

Table 5. Recommended Policies to Increase Waste Heat to Power Generation in China

Short term (2015-2016)	Long term (2017-2020)
• Provide rebates on electricity produced from waste heat • Formulate standards on quantifying waste heat potential and savings • Develop tools for waste heat assessment, technical, and economic potential analysis • Provide training of qualified specialists in waste heat standards and tools • Disseminate guidebooks on waste heat to power generation technologies	• Experiment with flexible financing schemes • Integrate waste heat management as a part of energy management systems and local energy targets • Recognize waste heat as non-fossil equivalent and incorporate into national policy schemes • Accelerate innovation and RD&D in waste heat to power generation through pilots and competition

Provide rebates on electricity produced. Under this policy option, investors of waste heat to power generation receive a rebate based on the amount of electricity produced from waste heat to power generation projects. The rebate will be in the unit of RMB/kWh. Compared to incentives on installed capacity, the rebate is designed to encourage actual utilization of waste heat, instead of installing the equipment but with little utilization. Compared to the current national energy-saving incentive, which is a small and one-time incentive, the rebate is more attractive. Compared to the current tax refund policy, which is very complex and often does not apply to the waste heat to power generation projects, the rebate is much easier to implement. In addition, verification and monitoring of the electricity produced is relatively simple and not expensive. This policy is designed to overcome the economic barrier, reducing the costs of investment, and making the project more attractive.

Formulate standards to quantify waste heat potential and savings. Standards on quantifying waste heat potential, project energy savings, and cost savings can help establishing a transparent and consistent method and reduce the distrust and uncertainties of waste heat to power generation projects. Industrial companies, energy service companies, and local or national governments can adopt the standards voluntarily. Formulating and adopting of standards set the foundations for developing software tools, training, and promoting energy-efficient technologies.

Develop tools and training. Tools can help estimate the potential of waste heat and calculate costs and benefits of implementing waste heat to power generation projects. Tools that are based on the formulated standards can help design the waste heat utilization system, and provide a standardized protocol. In addition, training plant managers and energy service companies can increase the pool of high-quality energy experts in the field and elevate the performance in the whole industry. Both of these polices are designed to reduce the barrier of lack of internal expertise and distrust of external energy services, as well as to minimize the risks and uncertainties from implementing waste heat to power generation in core production and savings.

Develop and disseminate technology guidebooks. Governments, research institutes, and industrial associations develop technology guidebooks to assist companies to identify key technologies in waste heat to power generation, understand potential impacts of using the technologies, and ultimately have more trust in the savings and benefits from the technologies. This policy is designed to overcome the organizational and behavioral barriers, such as lack of internal technical expertise and the risks of implementing the technologies.

Experiment with flexible financing schemes. Currently in China both the industrial companies and energy service companies (ESCOs) rely heavily on debt financing in the form of bank loans. Smaller companies that have limited credit history and/or smaller balance sheets could access much needed capital through flexible financing schemes, such as loan guarantees, energy performance guarantee insurance, and lease financing. Flexible financing schemes can also address the uncertainties of the projects by sharing or collectively reducing the risks across project stakeholders. Experimenting with flexible financing schemes is necessary to understand the advantages and disadvantages in the Chinese context and to identify favorable financing schemes for waste heat to power generation projects.

Implement waste heat management. A regulation on waste heat management can require companies to implement waste heat management principles, i.e., reduce, recycle, and recover. It could also include a requirement to conduct self-assessment of waste heat potential. Waste heat management could be an integral part of the energy management system at the company level, which China has been promoting since 2009. In addition, waste heat management could be incorporated into provincial governments' energy targets (such as through establishing energy-saving targets for waste heat management). This policy capitalizes on the strength of the Chinese government and aims at reducing regulatory and organizational barriers.

Integrate waste heat utilization with national policy schemes. Currently the waste heat resource has not been recognized as part of China's "non-fossil equivalent" target nor has it been explicitly integrated with other national policy scheme, such as the cap-and-trade pilots in the Chinese provinces and cities, energy trading pilots, or the Top-10,000 Energy-Conservation Program. Integrating waste heat with key national policies explicitly not only can raise the awareness of this invisible resource, but also provides incentives for companies to realize the potential. Moreover, by leveraging other policy schemes, companies can gain access to information, best practices related to waste heat, as well as potential funding sources. These national schemes, by establishing a platform among companies, also create “peer pressure” among companies to compete in energy efficiency and waste heat utilization.

Accelerate innovation and RD&D. Technical barriers, such as temperature restrictions and the chemical composition of heat steams, are among the most important barriers in waste heat utilization. Breakthroughs in materials, manufacturing processes, waste heat to power generation technologies, and advanced heat exchangers could have a significant impact. Innovative technologies, designs, and applications of waste heat are critical to waste heat utilization. Through the support for RD&D, new ideas, materials, and new technologies can be tested, demonstrated, and then further promoted to increase waste heat utilization in China’s industrial sector.

Benefit cost analysis

This section focuses one policy option, i.e., providing rebates on electricity generated from waste heat. It is one of the most important policy options that can be implemented quickly with large potential impact. Rebate programs are widely used in the United States to promote renewable energy and combined heat and power (CHP). Rebate programs account for more than 60% of the total heat recovery programs/ policies at the state level in the United States. Rebate programs also represent 77% and 78% of the currently implemented programs in the U.S. to promote steam system upgrades and energy-efficient manufacturing equipment, respectively (DSIRE, 2015). Detailed analysis of program costs, benefits, and feasibility of implementing such a program would be helpful for policymakers in China.

A benefit-cost analysis is conducted to identify a socially optimal rebate level that maximizes the social net benefits of implementing the rebate policy over a ten-year time horizon. The analysis considers the following costs and benefits that could results from implementing such a policy.

Costs:

- Costs of producing electricity through waste heat to power generation
- Costs of administering the rebate program
- Costs to society of using taxes to fund the rebate program (i.e., the marginal excess burden of taxation)

Benefits:

- Benefits of avoided costs of fossil fuel to generate electricity
- Benefits of avoided carbon dioxide emissions
- Benefits of avoided air pollution (PM2.5, PM10, SO_2, and NO_x)

Each cost and benefit is quantified and monetized. Ten-year cost and benefits are determined by discounting the total sum of monetary values to a present value with an 8% social discount rate. Assumptions used in the benefit-cost analysis can be found in Summary 5: Assumptions of the benefit-cost analysis.

The analysis shows that a socially optimal rebate level would be 0.20 RMB/kWh ($0.03 USD/kWh), with ten-year discounted total net benefits of 1 billion RMB ($160 million USD [2012 price]). Social net benefits would start to increase when the rebate level is higher than 0.11 RMB/kWh ($0.02 USD/kWh). But when the rebate level is higher than 0.33 RMB/kWh ($0.33 USD/kWh), the results will not pass the benefit-cost test, i.e., resulting negative total benefits (Figure 8).

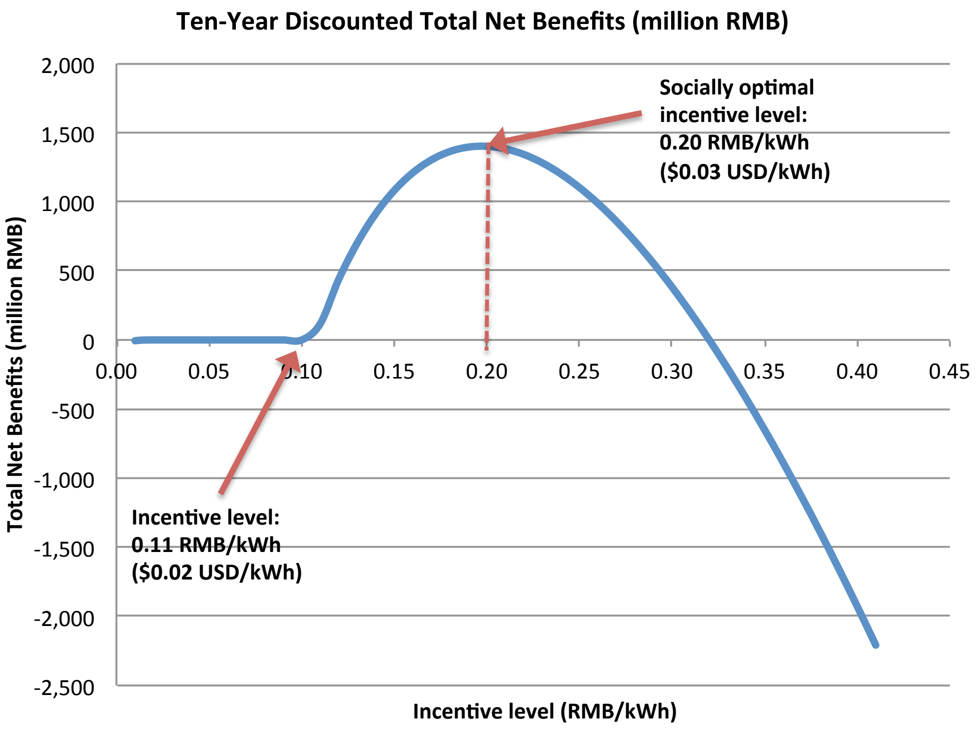

Figure 8. Ten-Year Discounted Net Benefits with Various Rebate Levels

Thus, it is recommended that if the Chinese government considers providing rebates on electricity generated from waste heat, a socially optimal rebate level would be in the range of 0.11 – 0.20 RMB/kWh ($0.02 – 0.03 USD/kWh).

Currently, the electricity tariff in China is in the range of 0.6 – 0.9 RMB/kWh ($0.10 – 0.15 USD/kWh), indicating the socially optimal rebate level is only about 10% to 30% of the electricity tariff (Figure 9). Comparing the rebate level with the typical capital cost of high-temperature waste heat to power generation projects, which is about 9,500 RMB/kWh ($1,500 USD/kW), the rebate level is about 5% to 16% of the total capital cost (the percentage varies by capacity factor). Both of these comparisons indicate that a socially optimal rebate level, incorporating social costs and benefits (such as air pollution), while being 10% to 30% higher than the current industrial electricity tariff, it can help push the industrial companies to overcome the economic hurdle and invest in waste heat to power generation technologies.

At the national level, industrial companies can apply for a one-time energy-saving award with a rate of 240 RMB/tce (in the east region) and 300 RMB/tce (in the middle and west regions). However, comparing the socially optimal rebate level to the national energy-saving incentive shows that the national energy-saving incentive is 3-5 times smaller (Figure 9).

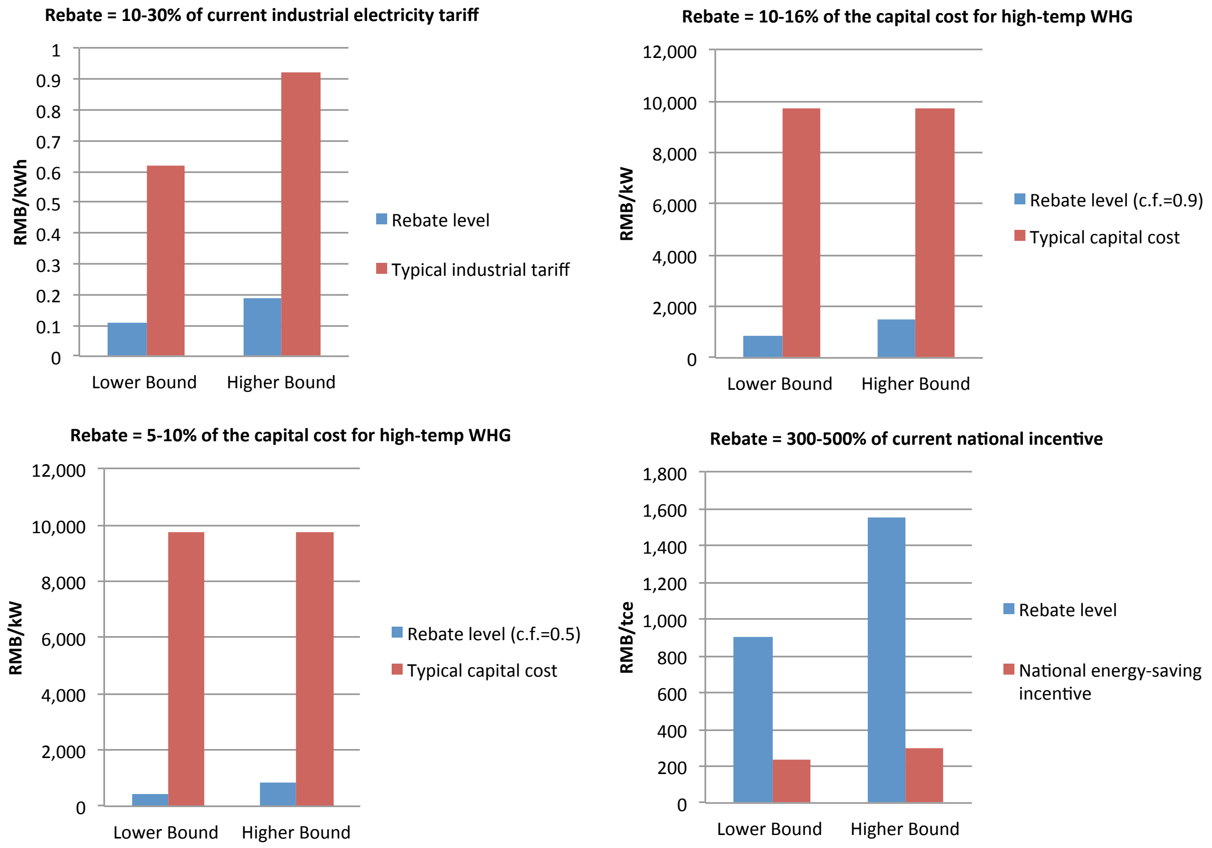

Figure 9. Compare the Proposed Rebate to Other Costs and Incentives
Note: WHG = waste heat to power generation; c.f. = capacity factor.

This sharp contrast in the level of incentives may be explained by the design of the national energy-saving incentive. There is no distinction in the national energy-saving program in terms of incentive levels among sectors, projects, technologies, or systems. This “one-size-fits-all” policy cannot reflect project characteristics, such as costs, financing, inherent risks, and expertise needed. As a result, it is very likely that the national energy-saving incentive only has a marginal effect on waste heat to power generation projects. Because these projects are more costly (compared to other projects, such as lighting projects), the national incentive has very little pulling effect to attract investment.

Therefore, it is recommended that the Chinese government shift the “one-size-fits-all” incentive policy on energy-savings to a “differentiated” incentive policy, with multiple or progressive incentive levels. Incentive policies can also be bundled with other non-monetary policies or programs, such as technical assistance, best practice exchange platforms, public recognition, mandates, and regulations, to strengthen the robustness of the incentive program.

Conclusions

Waste heat is an invisible energy resource. It can be used to provide electricity, steam, space heating, cooling, and hot water. Waste heat is a by-product of manufacturing processes, representing up to 50% of the sectoral fuel input. It is an invisible energy resource that requires careful management by following the “Reduce, Recycle, and Recover” principle.

