H2020 Work Programme

D1.2 - FIRST RELEASE OF SO WHAT INDUSTRIAL SECTORS WH/C RECOVERY POTENTIAL

Lead Contractor: MPI

Date: 7th December 2019

Project title				
Supporting new Opportunities for Waste Heat And cold valorisation Towards EU decarbonization				
Project acronym	SO WHAT		**Start / Duration**	June 2019 (6 months)
Coordinator	RINA-C			
Website	www.sowhatproject.eu			

Deliverable details			
Number	1.2		
Title	First release of SO WHAT Industrial Sectors WH/C recovery potential		
Work Package	1		
Dissemination level[1]	PU = Public	**Nature**	Report
Due date (M)	M6 – 30.11.2019	**Submission date (M)**	December 7th, 2019
Deliverable responsible	MPI		

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[1]   PU = Public

CO = Confidential, only for members of the consortium (including Commission Services)

Beneficiary	
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Document History			
Date	**Version**	**Name**	**Changes**
5/11/2019	1.0	O. Milling (MPI)	First Draft
21/11/2019	2.0	O. Milling (MPI)	Full draft including refined calculations available
06/12/2019	3.0	O Milling (MPI)	Comments from partners included in the final version
07/12/2019	4.0	F. Peccianti (RINA-C)	Minor changes and formatting

Abbreviations

°C: degrees Celsius

CHP: Combined Heat and Power

EI: Energy Intensity

EU: European Union

EAF: Electric Arc Furnace

LNG: Liquified Natural Gas

GJ: Gigajoule (10^9 Joules**)**

MJ: Megajoule (10^6 Joules)

OPC: Ordinary Portland Cement

ORC: Organic Rankine Cycle

PJ: Petajoule (10^{15} Joules)

t: tonne

TWh: Terawatt Hour (10^{12} watt hours)

WHF: Waste Heat Fraction

Executive summary

This report forms a background study as part of the SO WHAT project funded as part of the European Union (EU) Horizon 2020 programme, grant agreement number 847097. The project aims to develop a resource to assist industries and energy utilities in selecting, simulating and comparing alternative waste heat and cold technologies that can cost effectively balance the local heat and demand.

The report describes two methods for estimating the waste heat potential across the EU found in the literature. These estimates are then updated using the most recent available energy consumption data from the EU and the outcomes of the two methods compared.

The report reviews methods of waste heat and cold recovery used in different industries and demonstration countries involved in this project and discusses barriers to their implementation.

The recoverable waste heat potential is calculated to be 187TWh per year by method 1 and 167TWh per year by method 2.

These overall calculations provide an overall estimate for waste heat potential but lack the granularity describing the size of waste heat sources and do not reflect the waste heat potential of a single city or region. The SO WHAT tool will enable smaller scale views of waste heat potential to be built up enabling understanding and exploitation.

Approximately 2.9TWh of electricity might be generated per year from the recovered cold energy of liquid natural gas regasification in the EU. The technology to do this is proven but take up is very limited in the EU. Save for the regasification of LNG there is very little data available describing waste cold sources.

Studies cited in this report show that the majority of sinks for recovered waste heat from industrial processes can be found on the same site in which the waste heat is generated and that most of the waste recoverable waste heat produced by industry may be recovered economically. These studies also show that capital availability and perceived risk of implementation are the largest barriers to implementing energy recovery.

The tool being developed by the SO WHAT project will allow improved mapping of local sources of waste heat and cold and calculation of associated costs and risks of exploitation. This will allow greater understanding and exploitation of waste heat and cold energy sources.

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1   Introduction

This report forms a background study as part of the SO WHAT project funded as part of the European Union (EU) Horizon 2020 programme, grant agreement number 847097. The project aims to develop a resource to assist industries and energy utilities in selecting, simulating and comparing alternative waste heat and cold technologies that can cost effectively balance the local heat and demand.

The report starts by describing two methods for estimating the waste heat potential across the EU found in the literature. These estimates are then updated using the most recent available energy consumption data from the EU and the outcomes of the two methods compared.

The report reviews best methods of waste heat and cold recovery used in different industries and discusses barriers to their implementation.