China is the largest energy user and carbon dioxide (CO_2) emitter in the world. The industrial sector consumes about 70% of China’s energy where coal is the predominant fuel. As China sets its goal to peak CO_2 emissions around 2030 and plans to cap coal consumption, understanding, managing, and utilizing waste heat in China’s industrial sector will support China to achieve its energy, environment, 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 of the waste heat was 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.

This study analyzed the theoretical maximum potential and practical potential of waste heat in the cement, iron and steel, and glass sectors in China, based on thermal energy modeling, expert interviews, and literature reviews.

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, such as iron and steel, need to consider using waste heat as thermal energy rather than solely focusing on waste heat to power. Low temperature waste heat recovery has significant potential but key barriers exist in materials, technology designs, equipment, and costs.

This study finds that sectors such as glass and cement are favorable for implementing easily adopted and cross-sector waste heat to power technologies (such as Steam Rankine Cycle and Organic Rankine Cycle). They 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.

Glass sector, even though has a smaller energy profile compared to the cement and iron and steel sectors, has the highest waste heat to power generation potential on a per unit of production basis. However, the current penetration rate of waste heat to power generation technologies in the glass sector in China is very low, at about 10%. It is needed to understand the barriers to implementation of this technology in sectors that have high potential.

Key barriers to implementation of waste heat to power generation are identified in this study through surveys and interviews with industry experts and professionals. Economic hurdles, including long payback time, high first cost, and lack of access to capital, technical barriers to full utilization of the waste heat potential, and regulatory conditions such as low energy prices and lack of policy synergies are among the most important, in additional to organizational and behavioral barriers.

Therefore, to reduce these barriers and maximize the potential of waste heat, it is recommended to consider providing a rebate for electricity generated from industrial waste heat, at a level between 0.11 RMB/kWh ($0.02 USD/kWh) and 0.20 RMB/kWh ($0.03 USD/kWh). This range is determined through a benefit-cost analysis incorporating environmental benefits and the costs to adopt waste heat to power generation technologies. Technical assistance, such as formulating standards on waste heat assessments, developing software tools to quantify waste heat potential, providing technology guidebooks to screen domestic and international technologies, and conducting training workshops can be implemented quickly, to increase awareness, establish technical know-how, and reduce project uncertainties.

In the long term, it is recommended that the Chinese government to experiment with flexible financing schemes, incorporate waste heat into national energy or non-fossil targets, and integrate energy savings of waste heat projects explicitly with other policy schemes, such as the cap-and-trade program and the Top 10,000 program. Innovation, research, and development of new materials, innovative manufacturing processes, and advanced waste heat technologies need to be encouraged and accelerated through demonstration projects, pilot programs, awards, and competitions.

Limitations and Future Research

Limited research scope

This research estimated the technical potential of waste heat in selected industries, with an emphasis on waste heat potential in the 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 paper focused on exhaust gas waste heat, while other areas are not within the scope of the analysis.

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. This paper identified the key barriers to implementation of waste heat to power generation in China. More work is needed to understand the barriers and opportunities in utilizing medium to low temperature industrial waste heat.

Lack of plant-level details

This research aims 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.

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 this analysis 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., the 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 temperature. This may lead the results to reflect a lower-bound estimate of total available waste heat potential.

Future research

In this scope of this analysis, this study analyzed waste heat potential of three industrial sectors by using one standardized methodology. In the future, this method can be used in other energy-intensive sectors, such as petrochemicals, pulp and paper, and chemicals. In addition, this method can be used in countries other than China, such as Brazil and India. This makes international potential analysis on waste heat feasible.

Future research can also conduct the waste heat potential analysis at a deeper level. For example, sampling of industrial companies can be conducted. Collecting detailed plant-level data provides more accurate information on a number of assumptions, such as exhaust gas temperatures and technology adoptions. This type 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 on low-temperature waste heat 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 needed to help China achieve a low-carbon, sustainable urbanization development.

Policy analysis on how to integrate waste heat utilization in China’s energy and climate goals is needed. Such efforts could be 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” and incorporate waste heat savings into China’s non-fossil targets.

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Technical Summary

Summary 1: Literature review on waste heat potential

Sources of waste heat

Industrial waste heat mainly comes from manufacturing equipment, such as furnaces, kilns, ovens, boilers, reheaters, and reactors. In addition, it can come from wastewater from washing, drying or cooling as well as refrigeration systems, motors, and the exhaust air from production halls (Pehnt et al., 2011). During manufacturing processes, it is estimated as much as 20-50% of the energy used is lost via waste heat in the United States (US DOE, 2008).

Review of studies on waste heat potential

Improving waste heat utilization in industry is one of the key energy efficiency measures. By the U.S. Environmental Protection Agency (US EPA)'s estimate, it could improve industrial energy efficiency by 10% to as much as 50% (US EPA, 1998). There are a couple of nationwide waste heat potential analyses in the United States. From a whole-society, whole-system perspective, in 1974, Earl Cook estimated that about 50% of the energy input to the American 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.

The 1984 study conducted by the US 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 analysis 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 of 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 input, 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).

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, it is not clear from the report about the methodology used to estimate the waste heat potential.

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 the 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 pointed out a significant high energy-saving potential in industrial waste heat. 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 (Summary 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.

Summary Table 1. International Studies on Waste Heat Potential

Literature review	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 (≥140°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

For waste heat potential in China, there are very few studies available. 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 ranges 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 is probably 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), Zhou (2012), and Dong (2013) also provided valuable information on China's current status of waste heat utilization. Specifically, Lu (2010) provided estimates of additional waste heat to power capacities in the cement, glass, iron and steel, chemicals, and non-ferrous metals sectors. Zhou (2012) provided information on estimated waste heat potential in seven sectors, 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 on waste heat potential.

As shown in Summary Table 1 and Summary Table 2, there is a general consensus on the significance of the waste heat potential in industrial sectors. However, there is a lack of standardized methodology and engineering analysis approach to provide sectoral level analysis. This research aims to fill this gap by identifying available potential waste heat in key energy-intensive sectors in China through the use of a consistent and transparent methodology.

Summary Table 2. Chinese Studies on Waste Heat Potential

Literature review	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

Summary 2: Literature review on barriers

Barriers to improvement of energy efficiency

Conceptually, the notion of energy efficiency has been challenged since William Stanly Jevons famously established the Jevons Paradox in his *The Coal Question* published in 1865. Jevons pointed out that improvement of energy efficiency leads to increase of use; thus, increases in the rate of resource depletion. This is now referred to as the “Rebound Effect”. Jevons not only discussed the direct rebound effect (consumption increases as efficiency improves), but also pointed out the indirect rebound effect, i.e., the increased demand for other goods and services due to the income effect (Jevons, 1865). When implementing energy efficiency measures, people noticed that not all cost-effective measures are implemented. In fact, the adoption rates of energy efficiency measures in many areas are still low. This phenomenon is called “Efficiency Paradox” (DeCanio, 1998) or “Energy Efficiency Gap” (Jeffe and Stavins, 1994; Gillingham and Palmer, 2013; Koopmans and Velde, 2001).

Studies have been conducted to identify barriers to energy efficiency over the past few decades. The most recent Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) categorized barriers to low-carbon and energy-efficiency investment into the following: investment risks, policy risks, specific technology and operational risk, return on investment, cost of capital and access to capital, market and project size, human resources and institutional capacity (Gupta et al., 2014). More importantly, taxonomy systems of barriers of energy efficiency have been developed by researchers to categorize these barriers. Blumstein et al. (1980) first identified six categories, including misplaced incentives, lack of information, regulation, market structure, financing, and custom (inertia). Cagno et al. (2013) categorized barriers into internal and external barriers from the companies’ point of view. Sorrell et al. (2000) categorized barriers based on economic theories, including neo-classical economics, transaction cost economics, and organizational theory (see Summary Table 3). This structure is used as a key structure in other investigations of barriers to energy efficiency (e.g. Kostka et al. 2013).

Summary Table 3. Perspectives on Barriers to Improving Energy Efficiency

Perspective	**Examples**	**Actors**	**Theory**
Economic	Imperfect information, asymmetric information, hidden costs, risk	Individuals & organizations conceived of as rational & utility maximizing	Neo-classical economics
Behavioral	Inability to process information, form of information, trust, inertia	Individuals conceived of as boundedly rational with non-financial motives and a variety of social influences	Transaction cost economics, psychology, decision theory
Organizational	Energy manager lacks power & influence; organizational culture lead to neglect of energy/environmental issues	Organizations conceived of as social systems influenced by goals, routines, culture, power structures, etc.	Organizational theory

Source: Sorrell et al., 2000.

While Sorrell et al. (2000) provides a useful framework, this framework does not account for other important barriers, such as market barriers, regulatory barriers, technical barriers, and uncertainty issues. These barriers are discussed in other literature (such as Cargno et al., 2013; de Almeida et al., 2003; Painuly and Reddy, 1996).

Barriers to implementation of waste heat to power generation

Studies have also been conducted to investigate the barriers to waste heat recovery projects. Pehnt et al. (2011) categorized the barriers into structural, financial, informational, operational, legal, commitment, and technical barriers based on experiences from European countries, especially Germany. A Norwegian study carried out by ENOVA (Sollesnes and Helgerud, 2009) pointed out that the key barriers of recovery waste heat in industrial facilities are risks, energy price, technical, financial, resource, and competence. The U.S. Environmental Protection Agency's study on combined heat and power identified technical, business, and regulatory as the most important barriers for waste heat to power (US EPA, 2012). Technical reports conducted by PNNL (2006) and the U.S. Department of Energy (US DOE, 2008) focused on technical barriers in particular, including temperature restrictions, chemical composition, application constraints, inaccessibility, and transportability.

For waste heat to power generation projects in China, the key barriers are similar to international findings. A study of waste heat to power in the Chinese coal-gangue brick sector identified the lack of skillful and experienced staff for operation and maintenance as a non-technical barrier, as well as the high sulfur content in the waste heat as a technical barrier (Camco, 2010). Reports on Clean Development Mechanism projects showed that waste heat to power generation projects in China found that they were a number of barriers, including investment barriers (absence of financial instruments, limited access to financial resources, absence of energy service companies' high quality service, lack of alternative financing channels), technological barrier (high cost of imported equipment and limited reliability of domestic equipment), and risk barriers to implement new technologies (UNFCCC, 2006). Other barriers for implementing waste heat to power generation in China including lack of awareness and resistance by national electric grid operators (UNFCCC, 2010).

These studies provide useful insights and information on specific projects. However, there is still a lack of comprehensive studies focused on waste heat to power generation in China. Current studies have not identified the most important barriers. More importantly, policies to reduce or minimize these barriers are needed.

Summary 3: Methodology and data sources

Literature review

Literature review was conducted in two parts. The first part reviewed literature on waste heat potential in energy-intensive industrial sectors. International studies on waste heat potential in United States, Germany, Norway, and Chinese domestic studies on waste heat potential in Chinese industries were reviewed. Through this part of the literature review, the paper identified methodologies used to assess waste heat potential, key findings of these papers, and their limitations. This part of literature also provided a basis for key assumptions used in the thermal energy-modeling tool of this paper, such as exhaust gas temperatures. Based on the literature review, this paper aims to fill a research gap and apply a defined waste heat potential methodology to Chinese industrial sectors.

The second part of the literature review looked at key barriers to implementation of waste heat to power generation projects in China. This paper reviewed previous studies of "efficiency gaps" and general barriers to improving energy efficiency. Then, this paper focused on the main barriers to adopting waste heat to power generation in China and other international countries, such as United States, Germany, and Norway. Based on the literature review, this paper identified a list of barriers to be considered for waste heat recovery projects in China.

Thermal energy modeling

A thermal energy-modeling tool was developed to estimate the technical potential of waste heat. The method used in the tool is thermal enthalpy analysis, as shown in Equation (1), which takes into account of fuel input, fuel composition, and exhaust gas temperatures (US DOE, 2008).

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

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.

The predominant fuel input in Chinese industries is coal. Given the complexity in coal composition and coal types, this analysis assumes coal used in the studies 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 58 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 considers heavy fuel oil and uses a typical lower heating value of 9,700 kcal/kg (17,470 Btu/lb). Lastly, this analysis assumes that there is about 3% oxygen remaining after the combustion process is completed.

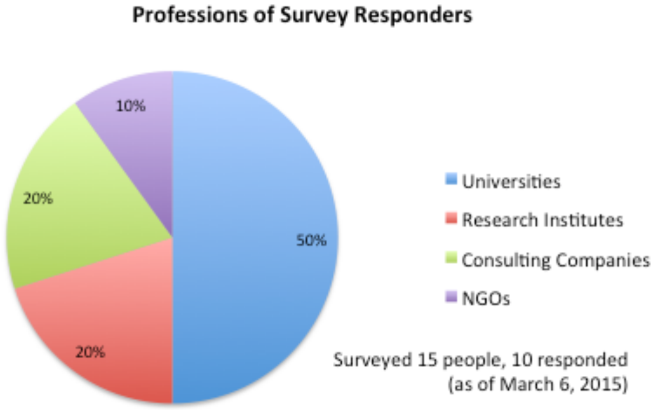
In order to calculate waste heat potential based on enthalpy, two reference temperature set points are used: 1) 25°C (77°F) ambient temperature to estimate the theoretical maximum potential; and 2) 150°C (300°F) to estimate the practical amount of waste heat potential.

This study then focused its attention on the amount of power that can be produced from waste heat. The Carnot Efficiency, which provides the maximum amount of heat that can be converted into power (no matter what technologies are used), is provided. This analysis also considers the efficiency of real-world equipment. Based on expert interviews and the 2004 report provided by Energetics (Energetics and E3M, 2004), this study assumes in practice about 20% of waste heat potential can be converted to produce electricity.

Survey of key barriers

A survey was conducted to identify the largest barriers to implement waste heat to power generation projects in China. A list of 25 barriers categorized in six areas was developed. The survey requested recipients to rank the importance of barriers with a rating from 1 to 5, with 1 being the least important and 5 being the most important. Recipients of the survey can also rank the barriers with a rating of "0", indicating the barrier is not important at all for China. In addition, recipients can add other barriers they regard as important.

This survey was sent to 15 professionals and experts of industrial energy efficiency in China (10 people), United States (3 people), and Netherlands (2 people). The author knows all of the people on the list (except for one) through her research and work experience. The author chose to contact them because of their expertise in industrial energy efficiency and their experience of working in China. The author also considered how much time each recipient may need to complete the survey. As of March 6, 2015, ten recipients (out of 15) responded with ratings to each barrier. The breakdown of the recipients' professions is shown in Summary Figure 1.



Summary Figure 1. Breakdown of Survey Responders

Expert interviews

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

During the interview, barriers to implementing energy efficiency projects in industrial companies and barriers to invest in waste heat to power projects were discussed as well. Opinions of industrial experts were documented and used as an important source for identifying the most important barriers, in parallel to the survey results.

Cross-examination of data

Cross-examination methods are used to crosscheck the outputs from the thermal energy modeling. The methods include comparing model outputs to the reported Chinese data (although only a few data points are available) and comparing to the results from estimating the differences between the theoretical minimum energy intensity and the practical energy intensities of the various industries.

Benefit-cost analysis

Benefit-cost analysis is used to estimate the potential benefits and costs resulting from implementing a hypothetical incentive policy. In this step, items of direct benefits and co-benefits (such as reduced coal use, carbon emissions and pollutants, and improved health impacts) and costs are identified. The impacts are monetized over a studied period of 10-year with a social discount rate of 8%.

Data sources

Industrial energy use data in China mostly is provided in the China Energy Statistical Yearbooks published by the National Bureau of Statistics (NBS). Sectorial data, such as production by technology and by process comes from sectorial yearbooks published by related industrial associations. Exhaust temperatures of current production processes as well as thermal efficiency and cost data of waste heat to power technologies are based on both literature review and interviews with industry experts in both United States and China. Penetration levels of current use of waste heat to power technologies relied on published government technology catalogues, industrial associations' surveys, interviews with experts, and literature research. Energy intensity levels for studied sectors relied on the Chinese minimum energy efficiency standards (MEPS) for industrial products.

Summary 4: Survey questionnaire

The following survey questionnaire was developed and sent to 15 professionals and experts in the field of industrial energy efficiency, in both China and other countries.

Barriers to Waste Heat to Power Generation in China's Industry Sector

Purpose:
I am doing this to finish my Master's thesis at UC Berkeley. My thesis focuses on waste heat potential in China's industrial sector. This questionnaire is designed to understand the key barriers to a greater use of waste heat to power generation in China.

Thank you so much for your time and inputs!

To start:
Please rank each of the barriers within its category from 1 to 5, with 1 being the smallest barrier and 5 being the largest barrier.

If you think the listed item is not a barrier, please rank it with 0.

If you have other barriers to suggest, please add them under the table.

Questions and comments - please contact:
Hongyou Lu, hylu@lbl.gov

Barrier Category	Barriers	Ranking (1-5)
Economical	High first cost for waste heat to power generation projects	
	Long pay-back time	
	Lack of access to capital	
Technical	Unable to fully utilize med-low temperature waste heat	
	Requires matches between heat supply and heat demand	
	Increase complexity in process controls	
Regulatory	Low-priced/subsidized energy prices	
	Long permitting process in construction and operation	
	Difficult to be connected to the grid	
Legal	Lack of experience in setting up the legal contracts	
Organizational	Lack of top leadership commitment	
	Lack of internal technical expertise	
	Lack of high quality external technical services	
Behavioral	Affecting core production	
	Uncertainty of savings	
Other Barriers?	(Please add here)	

Summary 5: Assumptions of the benefit-cost analysis

Economical Assumptions	**Value**	**Unit**	**Source/Note**
Capital Cost			
High-temp waste heat	1,500	$/kW	Expert interviews
Med-temp waste heat	2,500	$/kW	
Low-temp waste heat	3,000	$/kW	
Super low temp waste heat	5,000	$/kW	
Operation and Maintenance Cost			
High-temp waste heat	0.005	$/kWh	Expert interviews
Med-temp waste heat	0.004	$/kWh	
Low-temp waste heat	0.003	$/kWh	
Super low temp waste heat	0.003	$/kWh	
Administrative Cost			
Average worker salary	42,452	RMB/Year	China Daily, 2012
Average govt staff salary	60,000	RMB/Year	Author estimate
# units monitored by one govt staff	3		Author estimate
Other Economic Assumptions			
Marginal excess tax burden	0.25	$/USD	Boardman et al., 2011
Discount rate	8	%	Harrison, 2010
USD to RMB Rate	6.26	RMB	Market exchange rate
EURO to RMB Rate	6.65	RMB	Market exchange rate

Energy & Environment Assumptions	**Value**	**Unit**	**Source/Note**
Coal-related			
Coal-fired power plant efficiency	34	%	Ecofys, 2011
Heating content of coal	5,500	kcal/kg	Author analysis
Coal price	800	RMB/metric ton	CEC, 2012
Percentage of coal in electricity mix	78	%	NBS, 2013b
Emission Factors			
CO_2 emission factor of coal	2200	kg/metric ton	IPCC, 2006
PM2.5 emission factor of coal	0.18	kg/metric ton	ESP filtered, EPA 2002
PM2.5 emission factor of coal	20	kg/metric ton	Uncontrolled, EPA 2002
PM10 emission factor of coal	50	kg/metric ton	Yi et al., 2008
SO_2 emission factor of coal	18	kg/metric ton	Zhao et al., 2010
NO_x emission factor of coal	8	kg/metric ton	Zhao et al., 2010
Social Cost of Emissions			
CO_2	100	RMB/metric ton	FT, 2014
PM2.5	26,145	RMB/metric ton	Based on PM10
PM10	26,145	RMB/metric ton	Matthews and Lave, 2000
SO_2	12,161	RMB/metric ton	Matthews and Lave, 2000
NO_x	17,025	RMB/metric ton	Matthews and Lave, 2000

Summary 6: Waste heat potential in the cement sector

Cement Industry in China

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 about 60% of global production (USGS, 2014). The second largest cement-producing country is India, contributing about 7% of global cement production in 2012 (USGS, 2014a).

The growth of China's cement industry has closely followed the growth of the Chinese economy in the past 34 years. From 1978 to 2002, cement production in China increased from 65 million metric tons to 725 million metric tons, at a rate of 11% per year (CCA, 2014). The Chinese economy grew at 10.4% per year during the same period of time (NBS, 2013a). The increase of cement production further outpaced the growth of the Chinese economy during the last decade (2002-2012), with the cement production growing at 12% per year while the economy increased 9.6% per year (CCA, 2014; NBS, 2013a). This increase of cement production is largely contributed to the boom of China's real estate industry and building of infrastructure systems around the country, especially following China's stimulus spending program that was put in place after the global economic crisis of 2008. Summary Figure 2 shows the growth of cement production in China from 1978 to 2012.

It is worth noting that, in percentage terms, most of the Chinese cement production is consumed domestically. During 2005-2012, a maximum of 2% of cement production and 2% of clinker production were exported (CCA, 2014). However, given China is the largest cement producer in the world, a 2% of China's cement production is about 44 million metric tons in 2012, equivalent to a country's total cement production (such as South Korea, Mexico, or Thailand's production in 2012) (USGS, 2014a).

There are a large number of cement enterprises in China. As of 2012, China had 3,507 cement enterprises, which was a decrease from 5,130 enterprises in 2006 (CCA, 2014; CCA, 2008). In the meantime, the total capacity of cement production increased sharply from 1.7 billion metric tons in 2006 to about 3.1 billion metric tons in 2012 (Sinoma, 2007; CCA, 2014). It is expected that by the end of 2015 the Chinese cement industry will continue the process of industry consolidating, with a goal of having less than 1,000 clinker-producing enterprises, less than 2,000 cement grinding enterprises, and 35% of total production coming from the top 10 cement corporations[3] in China (Digital Cement, 2013).

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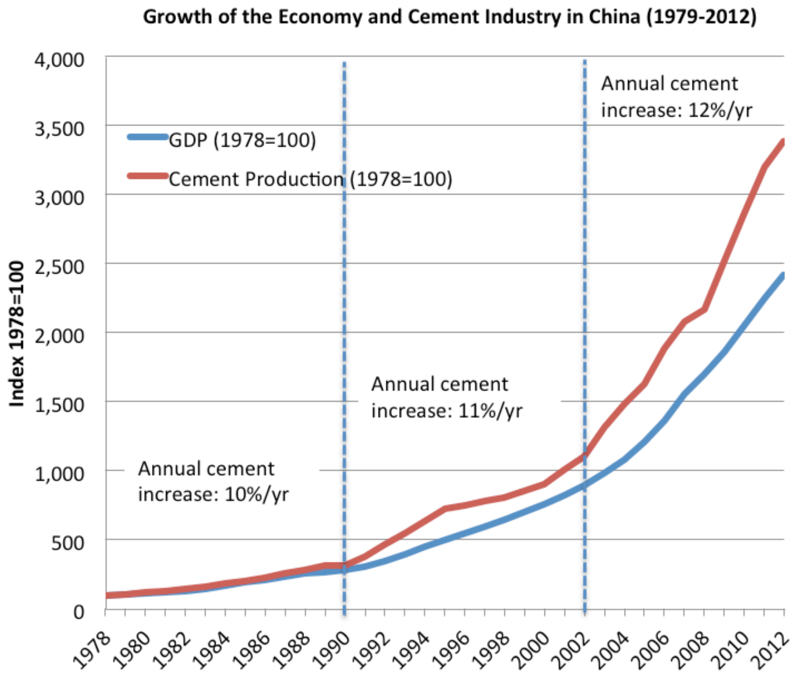
[3] As of 2014, the Top 10 cement corporations are (ranked by clinker production capacity): China Building Materials Company, Anhui Conch Cement Company, Sinoma, Jidong Cement, China Resources Cement, Sunnsy Group, Huaxin Cement, T'cement, Hongshi Group, and Tianrui Cement (Source: IBICN, 2014).



Summary Figure 2. Growth of China's Cement Production (1979-2012)

Source: CCA, 2014; NBS, 2013a.

Cement Manufacturing Processes

Cement is non-metallic substance with hydraulic binding properties. It is a fine power and can be mixed with water to form a paste, which hardens due to formation of cement mineral hydrates (Worrell and Galitsky, 2008). Mixing cement with mineral aggregates and water forms concrete, which is a key and common building material.

In China, cement is extensively used in buildings, the transportation sector, industry, and energy supply systems. In 2012, buildings, railways, roads, and other transport systems consumed more than half of cement produced in China (CCA, 2014). The remaining share of cement is used to build industrial facilities, power plants, distribution systems for power, heat, gas, and water, as well as other urban and rural infrastructure systems.

The process of cement manufacturing can be dated back to the Romans or even earlier. However, the modern cement manufacturing process started in the early 19th century when an established process was developed. This manufacturing process involves quarrying and crushing of calcareous rocks (usually limestone), grinding the calcareous material with other raw materials – such as shale, clay, slate, blast furnace slag, silica sand, and iron ore, and heating the raw materials at controlled high temperatures in a kiln to produce clinker (Worrell and Galitsky, 2008). After being discharged from the kiln, clinker (usually gray and in the size of marbles) is then cooled by ambient air. In the final stage of the process, cooled clinker is grounded and mixed with gypsum and limestone in cement grinding facilities. The general manufacturing process flow is depicted in Summary Figure 3.

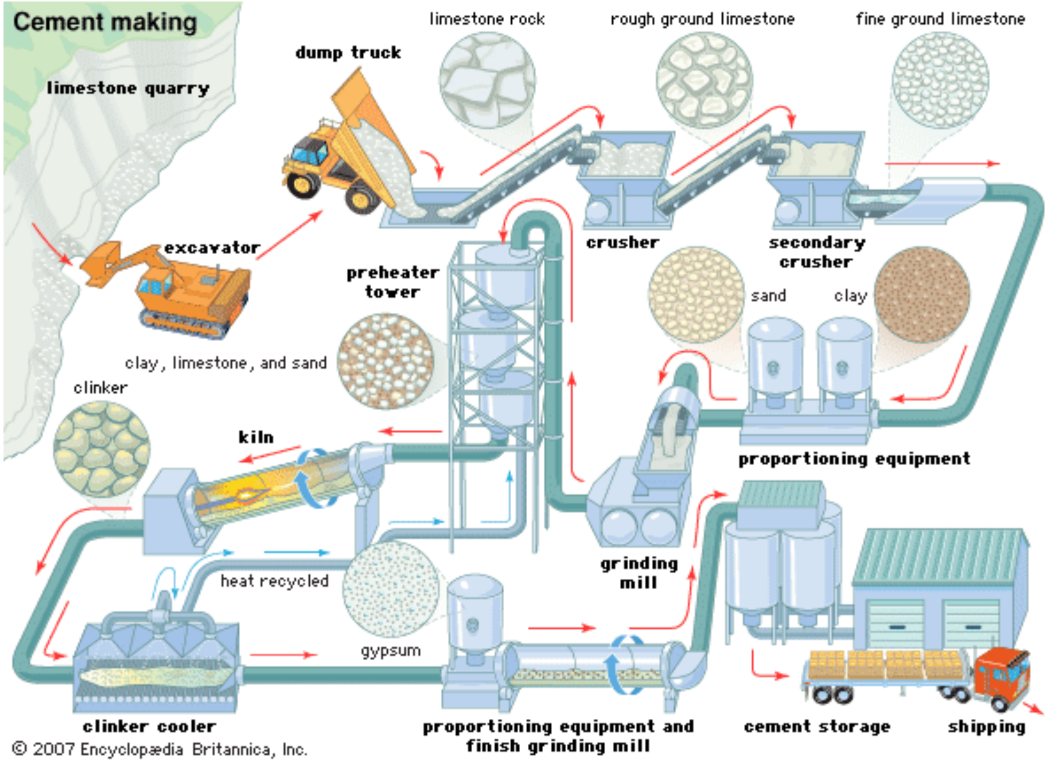
In China, the United States, and the world on average, Portland cement makes up of the most common type of cement product (PCA, 2012). Portland cement can be blended with other additives, such as blast furnace slag, fly ash, silica fume, and natural pozzolan to have different properties. Sections below explain the basic processes of cement manufacturing in more detail with a focus on energy use in this industry.

Mining and Quarrying

The first step of cement making is mining and quarrying raw materials. The main ingredient is usually limestone that provides the required calcium oxide. For ease of transportation, cement plants are usually located at or very close to limestone quarry sites, which can transport limestone after its extracted (often from open-faced quarries). The limestone is then crushed into smaller sizes in several stages (i.e., first crushing and secondary crushers).

Other raw materials are also used, such as shale, clay, slate, blast furnace slag, silica sand, and iron ore. These materials provide the necessary silicon, aluminum, and iron oxides. Limestone is then crushed and mixed with these materials, and proportioned to produce the desired chemical properties in the final product.

Mining and quarrying processes use electricity in crushing and conveying raw materials. Diesel fuel is also used for transporting raw materials. It is estimated that about 5% of CO_2 emissions from cement production are associated with this process (WWF, 2008).



Summary Figure 3. Cement Making Process

Source: Encyclopedia Britannia, 2007.

Raw Material Preparation
The second step in cement making is the preparation of kiln feed, also called raw mix or raw meal. The dry process is the most common, where proportioned raw materials are further grounded into a fine powder size. Typically horizontal ball mills or vertical roller mills are used in grinding the raw materials in the dry process (Worrell and Galitsky, 2008). The grounded raw materials (kiln feed) have a moisture content of 0.5% on average (Worrell and Galitsky, 2008).