2   Estimation of waste heat potential in the EU

2.1   Objectives, data sources and assumptions

To estimate the potential for waste heat recovery across the varied industrial sectors in the European Union, journal papers and previous European research project reports in this area were studied. This led to two methodologies being chosen to form the estimation of available waste heat and the recoverable potential for this study. The two methods were chosen for comparison as one uses a top down and the other a bottom up approach to estimation. Both methods are well referenced and have seen updates over the last 10 years.

The first method is based upon the methodology described in a journal paper by Papapetrou et al (1) and the second is based on the approach taken in the I-Therm project in the literature review for that project (2). For both these methods the starting point is the final energy consumption for industries in each EU country, provided by the Eurostat database (3) as shown in Appendix 1 Table 1. The Eurostat database is provided by the statistical office of the EU and is a reliable source of data that will give consistency between the two estimation methods chosen and allow good comparison of the methods. The most recent figures available for energy consumption are those corresponding to 2017. The Eurostat database uses the unit of thousand tonnes of oil equivalent (ktoe). For this report the unit of a Tera Watt hours (TWh) is used ($1 TWh = 10^{12} Wh$). The first method also requires relative energy intensities per country, in the original study these were sourced from the Odyssee-Mure database. The Odyssee-Mure database is focused on energy usage and efficiency in the EU and is supported by Enerdata and the Fraunhofer Institute. For repeatability of the underlying study the same data source was chosen, but using the most recent available data from 2016.

2.2   Methodologies used

2.2.1   Method 1

The first method is based upon a calculation of the percentage of heat demand that is recoverable from surplus heat output from major industrial processes. This calculation methodology was first proposed by Hammond et al (4) in a study using data from a 2002-2003 industry study.

This method uses a top down approach based on two key reference studies in two EU countries with significant levels of industrial activity. A 2012 study of the energy consumption by end use for industry in Germany is used to estimate the percentage of energy consumption that is used for heat demand. A study of industrial sites in the UK in the period 2000-2003 is used to estimate the percentage of heat demand that is recoverable from waste heat. This percentage is then modified to be country specific, by using the ratio of energy intensity between each country and the UK but is clearly still heavily dependent upon the initial percentage from the UK study. The accuracy of this method is dependant on the validity of projecting the results of these two country specific studies to represent industry across the EU.

Step 1
The proportion of heat demand that is output as surplus heat in a recoverable form in specific temperature bands in each UK Industry is termed a waste heat fraction (WHF). These WHFs are calculated by applying practical recovery efficiencies for the three main methods of waste heat recovery for UK industries, calculated in a previous study by the same research group (5). The main methods for using waste heat stated are heat pumps, heat to chilling and heat to electricity. For heat pumps an efficiency of 55% of the maximum theoretical efficiency (Carnot's efficiency) is used. Heat to chilling using absorption chillers is split by temperature range. Below 170°C a single effect chiller is assumed to be used with an efficiency of 0.7 and above this a double effect chiller, with an efficiency of 0.8 is assumed. Heat to electricity is assumed to be done by Organic Rankine cycle technologies below 400°C and traditional Rankine cycle technologies above this. Net efficiencies reported by manufacturers of these technologies spanning the temperature range have been used to model an efficiency vs temperature for Rankine cycle technologies. This gives a percentage of the Carnot's efficiency for heat to electricity that is in the range 40-50%.

Step 2
The WHFs calculated for the UK in step 1 are used as a reference case to create equivalent fractions for industries in countries in the EU. This is done by using the relative difference in Energy Intensity (EI) for each EU country compared to the UK in the period 2000-2003. These EIs are sourced from the Odyssee-Mure database (6).

Step 3
The WHFs for each country and industry are updated by comparing the average EI of each country in 2000-2003 with that countries EI in 2016 from the Odyssee-Mure database.

Step 4
The final step applies these WHF to heat demand data for Industries in each EU country. Heat demand is calculated by combining the energy consumption data with a measure of each industry's energy heat share percentage from a German study by Naegler et al (7). This study was conducted on data from German industries in 2012 and shows the proportion of energy consumed in each industry by end use. These end uses are warm water, space heat, process heat, process cooling, space cooling, information & communication, mechanical energy and lighting. The study identifies the first three of these as energy consumed for heat demand. These proportions are used for every country in this study.