If using the wet process, the moisture content of the kiln feed will be significantly higher, in the range of 24-48% (Worrell and Galitsky, 2008). Originally water is added in the wet process to facilitate grinding; however, the added water also increases fuel consumption in the kiln. In between the dry process and the wet process, there is also semi-wet/semi-dry process, with a moisture content in between 17% and 22% (Worrell and Galitsky, 2008). In the past decades, the wet process has become less and less common as the adoption of improved grinding technologies and proportioning technologies has increased.

The raw material preparation process mostly uses electricity, with an electricity intensity of 25-35 kWh/metric ton (Worrell and Galitsky, 2008). Process waste heat from other parts of the cement-making systems, mainly from kiln exhaust gas and clinker cooler, are often used to dry the raw materials.

Clinker Production
Clinker making, also called pyro-processing, is the core of cement manufacturing. It not only produces the most critical ingredient of cement – clinker – but also uses more than 90% of total cement industry energy use (Worrell and Galitsky, 2008).

Based on the temperature of the kiln feed in the kiln, the clinker production process can be divided into four stages: evaporation, dehydration, calcination, and reaction (US EPA, 1995). First, “uncombined water from raw materials” will be evaporated as the kiln feed enters into the kiln and material temperature increases to 100°C (212°F). Secondly, materials start to form oxides of silicon, aluminum, and iron in the dehydration stage as the material temperature increases from 100°C (212°F) to 430°C (800°F). Then, calcium carbonate ($CaCO_3$) is calcinated to form calcium oxide (CaO) between the temperature of 900°C (1,650°F) and 982°C (1,800°F). The reaction occurs in the last stage of this process, where “the oxides in the burning zone of the rotary kiln form cement clinker” at a temperature of about 1,510°C (2,750°F) (US EPA, 1995).

Due to its relative high-energy efficiency and productive capacity compared to the wet process, the most commonly used technology for clinker production today in China and in the world is the rotary kiln (dry process). By 2012, the share of rotary kilns in China increased to more than 92% compared to less than 40% in 2005 (CCA, 2014; MIIT, 2011b). Thus, this paper focused on the rotary kiln (dry process).

A rotary kiln is a type of furnace in the shape of a tube, with a diameter up to 8 meters (25 feet), and a length varying from 60 to 300 meters (200 to 1,000 feet) (US DOE, 2008). The rotary kiln is installed at a 3-4 degree angle (Worrell and Galitsky, 2008). The kiln feed enters into the kiln at the elevated end while fuel is usually combusted at the lower end of the kiln. As the kiln slowly rotates 1-3 times per minute, the kiln feed continuously moves to the lower end, and combustion gas flows up to the elevated end.

To further utilize the countercurrent manner of gas flow and material flow, preheaters can be added to the rotary kiln. Cyclone-type preheaters can be arranged vertically where the kiln feed moves downward from top to the elevated end of the rotary kiln. During this process, hot exhaust gas from the kiln moves upward bypassing the kiln feed in preheaters. More than one preheater can be added; the building structure that supports the preheaters is called a preheater tower. The typical arrangement in China is a four-stage or five-stage preheater tower. Thermal efficiency of the clinker production process can be further improved by adding a calciner vessel at the base of the preheater tower (US EPA, 1995).

Coal is the main energy input in clinker production, although alternative fuels such as tires, sewage sludge, and municipal solid wastes can also be used. Electricity is used but only contributes to a small share in total energy input of this process. For a dry kiln with four or five-stage preheating, the typical fuel consumption is reported to be in between 3.2 and 3.5 GJ/metric ton of clinker (Worrell and Galitsky, 2008).

The last step of the clinker production process is clinker cooling. In this process, the clinker is cooled rapidly from 1,093°C to less than 93°C (2,000°F to 200°F) by ambient air (US EPA, 1995). Technologies used for clinker cooling include grate coolers, planetary coolers, or rotary coolers. The preheated ambient air can enter into the kiln and be used as combustion air (US EPA, 1995). If reciprocating grate coolers are used, clinker can be cooled down to an even lower temperature as additional ambient air is used for cooling. However, the kiln cannot effectively utilize this additional amount of air for combustion. The additional air used for clinker cooling is either vented to the atmosphere, used for preheating coal, or used as combustion air at the precalciner (US EPA, 1995).

Finish Grinding

Some cement facilities only produce clinker so when clinker is made, they will store clinker for sale, either directly to clinker-purchasers or to cement-grinding facilities. Some cement facilities will have cement-grinding machines onsite to do finishing grinding. This is the final process of cement making, where clinker is added to about 5% gypsum or natural anhydrite and ground in ball mills or roller mills (Worrell and Galitsky, 2008; US EPA, 1995).

This grinding process is electricity-intensive, and the intensity depends on “the surface area required for the final product and the additives used” (Worrell and Galitsky, 2008). The electricity intensity of finishing grinding also depends on technologies used. For example, common ball mills may have an intensity of 32 to 37 kWh/metric ton while the state-of-the-art technologies may be more energy efficient (Worrell and Galitsky, 2008).

Cement Sector Energy Use and Emissions Impact

The cement industry is the third largest energy-consuming manufacturing sectors in China, ranked after the ferrous metals and chemicals sectors in 2012 (NBS, 2013b). In 2012, China's cement industry consumed about 176 Mtce (5,158 PJ) per year (CCA, 2014). This represents about 12% of China's total manufacturing energy use[4], or about 5% of China's total energy use in 2012 (NBS, 2013b).[5]

China's cement industry is very fuel-intensive and uses coal as the main fuel input. From 2008 to 2012, about 90% of the energy input of the Chinese cement industry was fuel while around 10% of energy came from electricity (CCA, 2008-2014). Coal is the predominant fuel source in the Chinese cement industry, contributing around 97% of total fuel input. During China's 11th and 12th Five-Year Plan, the Chinese government has been promoting the use of alternative fuels and raw materials in China's cement industry. The share of gangue (a solid waste from the coal mining and washing industry), industrial wastes, sewage sludge, and municipal solid wastes has increased to about 1-2% of total fuel input.

In addition, China's electricity relies on coal as a key generation source. Although the share of coal use in total electricity production decreased from the peak in 1997 (71% of total power generation came from coal), coal still accounted for 61% of total electricity generation as of 2012 (Summary Figure 4). Oil-fired power plants are less used but natural gas-fired power plants are gaining popularity, driven by government goals to reduce energy-related carbon dioxide emissions. Non-fossil energy, such as hydro, nuclear, wind, and solar, has been promoted in order to decarbonize China's power sector. By 2012, non-fossil electricity production accounted for 38% of total electricity production (Fridley et al., 2014). Heavy reliance on coal poses challenges for China and the Chinese industry in meeting energy and emissions intensity reduction goals.

The cement industry is also one of the most important carbon dioxide emitting industries. This is not just because the cement industry is energy-intensive, but also because chemical reactions occur in the clinker making process to produce CO_2. This is the process where limestone ($CaCO_3$) is calcinated to form calcium oxide (CaO) and releases CO_2. These "process emissions" are typically around 540 kg CO_2 per metric ton of clinker produced and are nearly constant (WBCSD, 2009). Globally speaking, depending on the thermal efficiency and generation sources of electricity used on-site, the cement industry's total CO_2 intensity (including both process emission and emission from energy use) is in the range of 800 kg to 1,000 kg CO_2 per metric ton of clinker produced (WBCSD, 2009). Based on 2008-2009 data, the CO_2 intensity of the Chinese cement industry is about 820 kg CO_2 per metric ton of clinker produced.

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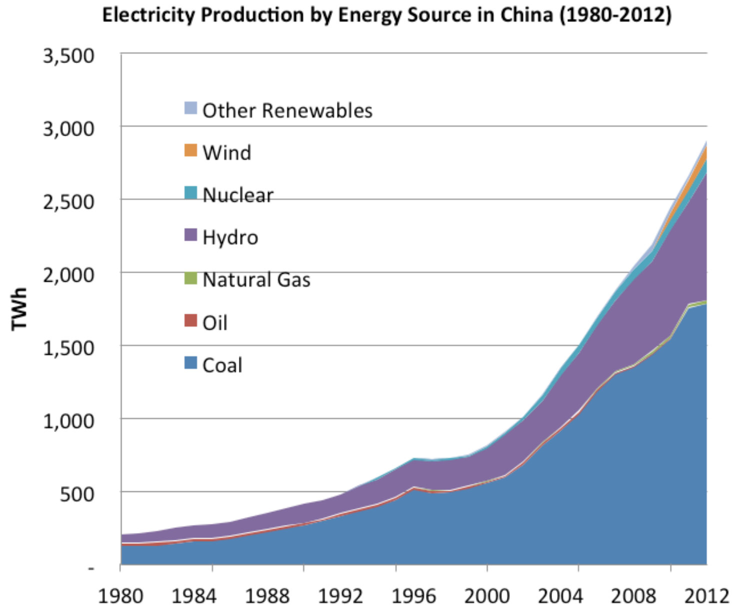
[4] Based on the Chinese energy statistical definition, industrial energy use = energy use for mining and quarrying, energy use for manufacturing, and energy use for water, power, and gas distribution.

[5] Electricity is converted at calorific value.



Summary Figure 4. Electricity Production by Source in China (1980-2012)

Note: Natural gas also includes liquefied natural gas; other renewables includes solar, geothermal, tidal and other renewables.
Source: Fridley, et al., 2014.

China has pledged to reduce its carbon intensity (carbon dioxide emissions per unit of gross domestic product) by 40-45% by 2020 from the 2005 level. This is a domestic announcement, which was then included in the United Nations Framework Convention on Climate Change (UNFCCC) Copenhagen Accord in 2009. In November 2014, China announced its intention "to achieve the peaking of CO_2 emissions around 2030" and striving to "peak early" (U.S. White House, 2014). Energy efficiency is one of the important ways in which China's cement industry can improve its energy performance. Depending on energy costs and energy-saving potential, adopting energy efficiency measures in the cement sector can be either "no-regret" measures to implement or have a relatively short payback period to recover investment, see examples from China (Price et al., 2009) and Thailand (Hasanbeigi et al., 2010).

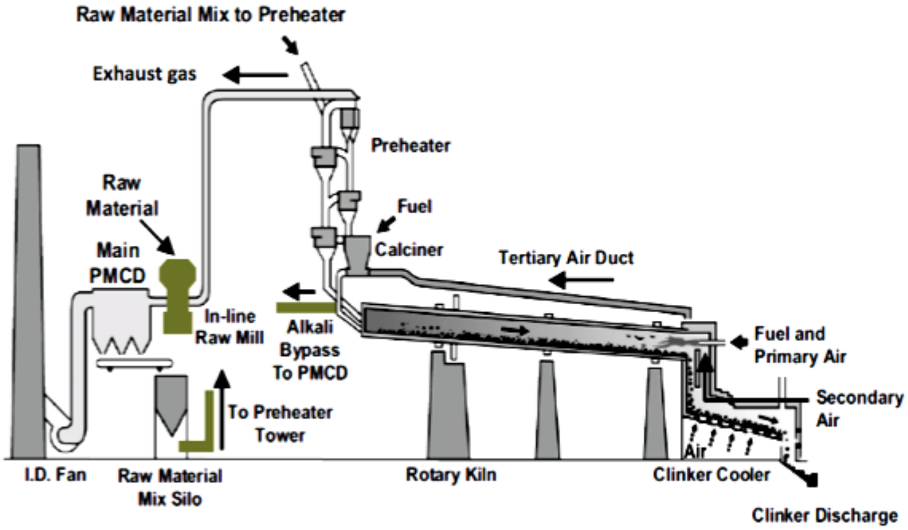
Cement Sector Waste Heat Potential

Sources of Waste Heat

Waste heat from cement making can come from a variety of sources, such as hot gases from combustion products, heat loss through radiation and convection, sensible latent heat in heated product, heat loss to cooling water or other liquids, and hot air/gas from cooling and/or heating systems (Thekdi, 2009). The amount and the quality of the waste heat depend on: 1) the availability of the waste heat, i.e., whether the waste heat is continuous or intermittent; 2) the temperature of the waste heat, i.e., low temperature or high temperature; and 3) the flow rate of the waste heat.

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, as illustrated in Summary Figure 5. In this analysis, attention is focused on the waste heat from the kiln exhaust and the clinker cooler.



Summary Figure 5. Cement Making in a Rotary Kiln with Preheaters
Source: Thekdi, 2012.

Data Input

As of 2012, a large majority of China's cement kilns are dry process rotary kilns, referred to as "New Suspension Preheaters" (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 in Summary Table 4, about 37% of clinker was produced from NSP kilns larger than 4,000 metric tons of clinker per day (tpd) in China. NSPs in the size of 1,000-2,000 tpd accounted for another 36%. Small NSP kilns (<1,000 tpd) contributed to 15% of total clinker production.

Summary 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. This standard prescribed minimum energy performance (i.e., the maximum amount of energy could be used to produce one unit of production) for existing cement plants, minimum energy performance 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 the compliance rate of the MEPS standard may not be 100%; however, this study also finds some cement plants (typically large and newer plants) report and/or have lower energy intensity levels than required by the MEPS. It is for these reasons that this study uses 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 Summary 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 the Lawrence Berkeley National Laboratory and the World Bank in 16 cement plants in Shandong Province, China in 2008 (Price et al., 2009).

Summary Table 5. Energy Intensity of Cement Production in China

Kiln type/ size	Fuel Intensity (kgce/t clinker)	Electricity Intensity (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.

Key Assumptions

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 assumes 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) (ERI, 2011; Harrell, 2014; US DOE, 2008). Summary Table 6 shows the estimated energy use and typical exhaust gas temperature by cement kiln.

Summary Table 6. Fuel Use and Exhaust Temperature by Cement Kiln (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

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 promoted energy-saving projects. By the end of 2010, 55% of the 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).

Results

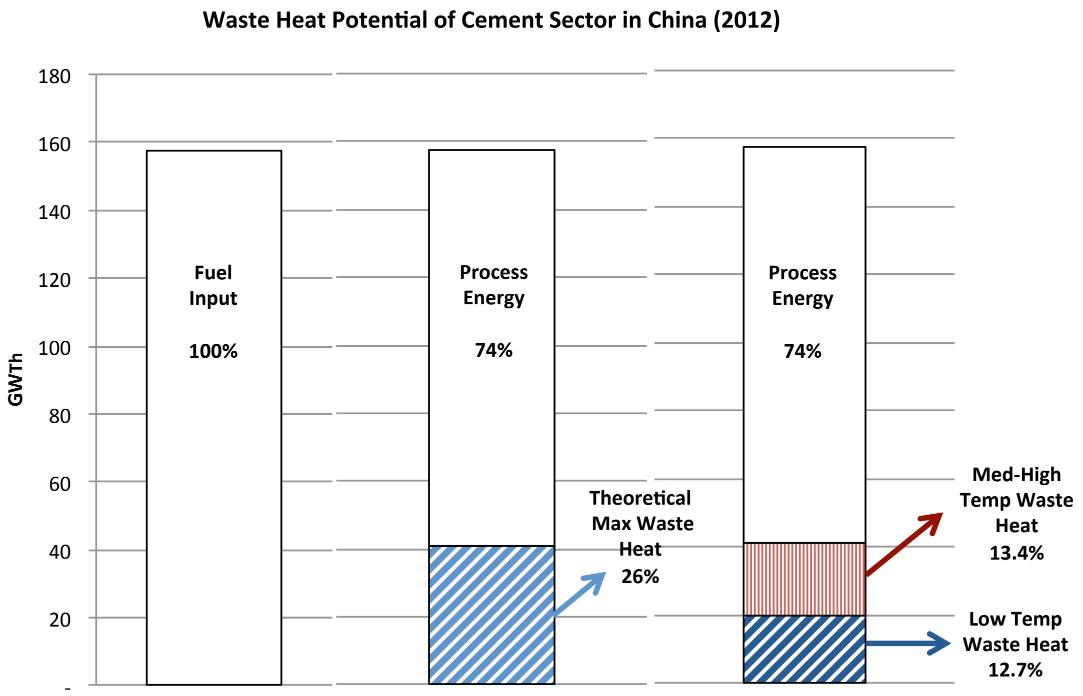
With a reference temperature of 25°C (77°F), the theoretical maximum waste heat from the kiln exhaust is calculated to be a little higher than 41 GW_{Th}, indicated as “Theoretical Waste Heat Potential” in Summary Table 7. However, to recover waste heat from such a low temperature is very difficult. Technically, the current commercial waste heat recovery technologies need to be improved to overcome material, chemical, and physical constraints. For example, due to the sulfur content in the exhaust, dropping the exhaust gas temperature below sulfur’s dew point (128°C [262°F]) will lead to corrosion in heat exchangers. Economically, in order to reach such a low temperature, the cost of waste heat recovery technologies will increase significantly. Thus, this analysis also considers a practical waste heat potential, which refers to recovering the waste heat above the temperature of 150°C (300°F). This provides a waste heat potential of 21 GW_{Th} in China’s cement sector, indicated as “Practical Waste Heat Potential” in Summary Table 7.

Waste heat can be used to produce steam, generate electricity, and provide space heating, cooling, and hot water. This analysis specifically focused on converting thermal energy to power, because electricity is easier to transport and can be used in all end-use sectors. The additional need for infrastructure building is much less for electricity compared to distribution of heat in China. The cost of transmission and distribution of electricity is also lower than transporting heat.

The Carnot Efficiency indicates the maximum amount of power that can be generated from the available thermal energy. If there were no technical or economic barriers, the maximum amount of power could be produced from the theoretical maximum of waste heat potential by following the Carnot Efficiency. This "Theoretical Power Generation Potential" is estimated to be 21 GW_e in the China's cement sector (based on 2012 data).

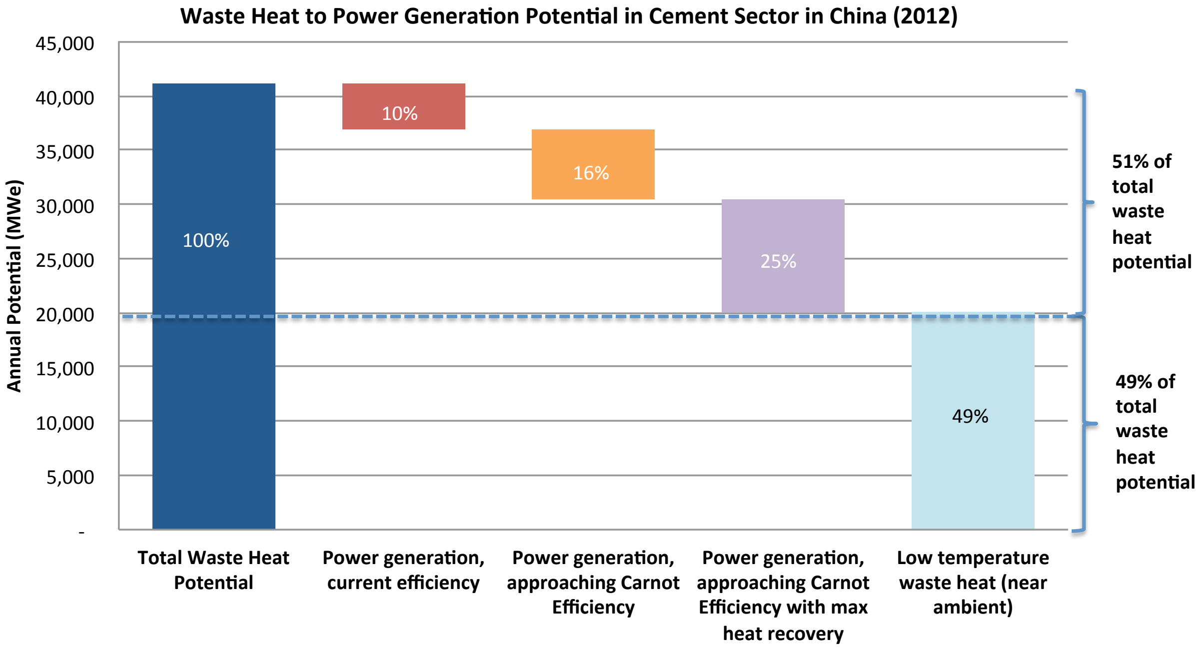
However, there are many constraints when converting thermal energy into power. The two most important barriers are: 1) the difficulty to convert thermal energy that has a temperature below 150°C (300°F) into power; and 2) the real-world efficiency of converting thermal energy to power is much lower than the Carnot Efficiency. "Practical Power Generation Potential (Carnot Efficiency)" is determined based on the practical amount of waste heat potential (i.e., temperature higher than 150°C [300°F]) and the Carnot Efficiency. This shows the maximum amount of power (at about 11 GW_e) that can be generated given the temperature constraint. "Practical Power Generation Potential (Practical Efficiency)" takes into account both the temperature constraint and the efficiency constraint and shows the real-world practical amount of power (at about 4.2 GW_e) that can be generated from the feasible waste heat potential (Summary Table 7).

The results show the maximum technical waste heat potential of the kiln exhaust is about 26% of the total fuel input in China's cement sector. The practical waste heat potential, i.e., waste heat with medium to high temperature, is about 13.4% of the fuel input. Low temperature waste heat accounts for about 12.7% of the total fuel input (Summary Figure 6).



Summary Figure 6. Waste Heat Potential of the Cement Sector in China (2012)

Considering the commercialized technologies and the real-world efficiency, the practical potential of producing power from the waste heat is about 10% of the total theoretical maximum waste heat potential, as illustrated in Summary Figure 7. However, if technical and economic barriers were removed in the future, the potential to produce power from waste heat could be significantly improved. As shown in Summary Figure 7, when efficiency approaches the Carnot Efficiency, power generation potential could be as much as 26% of the total waste heat potential. When developments in materials, physics, and chemistry reduce the temperature and efficiency constraints, a maximum of 51% of the waste heat potential could be converted to power.



Summary Figure 7. Waste Heat to Power Generation Potential in Cement Sector (2012)

The “untapped potential of power generation” in Summary Table 7 takes into account the current penetration of waste heat to power in China’s cement industry. Assuming the technologies are operated to achieve its designed efficiency, this leaves a much smaller potential for power generation. However, this also demonstrates the waste heat technologies are mature and can be scaled up. Waste heat utilization is an effective energy-efficiency measure that can be used in other energy-intensive sectors, such as glass and iron and steel.

Summary Table 7. Waste Heat Potential of the Cement Sector in China (2012)

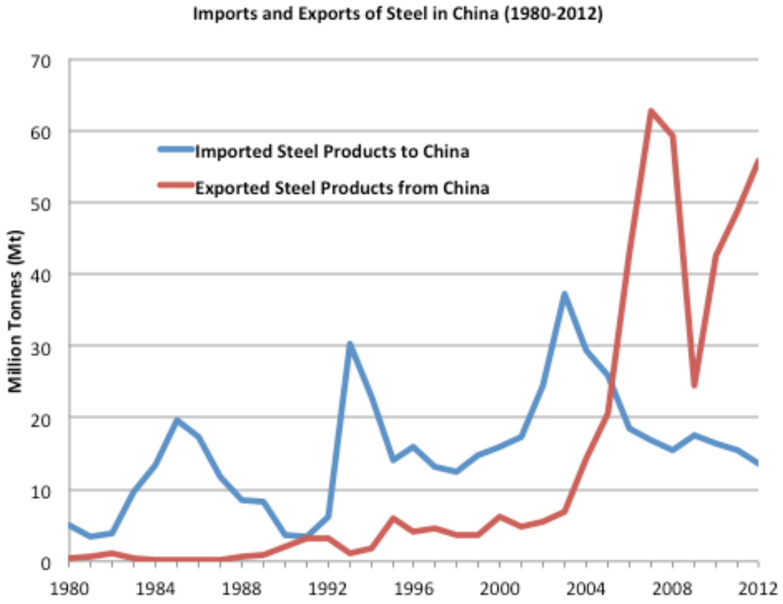
Cement Sector	Thermal Energy Potential (in the form of heat)		Electricity Potential (in the form of power)			
	Theoretical Waste Heat Potential [T_{ref} =25°C (77°F)]	Practical Waste Heat Potential [T_{ref} =150°C (300°F)]	Theoretical Power Generation Potential [Theoretical Thermal Potential × Carnot Efficiency]	Practical Power Generation Potential [Practical Thermal Potential × Carnot Efficiency]	Practical Power Generation Potential [Practical Thermal Potential × Practical Efficiency]	Untapped Power Generation Potentia [Practical Thermal Potential × Practica 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

Summary 7: Waste heat potential in the iron and steel sector

Iron and Steel Industry in China

China is the world's largest iron and steel producer. In 2012, China produced 670 million metric tons (Mt) of pig iron nationally and a total of 731 Mt of crude steel (Editorial Board of China Steel Yearbook, 2013), accounting for 60% of global pig iron production and 46% of global crude steel production (USGS, 2014b). The second largest pig iron making country in 2012 was Japan, contributing about 7% of global pig iron production. The second largest steel-making country in 2012 was the United States, produced 88.7 Mt, or about 6% of global crude steel (USGS, 2014b).

China became a net steel exporter in 2005 (see Summary Figure 8). The net export of finished steel in 2012 was 42 Mt, with about 56 Mt in export and about 14 Mt in import (Editorial Board of China Steel Yearbook, 2013). Compared to domestic steel consumption, the net export of steel is still small (about 6% of total finished steel production was exported in 2012). As of 2014, exports of Chinese steel increased to a record high, reaching to about 94 Mt (Bloomberg, 2015). This was partly driven by sagging domestic consumption in the construction industry, a potential government cancelation on export tax rebates, and relatively low Chinese steel prices (Bloomberg, 2015; Wall Street Journal, 2014). In 2012, the top destination for Chinese steel exports was South Korea, representing about 18% of the total exports. Thailand, Vietnam, Singapore, and India were the other large importers of the Chinese steel. The United States ranked the sixth in terms of importing Chinese steel, accounting for approximately 4% of total exported Chinese steel (Editorial Board of China Steel Yearbook, 2013).

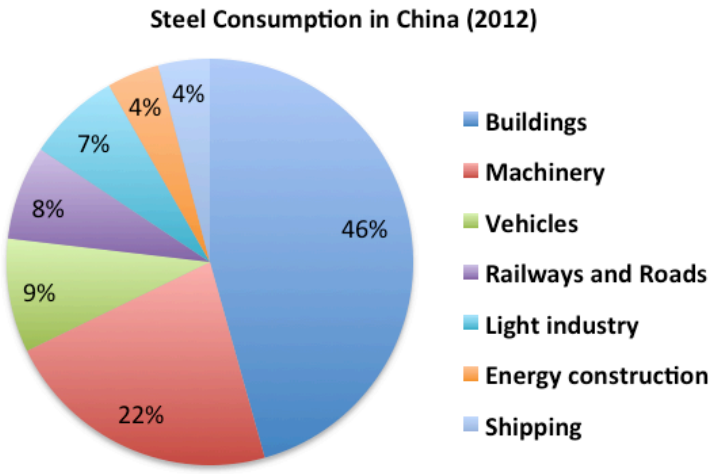


Summary Figure 8. Imported and Exported Steel Products in China (1980-2012)

Source: Editorial Board of China Steel Yearbook, 2013.

Steel is widely used in other end-use sectors in China. By product end-use, steel consumption can be divided into three categories: 1) steel used in building construction and civil engineering projects, such as railways, road construction, airports, and infrastructure building; 2) industrial use steel in machinery, vehicles, shipping, and light industries; and 3) other special uses, such as national defense. Summary Figure 9 shows the breakdown of finished steel consumption in 2012. According to the Chinese statistics, with a total consumption of 634 Mt (exclude other special use consumption), 46% was used for buildings, such as residential and commercial buildings, sports stadiums, and buildings used by industrial facilities. Steel used for the machinery industry represented about 22% of the total. The vehicle industry, the railway & road construction, and light industry accounted for 9%, 8%, and 7% of the total consumption, respectively. Light industry mainly includes appliances and hardware. Energy construction consumed about 4% of the total, including steel used for power plants, oil refining, and petrochemicals. Overall, the Chinese iron and steel industry plays an important role in the Chinese economy, accounting for about 10% of China's industrial value-added (MIIT, 2011c).

The Chinese iron and steel industry is highly fragmented. As of 2009, there were a total of 1,200 steel producers, of which about 70 were medium to large sized companies (Xinhua News, 2009). It is not clear the exact age of the steel production lines in China. However, as indicated in Price et al. (2011), the majority of the steel production capacity in China has been constructed since 2000 and about 80% of the production was from the production lines that are ten years old or younger.



Summary Figure 9. Steel Consumption by End-Use in China (2012)

Source: Editorial Board of China Steel Yearbook, 2013.

Note: Not include other special use consumption.

Product quality is one of the key weaknesses of the Chinese iron and steel industry. According to the Chinese Ministry of Industry and Information Technology (MIIT), only about 30% of the Chinese steel production achieves international advanced levels (MIIT, 2011c). Product quality in the whole industry varies significantly. China still relies on imports for high-strength, corrosion-resistant, and long-lifetime steel products (MIIT, 2011c).

As Chinese steel production increases, overcapacity of the Chinese iron and steel industry is a concern for both Chinese and international steel-makers. The current steel-making capacity has exceeded 1 billion metric tons, with a utilization rate of 70% in 2013 (MIIT, 2013). However, the capacity still increased in 2013, with a newly added crude steel capacity of 40 Mt (MIIT, 2013). Overcapacity directly affects the prices of products as production increases much faster than demand. This may lead to low profit margins for small steel producers domestically and low-cost and low-quality products in the global steel market.

Iron and Steel Manufacturing Process

There are two ways to produce steel (Summary Figure 10). Primary steel making uses iron ore to produce iron and then make crude steel in blast furnaces (BF) and basic oxygen furnaces (BOF). Secondary steel making uses scrap steel (i.e., recycled steel) in electric arc furnaces (EAF). These two methods are expected to remain the primary production methods in the years to come (Worrell et al., 2010). Other production methods do exist, such as Direct Reduction Iron (DRI) and Smelting Reduction Iron (SRI). However, current production using the DRI or SRI method is very small in China. Thus, this research does not consider these process routes.

Depending on which production method the plant uses, there are two types of steel mills: integrated mills and secondary mills. Integrated mills mainly adopt the primary steel making method, which requires preparing raw materials (sintering and pelletizing) and fuel (coking), producing molten iron in a BF, and then making crude steel in a BOF. Secondary mills have a shorter process, which only requires purchasing scrap steel and other raw materials to produce crude steel in an EAF. Integrated mills and secondary mills are also called the long process steel-making and short-process steel-making in China, respectively.

Because this research focused on the iron and steel sector at the national level and the key question of this research is to understand waste heat potential from fuel use, this research focused on the iron-making process. The subsections below briefly explained the processes of raw material preparation (sintering and pelletizing), fuel preparation (coking), iron making, steel making, and casting and rolling.

Sintering and pelletizing

Sintering and pelletizing are complementary processes, both with the goal of preparing the raw materials to improve permeability and reducibility in blast furnaces. In general, sintering plants are located onsite in the integrated mills while pelletizing plants are normally located near the mines or shipping ports (European Commission, 2013b).

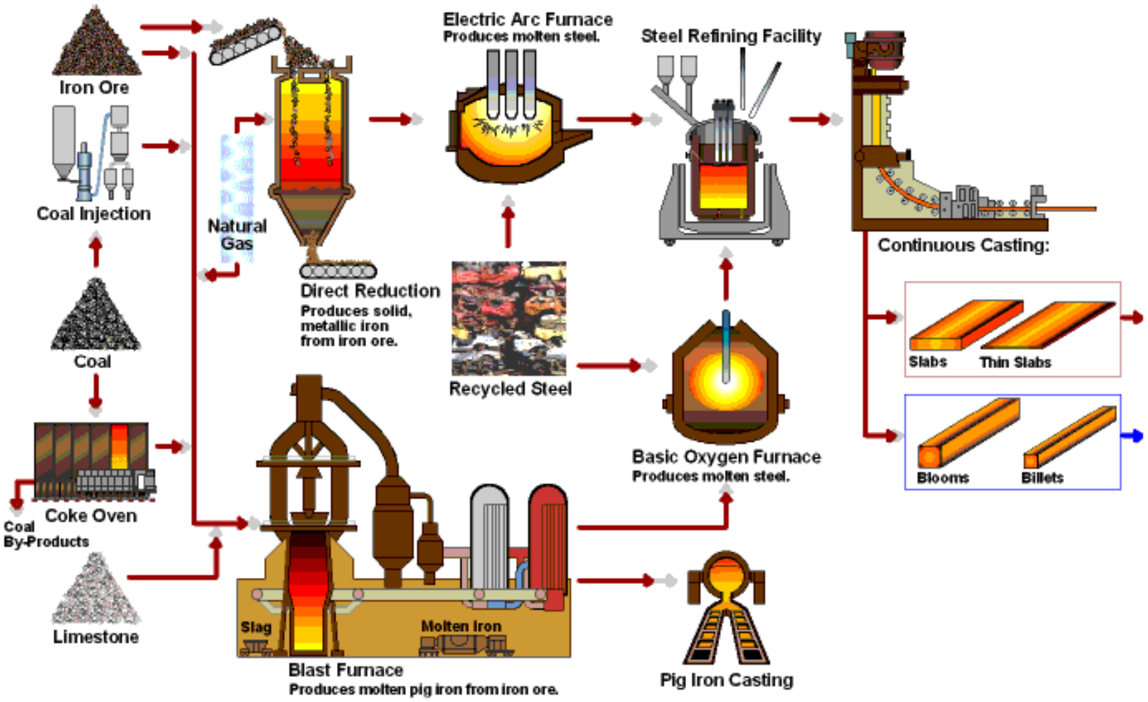
The sintering process uses a mixture of fine particles, including fine iron ore, additives (lime or olivine), and recycled iron-bearing materials (such as coarse dust and sludge from blast furnaces and recycled sinter) (European Commission, 2013b). Coke breeze (with a particle size of < 5mm [<0.2 inch]) is used as the fuel input. The ore mixture and coke breeze is blended, dampened, and combusted to produce porous lumps (sinter). The process temperature is in the range of 1,300-1,800°C (2,372-3,272°F) (Worrell et al., 2010).

The pelletizing process uses iron ore and additives to form small-crystalized balls with a size of 9-16 mm (0.36-0.6 inches) (Worrell et al., 2010). After grinding, drying, and mixing, the process prepares green ball, which is then thermally treated in a step called induration. Induration has a typical temperature of 1,250-1,350°C (2,282-2,462°F). This step increases the iron concentration to 60-65% (Worrell et al., 2010).

Coking

Coking is the process of heating coal in an oxygen-free condition for a continuous amount of time, usually varying from 14 to 28 hours. The product of the coking process, coke, is a critical reducing agent for iron making in blast furnace. Gasified coke provides needed heat in the iron reduction process and is a permeable support to allow a free flow of gases through the furnace (Worrell et al., 2010).

Coking coal (or Bituminous coal) is heated up to 1,000°C to 1,100 °C (1,832°F to 2,012°F) in the coke oven, which has multiple chambers installed in a series of batteries (see Summary Figure 10). The exhaust gas from the coke oven gas needs to be dried and cleaned, as it often contains moisture, volatile matter, sulfur, tar, and other chemical compounds. The cleaned coke oven gas is a fuel and can be reused in the coke oven.



Summary Figure 10. Iron and Steelmaking Process

Source: Steelworks, 2015.

Iron making

The blast furnace is used to produce molten iron. The charge materials to the blast furnace, often called “the burden”, include raw iron ore, sinter or pellets, coke, and lime. The furnace is installed vertically and the charging materials are supplied from the top to the furnace layer by layer.

Hot compressed air is injected from the bottom of the furnace. It combusts the coke and starts the chemical reaction between the combustion gases (carbon dioxide and carbon monoxide) and the other iron-based charging materials. After slag is removed, the reduced and melted iron is collected at the bottom of the furnace and is then transported to the basic oxygen furnace for steel making.

The temperature within the blast furnace is the highest at the bottom and decreases as the gases move upward. The gasification temperature is around 2,200°C (3,992°F) and it gradually decreases to around 200°C (392°F) at the top of the blast furnace. The discharged molten iron has a temperature of 1,400°C -1,500°C (2,552°F - 2,732°F) and the slag is about 1,450°C - 1,550°C (2,642°F - 2,822°F) (European Commission, 2013b).

The blast furnace also produces a low calorific by-product, blast furnace gas. After cleaning, it can be used as fuel and/or mixed with coke oven gas or other gasified fuel. In addition, blast furnace gas can also be used in hot blast stoves as a fuel and/or preheat the combustion air.

Steel making

As discussed above, there are two main ways to produce steel, i.e., through a BF-BOF route or with an EAF. Other methods such as DRI and SRI also exist but with limited applications so far. Due to the scope of this research (waste heat from fuel combustion), the discussion below focuses on BF-BOF route steel making.

The basic oxygen furnace is used to reduce the carbon concentration in pig iron from about 4% to less than 1% and to reduce impurities. This process uses pure oxygen to oxidize carbon and other impurities (such as silica, manganese, and phosphorus) in the pig iron. This process is exothermic, i.e., releases a significant amount of heat. The temperature inside the BOF can be around 1,600°C -1,650°C (2,912°F -3,002°F).

The BOF steel making process sometimes is considered a zero-energy process. In fact, in some Chinese research papers it is often called “use negative energy to make steel” (负能炼钢). However, these names do not reflect the true nature of the BF-BOF process. BOF is an exothermic process and significant energy is consumed in the coke ovens and blast furnaces. In addition, installing and operating the BOFs and ladles, producing oxygen and additives (lime), and operating auxiliary systems consumes energy as well.

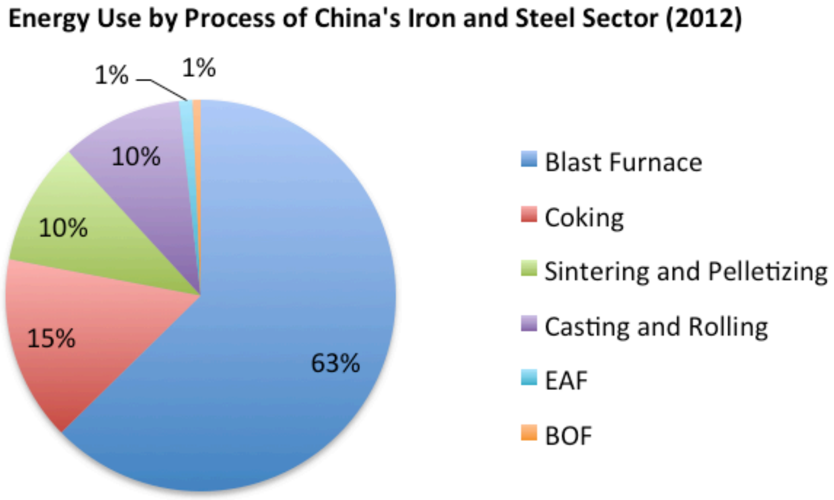
Casting and rolling

Once steel has been produced, steel is then casted, rolled, and shaped into final products with desired chemical and physical properties. Continuous casting is the most adopted casting technology today where molten steel is cast in a continuous strand. As of 2012, 98% of the steel in China is cast continuously (Editorial Board of China Steel Yearbook, 2013). The rest of the steel is ingot cast. Steel is then rolled (hot rolling and cold rolling) to the desired thickness.

Iron and Steel Sector Energy Use and Emissions Impact

The iron and steel sector is one of the largest energy sectors in China. Its energy consumption accounts for 10-15% of the total energy use and 15-20% of the total industrial energy use (Ma et al., 2012). The energy efficiency of China's iron and steel sector has improved over the last ten years while production has increased at a fast rate. However, China's specific energy consumption of iron and steel sector is still 20% higher than international advanced level (Ma et al., 2012). Studies conducted by the Lawrence Berkeley National Laboratory (LBNL) and the China Iron and Steel Research Institute showed that specific energy consumption depends on a number of factors, such as conversion factors, boundary definition, and industry structure (Price et al., 2011).

Iron making (blast furnace) is the most energy-intensive process in the iron and steel sector in China. In 2012, it accounted for 63% of the total energy use in China's iron and steel sector (Summary Figure 11). Coking follows, consuming about 15% of the sectoral energy use. BOF and EAF processes use much less energy.



Summary Figure 11. Energy Use by Process in China's Iron and Steel Sector (2012)
Source: Editorial Board of China Steel Yearbook, 2013 and author calculations.

More than 96% of energy input in China's iron and steel sector came from fuel. Electricity accounted for 4% of total sectoral energy use. Based on Price et al. (2011), coke, washed coal, and raw coal are the largest sources of fuel input, representing about 42%, 38%, and 12% of total sectoral energy use in 2006.

Iron and Steel Sector Waste Heat Potential

Sources of Waste Heat

The exhaust from coke ovens is called coke oven gas, which is a valuable waste heat source and can be cleaned and reused. Coke oven gas can be used to provide additional heat needed in the coke oven, or can be mixed with other fuels (e.g., blast furnace gas or natural gas) for other processes. Exhaust gas from combusting coke oven gas can also be cleaned and recovered to preheat combustion air and/or fuel. Another source of waste heat recovery in coke ovens is the sensible heat from coking. For example, Coke Dry Quenching (CDQ), which recovers waste heat from coke quenching gas in the coke production process, has become increasingly popular in integrated steel mills in China.

The blast furnace produces blast furnace gas as one of the main by-products. Similar to coke oven gas, blast furnace gas (BFG) can be cleaned and reused as a fuel. BFG can be combusted or mixed with coke oven gas in blast furnace stove to preheat combustion air (the blast) for use in the blast furnace. Exhaust gas from burning BFG can also be cleaned and recycled to preheat the blast furnace stove.

In addition to waste heat, there is also waste pressure available for recovery. One notable example is the application of Top Pressure Recovery Turbines (TRT) for the blast furnace. This technology captures the positive pressure released at the top of the blast furnace, cleans it, and uses it to produce electricity. Sensible heat from the slag can also be recovered and the technologies for this application are rapidly developing. However, fully commercialized technologies are not widely available.

Other processes, such as BOF, EAF, sintering, pelletizing, casting and rolling also have waste heat recovery opportunities. Because the blast furnace is the largest energy consuming process in the iron-making and steel-making process, this paper focused on waste heat recovery potential in blast furnaces.

Data Input

Specific energy intensities by processes and 2012 production data at the national level were obtained from the 2013 China Iron and Steel Yearbook (Editorial Board of China Steel Yearbook, 2013). “Recovered Energy” (as shown in **Summary Table 8**) refers to energy that is recovered and reused in the processes. The China Energy Statistical Yearbook (NBS, 2013b) reported the recovered amount of coke oven gas, blast furnace gas, and basic oxygen furnace gas. In addition, this paper takes into account the current adoption of waste heat recovery technologies in China’s iron and steel sector. Based on the estimated implementation rates and typical energy recovery rates, this analysis estimated the amount of recovered energy in CDQ, sintering machines, TRT, recovered steam from BOF, as well as waste heat recovery in EAF.

China’s iron and steel sector is largely fuel-intensive; however, electricity is also used and becoming increasingly more important. Based on reported data from China’s Iron and Steel Association (Huang, 2013), this analysis used the reported shares of electricity in total consumption in each process. As shown in **Summary Table 8**, the blast furnace process consumes more than 60% of the total energy use and predominantly uses fossil fuels (such as coke, washed coal, and raw coal). Therefore, this paper focused on analyzing the waste heat potential of the blast furnace only.

Summary 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**

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

Key Assumptions

For energy recovery potential in the blast furnace, typically there are four main areas: 1) recovering the blast furnace gas (which is a fuel); 2) recovering the positive pressure at the top of the furnace; 3) recovering the waste heat from blast stove exhaust; and 4) recovering the sensible heat from the slag. For the scope of this analysis, which is on waste heat specifically (not including by-product fuel or pressure), the focus is recovering energy in the blast-stove exhaust. Based on expert interviews and literature review (such as the US DOE (2008) study), this analysis assumes the blast stove exhaust has a waste heat temperature of 220°C (430°F).

Recovered energy from the blast-stove exhaust can be used to preheat combustion air and fuel in the blast stoves. In China, this method[6] has not been widely implemented and it is estimated that the current penetration level is about 5% (Huang, 2013).

Results

The potential of recovering waste heat from hot stove exhaust is relatively small comparing 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.

For blast stove exhaust, the analysis shows that a maximum technical waste heat potential of 2.9 GW_{Th} is available (with a reference temperature of 25°C [77°F]). The practical waste heat potential is determined to be 1 GW_{Th} (with a reference temperature of 150°C [300°F]), as shown in Summary Table 9.

Waste heat to power generation potential of the blast-stove exhaust is relatively low, mainly due to its low temperature. As illustrated in Summary Figure 12, practical power generation potential is about 7% of the total waste heat potential, or about 215 MW_e. If energy efficiency of converting thermal energy to power could be improved to approaching the Carnot Efficiency, another 7% of total waste heat potential (212 MW_e) can be converted to produce power from the available waste heat. If the waste heat recovering temperature constraint could be reduced to near the ambient temperature, the potential of waste heat power generation could be increased by another 25%. However, even with all the potential technical improvements, there is still at least 60% of the waste heat potential of the host stove exhaust remaining as low-temperature heat.

The current implementation rate of recovering blast stove exhaust for power generation in China is very low, at about 5% (Huang, 2013). Thus, the untapped power generation potential from blast-stove exhaust is about 205 MW_e.

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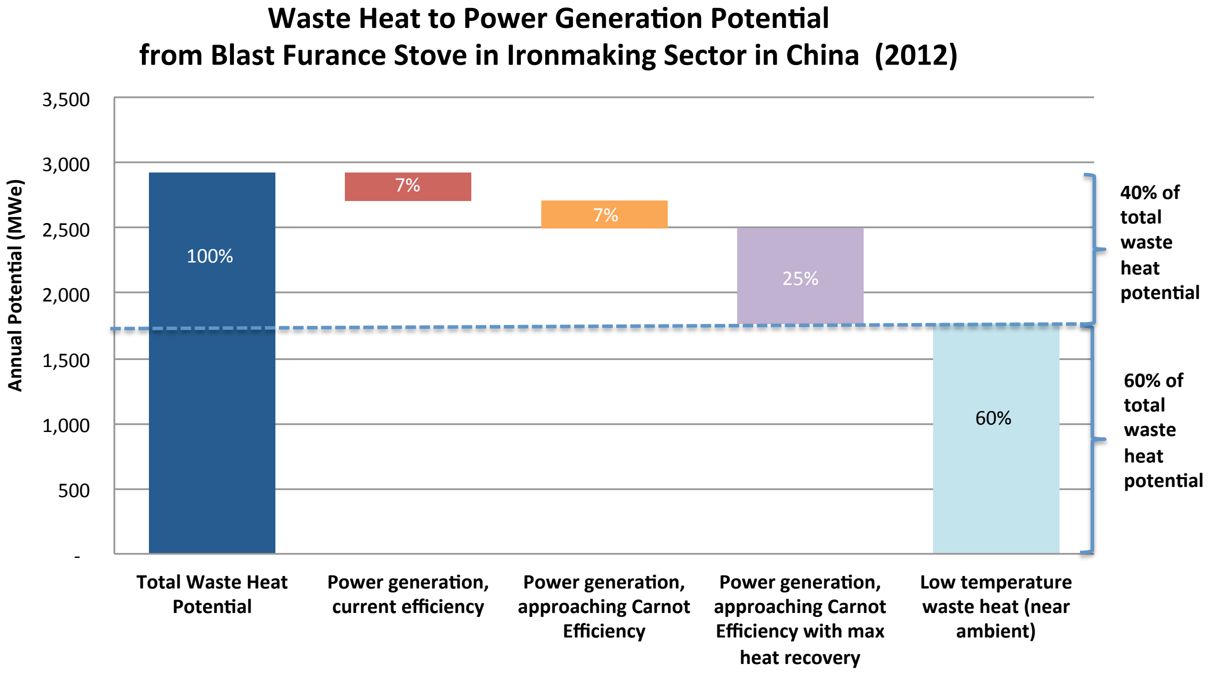
[6] The method of recovering energy from blast-stove exhaust is called "高炉热风炉双预热技术" in Chinese.

Summary Table 9. Waste Heat to Power Generation Potential of Blast Stoves (2012)

Blast Stove Exhaust	Theoretical Waste Heat Potential [T_{ref} =25°C (77°F)]	Practical Waste Heat Potential [T_{ref} =150°C (300°F)]	Theoretical Power Generation Potential [Theoretical Thermal Potential × Carnot Efficiency]	Practical Power Generation Potential [Practical Thermal Potential × Carnot Efficiency]	Practical Power Generation Potential [Practical Thermal Potential × Practical Efficiency]	Untapped Power Generation Potential [Practical Thermal Potential × Practical Efficiency × (1-Penetration Rate)]
	MW_{Th}	MW_{Th}	MW_e	MW_e	MW_e	MW_e
Potential	2,925	1,077	1,160	427	215	205

The analysis of waste heat potential in the iron and steel sector shows several important points. First, waste heat to power generation is a valuable option and has room to develop in the future. Second, other ways to recycle and recover waste heat, such as Coke Dry Quenching, Topping Recovery Turbine, and recovering sensible heat from slag are equally important as waste heat to power generation. Lastly, the potential for waste heat to power generation may not be as large as the waste heat recycling and reuse. In other words, this analysis finds that iron and steel sector has potential to develop waste heat to power generation, but the industry characteristics are more suitable or favorable to utilize waste heat as thermal energy.



Summary Figure 12. Waste Heat to Power Generation Potential of Blast Stoves (2012)

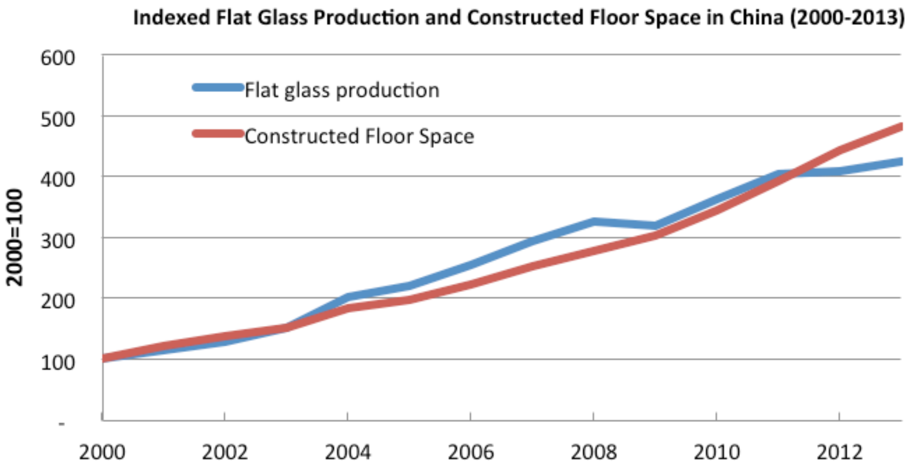
Summary 8: Waste heat potential in the glass sector

Glass Industry in China

Flat glass is the main glass product in China, representing about 70% of total glass production nationally. As of 2011, China produced 739 billion weight cases of flat glass (equivalent to 36.9 million metric tons), and 13.73 million metric tons of container glass (Sina News, 2012). Production of other types of glass products, including container glass, fiberglass, and specialty glass, is much smaller. From 2000 to 2012, China's flat glass production grew at an average rate of 13% per year (NBS, 2013a).

The dominance of flat glass in China is quite different from developed countries. In the United States, container glass is the largest glass industry segment. It accounts for roughly 50% of total glass product production, and 25% of total market value. Flat glass is the second largest glass industry segment, and it is about 25% of total glass production, and 18% of total market value. Specialty glass and fiberglass segments together contribute to 25% of the total production, while represent about 50% of the total market value. The total primary energy use of each of the four glass products in the U.S. is roughly equivalent, about 22%-25% of the total (Worrell et al., 2008). In the European Union (EU-25), container glass is the largest subsector of the glass industry. In 2005, it accounted for 53% of total production. Flat glass is the second largest in terms of production, representing about 25% (European Commission, 2013a).

Flat glass is used for residential and commercial construction, automotive applications, tabletops, and mirrors. Container glass is used for packaging of food, beverages, household chemicals, pharmaceuticals, and cosmetics. China is now undergoing a rapid urbanization process, and the demand for flat glass is largely driven by its use in buildings (Summary Figure 13) and automobiles. As the Chinese economy further develops and people's demand for consumer products increases, the demand for container glass may increase while the demand for flat glass may level off.



Summary Figure 13. Flat Glass Production in China (2000-2013)

Source: NBS, 2013a.

Domestically, China's glass manufacturers are quite dispersed. Industry consolidation in the Chinese glass sector is still relatively low, and each manufacturer has a small market share and production. In 2010, China had around 280 flat glass production lines, and about 240 of them use floating glass processes (ERI, 2011). In comparison, the 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 made it to the top 4 glass companies, including Asahi Glass (AGC Flat Glass Europe), Guardian Industries (United States), NSG (Pikington, UK), and Saint-Gobain (France) (European Commission, 2013a). Europe is the second largest market for flat glass, representing about 17% of the total. North America ranked the third, contributing about 7% of the total production in the world (NSG, 2011). It is estimated that about 37% of the global flat glass production is low quality and mainly comes from China (IIP, 2014).

Flat Glass Manufacturing Process

Currently, the float glass process is the most common process to produce flat glass globally. This process was invented by Pilkington (UK) in the early 1960s and has the advantages of reducing costs, increasing product range, decreasing wastes, and increasing product quality (European Commission, 2013a). In China, the float glass process is the dominant production process for making flat glass. In 2010, the share of floating glass process of total flat glass produced reached to more than 85%, and it is projected to reach 90% by 2015, according to China's 12th Five-Year Plan for Building Materials Industry (MIIT, 2011a). This section briefly explains the manufacturing process of making flat glass (Summary Figure 14).

Batch Preparation

A number of raw materials are needed for glass production, including sand, soda ash, lime, and other materials. The composition of raw materials determines the physical and chemical properties (such as chemical durability, thermal expansion, and transmission capability) of the glass. Recycled clean cullet can also be used as a way to reduce energy consumption and raw material use. For flat glass, raw materials are grounded and then proportioned based on the product requirements. Summary Table 10 gives the typical raw material composition for flat glass.

Summary Table 10. Typical Flat Glass Composition

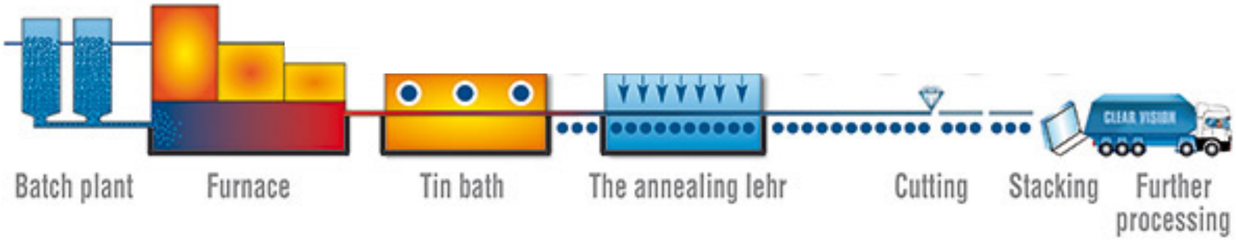
Material	Chemical component	Mass percentage (%)
Sand	Silicon dioxide (SiO_2)	72.6
Soda Ash	Sodium oxide (Na_2O)	13
Limestone	Calcium oxide (CaO)	8.4
Dolomite	Magnesium oxide (MgO)	4
Alumina	Aluminum oxide (Al_2O_3)	1
Others	e.g., potassium oxide (K_2O), sulfur oxide (SO_3)	1

Source: European Commission, 2013a; Pilkington, 2014.

Melting and Refining

The melting process is the key process in flat glass manufacturing. The mixture of the raw materials batch is usually charged to the melting furnace (also called tank) continuously as the withdrawal of the molten glass is also at a continuous rate (Worrell et al., 2008). The melting process has a temperature of 1,500°C (2,732°F). During the melting process, a series of chemical reactions occur, including melting, dissolution, volatilization, and oxidation-reduction (Energetics, 2002). In the melting furnace, refining and homogenizing also take place in order to produce glass flow that is free of bubbles and inclusions (Pilkington, 2014). The rate of melting and the degrees of refining and homogenizing depends on a number of factors, such as the furnace temperature, composition of the batch, the size of the batch ingredients, desired quality requirements, and the costs (Energetics, 2002). The use of cullet can reduce the amount of time used for melting but may increase the complexity of homogeneity (Energetics, 2002).

Through a refractory-lined canal, the molten glass then enters into the float tank (also called tin bath or float bath), which has a temperature of 1,100°C (2,012°F) (Pilkington, 2014). The float tank is about 55 to 60 meters (180 to 197 feet) long and 4 to 10 meters (13 to 33 feet) wide. The molten tin is used as the bath liquid to provide the needed manufacturing properties. As molten glass passes through the surface of the tin bath, it develops a uniform thickness and flatness (European Commission, 2013a) and forms as a solid ribbon. The temperature of the glass decreases from 1,100°C (2,012°F) to about 600°C (1,112°F) at the exit of the float tank. The thickness of the glass ribbon can vary from sub-millimeters to 25 milimeters (1 inch).



Summary Figure 14. Flat Glass Manufacturing Process
Source: adapted from ISRA Glass Vision, 2014.

In general, small glass plants use discontinued furnaces (e.g., pot furnaces and dry tanks) and the large glass plants use continuous furnaces. During China's 11th and 12th Five-Year Plan, the government launched the "Phasing Out" program in energy-intensive sectors to phase out the small and old production units. As mentioned earlier, the floating process dominates the current Chinese glass sector and the majority of the glass plants in China use the continuous furnaces.

Continuous furnaces operate continuously over a period of years. Depending on the energy input and the technology, there are generally four types of continuous glass furnaces: direct-fired, recuperative, regenerative, and electric (Energetics, 2002). Direct-fired furnaces are often used for small-scale production (at about 20-150 metric tons per day). Recuperative furnaces are commonly used in China (Wang, 2011). This type of furnace installs a recuperator on a direct-fired furnace to recovery the heat from exhaust gases. The Chinese glass industry also uses regenerative furnaces, with an increasing adoption rate. This type of furnace has a high production capacity and is relatively more energy efficient than direct-fired or recuperator furnaces. All-electric and electric boosted furnaces are gaining the popularity in China, but the share is still very low (Wang, 2011). Oxy-fuel furnaces, i.e., furnaces use oxygen-enriched air or pure oxygen for combustion, can save energy by reducing the need to heat nitrogen. However, the share of adopted oxy-fuel furnaces in the Chinese glass sector is very low and mostly in specialty glass production (Wang, 2011).

Forming and Annealing

The glass ribbon out of the float tank is then passed through a temperature-controlled tunnel (called lehr) for annealing. This process is used to release the stresses that are developed in the ribbon as it cools. The glass ribbon will first be heated and then will be gradually cooled. The temperature of the glass ribbon is cooled from 600°C (1,112°F) to 60°C (140°F) (European Commission, 2013a). The cooling can be done by natural convection and/or by fan air. This process requires time and space. It is reported the annealing takes about one hour and the distance from the float tank to the end of the annealing lehr is about 200-meter (656 feet) (Worrell et al., 2008; European Commission, 2013a)

Cutting and Finishing

The glass ribbon will then be cut, usually online by a traveling cutter (European Commission, 2013a). Coating can be applied to flat glass to give it a new physical, chemical, and optical properties, such as low-emissivity glazing. For example, Pilkington uses an online Chemical Vapor Deposition (CVD) coating system to provide a unique optical property to its flat glass (Pilkington, 2014). The coating system may increase the emissions of acid gases and fine particulates, which are treated in an abatement system (European Commission, 2013a). The finished product is then packaged, stored, or shipped.

Glass Sector Energy Use and Emissions Impact

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, 2013b). The flat glass industry in China mainly relies on coal and fuel oil as energy input. Other types of fuels, such as natural gas, coke power, crude oil, and petroleum coke are also used. As of 2006, electricity consumption accounted for 5.3% of the total energy consumption in this sector (China Economic Net, 2007). It is reported that more than 63% of the total fuel input in the melting and refining process comes from coal. Heavy fuel oil accounts for about 29% of total fuel input (Wang, 2011). This is very different from developed countries. In United States, natural gas is the dominant fuel, about 73% of the total energy use. Electricity is also used, about 24% (US EIA, 2013).

The energy consumption characteristics of flat glass and container glass are similar. Flat glass and container glass have very similar compositions, and can be collectively called soda-lime glasses. In the US, the average specific energy consumption for melting and refining flat glass is about 7.5 GJ/metric ton. The average specific energy consumption for melting and refining container glass is about 6.7 GJ/metric ton (Worrell et al., 2008).

A typical energy distribution of a float glass process shows that the melting and refining process consumes about 83% of total energy inputs. Forming and annealing process consumes another

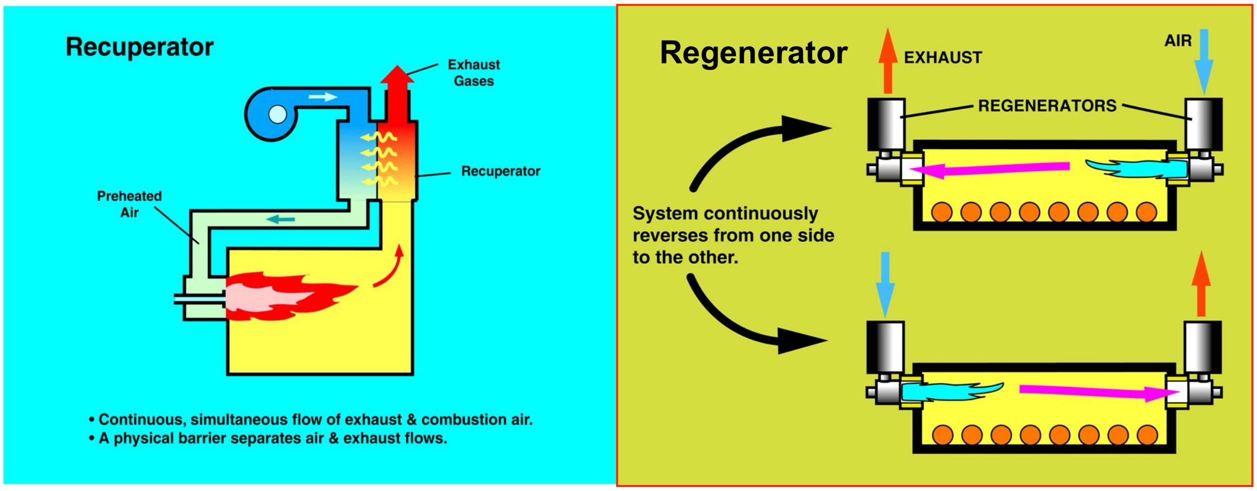
5%. Cutting the glass and energy use in other auxiliary systems account for 2% and 10%, respectively (Worrell et al., 2008; European Commission, 2013a).

In the U.S., about 80% of the melting furnaces for flat glass making are regenerative, with an average fuel intensity of 9.8 GJ/metric ton and an average electricity intensity of 0.33 GJ/metric ton. About 70% of the furnaces for container glass are regenerative, and its average fuel intensity and electricity intensity are 8.7 GJ/metric ton and 0.33 GJ/metric ton, respectively (Worrell et al., 2008).

Glass Sector Waste Heat Potential

Sources of Waste Heat

The main source of waste heat in the float glass process is the exhaust from the glass furnace in the melting and refining process. Without any heat recovery, the exhaust temperature could be more than 1,315°C (2,400°F) (US DOE, 2008). Both recuperative and regenerative furnaces provide waste heat recovery, i.e., utilizing the exhaust gas to preheat combustion air. Recuperators are less energy-efficient than regenerative furnaces; the final exhaust gas from a recuperative furnace has a temperature of 982°C (1,800°F) (US DOE, 2008). For regenerative furnaces, the temperature of the exhaust gas leaving the furnaces is between 316°C to 593°C (600°F to 1,100°F) (Worrell et al., 2008). Summary Figure 15 shows the designs of waste heat recovery in recuperative and regenerative furnaces.



Summary Figure 15. Recuperative (left) and Regenerative (right) Furnaces

Source: Thekdi, 2012.

In the current practice, the recovered waste heat is usually used to preheat combustion air. In addition, waste heat can be used to preheat the batch materials, cullet material, and produce steam through a waste heat boiler. The steam can then be used to generate power, provide heating, provide machine-use steam, and/or provide cooling. Below, the analysis focused on utilizing available waste heat from the exhaust, especially for power generation.

Data Input

This analysis categorizes 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 year 2012 is the base year of this analysis, the average values of the energy intensity between the two standards are used for this study (Summary Table 11). Similar to the cement sector analysis, the average value of the MEPS for existing glass plants are used.

Summary Table 11. Energy Intensity of Flat Glass Production in China (2012)

Furnace size	Energy Intensity (kgce/weight case)	Energy Intensity (kgce/kg)	Fuel Intensity (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 assumes 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 assumes 25% of flat glass production in 2012 came from furnaces larger than or equal to 800 tpd (MIIT, 2011a). Summary Table 12 shows the production of flat glass by furnace sizes in 2012.

Summary Table 12. Production of Glass by Furnace Size in China (2012)

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

Source: NBS, 2013a; 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 (Summary Table 13). 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).

Summary Table 13. Energy Use by Furnace Size in the Glass Sector in China (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.

Key Assumptions

As discussed above, about two-thirds of the fuel input in China's glass sector is coal. Heavy fuel oil also is used. The share of natural gas and electricity is quite small. In addition to other key assumptions, including typical coal composition in China, oxygen level after combustion, and temperature reference levels, the exhaust temperature from the glass furnace is an important parameter in the analysis. Exhaust temperature varies depending on technologies used. As shown in Summary Table 14, 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 (thus, saves 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.

Summary Table 14. 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

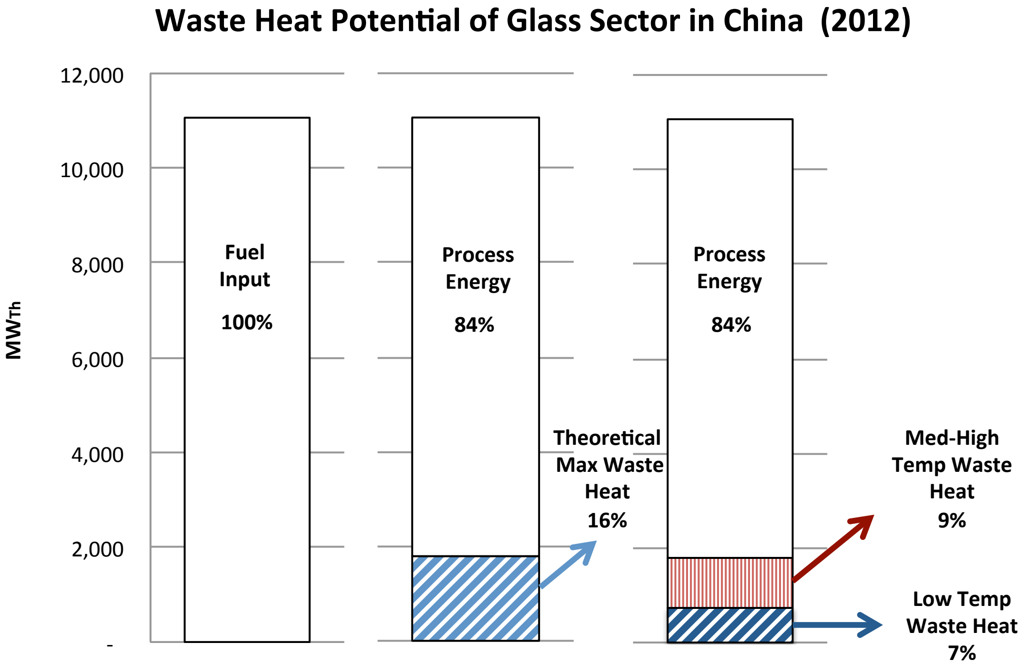
Source: US DOE, 2008.

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 assumes 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 the 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 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 assumes the current penetration of waste heat to power generation technologies in the flat glass sector is about 8%.

Results

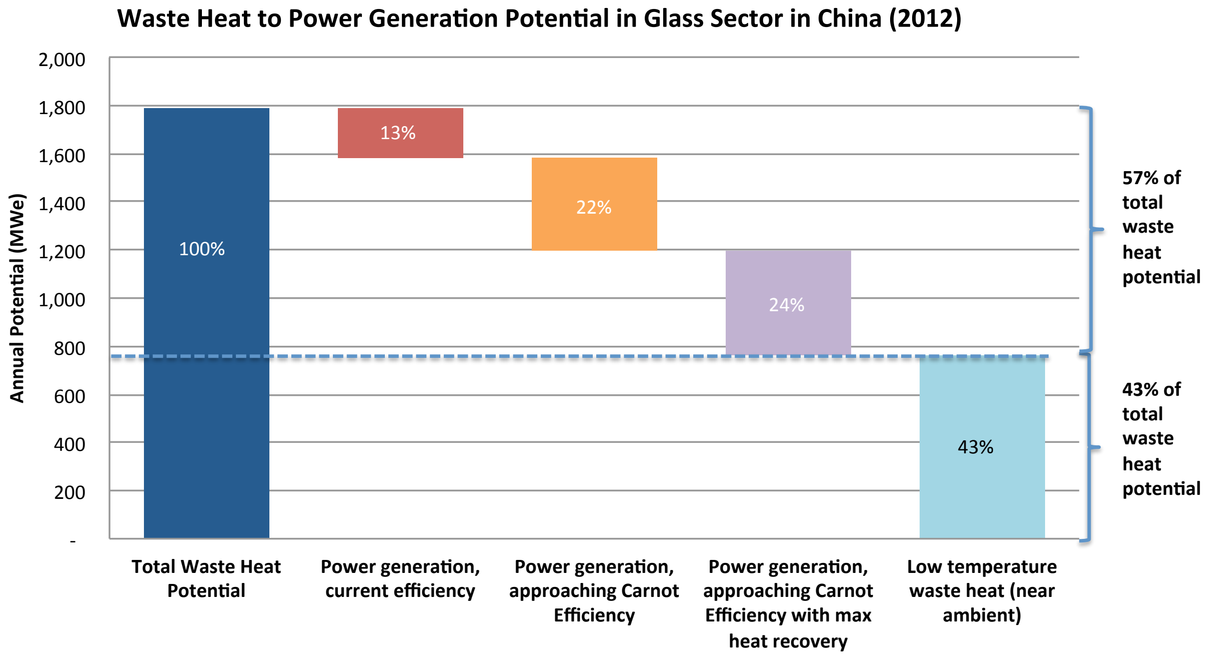
The theoretical maximum waste heat potential in China's flat glass industry is about 1.8 GW_{Th} based on the 2012 data. A practical waste heat potential, i.e., recovering waste heat above the temperature of 150°C (300°F), is estimated to be around 1 GW_{Th} (Summary Table 15). This shows the total waste heat potential is about 16% of the industry's fuel input in 2012. The practical waste heat potential is about 9% of the total fuel input. Summary Figure 16 below illustrates the percentages of waste heat in comparison to process energy and fuel input.



Summary Figure 16. Waste Heat Potential in the Glass Sector in China (2012)

For power generation potential, the practical 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.

This analysis also provides another estimate of the practical power generation potential by using the Carnot Efficiency, instead of the real-world efficiency, in order to take into account future developments in technology and/policies (e.g., R&D and reduced costs of technologies). This results a potential of 594 MW_e. A theoretical maximum power generation potential, or 57% of the total waste heat potential is determined, if the barriers to recovery of power from low-temperature waste heat were reduced and the energy conversion efficiency approached the Carnot Efficiency (Summary Figure 17).



Summary Figure 17. Waste Heat to Power Generation Potential in the Glass Sector (2012)

Given the current penetration of waste heat to power generation in China's flat glass sector is estimated to be around 10%, this indicates that an untapped potential of 190 MW_e is still available. This may be an underestimate of the total waste heat to power generation potential, as this analysis used conservative assumptions in exhaust gas temperatures and waste heat to power efficiency. However, this provides a lower bound of the actual potential in the flat glass industry.

Summary Table 15. Waste Heat Potential in the Glass Sector in China (2012)

Glass Sector	Thermal Energy Potential (in the form of heat)		Electricity Potential (in the form of power)			
	Theoretical Waste Heat Potential [T_{ref} =25°C (77°F)]	Practical Waste Heat Potential from [T_{ref} =150°C (300°F)]	Theoretical Power Generation Potential [Theoretical Thermal Potential × Carnot Efficiency]	Practical Power Generation Potential [Practical Thermal Potential × Carnot Efficiency]	Practical Power Generation Potential [Practical Thermal Potential × Practical Efficiency]	Untapped Power Generation Potential [Practical Thermal Potential × Practical Efficiency × (1-Penetration Rate)]
	MW_{Th}	MW_{Th}	MW_e	MW_e	MW_e	MW_e
Potential	1,790	1,035	1,027	594	207	190

Summary 9: Overview of waste heat to power generation technologies

The Steam Rankine Cycle is the most commonly used technology for producing power from thermal energy. 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 temperature is also acceptable; however, it is much less cost-effective and requires 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 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 CO_2 Power Cycle uses supercritical CO_2 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). Summary Table 16 summarizes the temperature ranges, working fluids, conversion efficiencies, and reported costs of these four types of commercialized waste heat to power generation technologies.

Summary Table 16. Technologies of Waste Heat to Power Generation

Comparison	**Steam Rankine**	**Organic Rankine (ORC)**	**Kalina Cycle Ammonia (NH3) - Water**	**Supercritical CO_2 Power Cycle**
Source 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

Source: E3M, Inc. and Energy Management Services.

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 to 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.