2.2.2 Method 2

The second method is based upon the estimation methodology used in the I-Therm project that uses estimated energy recovery percentages for each Industry that are based upon calculations from a study estimating global waste heat potential by Forman et al (8).

This method uses a bottom up study of all the technologies that are used in each industry to estimate surplus output energy streams with recoverable waste heat at three temperature levels. The energy consumption for each industry is proportioned into these temperature bands based on the number of technologies the industry has in each temperature band. These proportions are then assumed to be identical across every country's industries. The accuracy of this method is clearly heavily dependent upon how close to this standard proportion of energy consumption and specific technology usage each country's industries are.

Step 1

Data are derived from a global Sankey diagram for energy flows for all primary carriers (power sources) to all users (Electricity generation, Industrial, Residential and Commercial) with their output split into energy service (used in process) and rejected energy (waste) in 2012. The study allocates the types of energy for each 'user' to technologies grouped into several sectors. These technologies have balance factors that show the energy service share as well as splitting the rejected energy into recoverable waste streams (exhausts & effluents at a temperature) and non-recoverable energy (losses). For example, an electric arc furnace (EAF) is one of the technologies in the Iron and Steel sector that uses energy in the form of electricity. An EAF has a balance factor of 55% to energy service, 18% to recoverable waste and 27% to losses. Of the recoverable waste 55% is an exhaust (bound to gas) at 1000°C and the remaining 45% is effluent (output as liquid) at 85°C. Technologies across all sectors are estimated and used to make an estimation of the percentage of input energy that is then output in a recoverable form in three temperature bands for each industry.

Step 2

A second percentage based on Carnot's technical work potential calculates the maximum theoretically recoverable energy from each of these waste energy streams, by applying Carnot's theorem. The overall percentages for industrial users are shown in **Error! Reference source not found.** below. Note that the Carnot energy is the percentage of the total input energy that may be recovered.

Table 2-1: Waste heat & Carnot's potential percentages for Industrial users by temperature band

Temperature Band	Low (<100°C)	Medium (100<300°C)	High (≥300°C)
Waste Heat	12.60%	6.00%	11.40%
Carnot's	1.73%	2.04%	6.43%

The method used in the I-Therm report proportions the waste heat from each industrial sector into these temperature bands and is described in more detail in a journal paper by Panayiotou et al [9]. The industry specific waste heat and Carnot's potential percentages are shown in Table 2-2.

Table 2-2: Industrial sector specific waste heat & Carnot's potential percentages

Industry	Waste Heat	Carnot's
Iron & Steel	11.40%	6.40%
Chemical & Petrochemical	11.00%	5.13%
Non-ferrous Metals	9.59%	4.93%
Non-metallic Minerals	11.40%	6.40%
Food & Tobacco	8.64%	1.89%
Paper, Pulp & Print	10.56%	4.59%
Wood & Wood Products	6.00%	2.00%
Textile & Leather	11.04%	2.72%
Other Industry	10.38%	4.84%

Step 3

The second and final step applies these percentages to the energy consumption data for industries in each EU country, from the Eurostat database (3).

3 Estimation of waste heat & cold potential

This section applies the two methods described in section 2 to the EU energy consumption data from 2017, the most up to date data available. Section 3.1 compares the estimates from both methods totalled across all countries to show an EU wide comparison per industry. The results per industry comparing each country's estimated potential from both methods are then discussed in section 3.2.

The EU energy consumption data for industry in 2017 is shown in Table A-1 of Appendix 1. This data is expressed as a percentage of each country's total energy consumption in Table A-2 of Appendix 1. Appendix 2 contains seven figures that represent each country's estimated waste heat potential in the seven industry categories used in this study.

3.1 Recoverable Waste Heat Potential for the European Union

Figure 3-1 shows three different quantities of energy in the EU across the major industries for 2017. The blue bar for each industry represents the total consumption of all forms of energy. The middle red bar is an intermediate step in method one and represents the energy used to meet demand for heat in the respective industries. The final grey bar is an intermediate step in Method 2 that represents the total surplus energy output as heat in each industry.
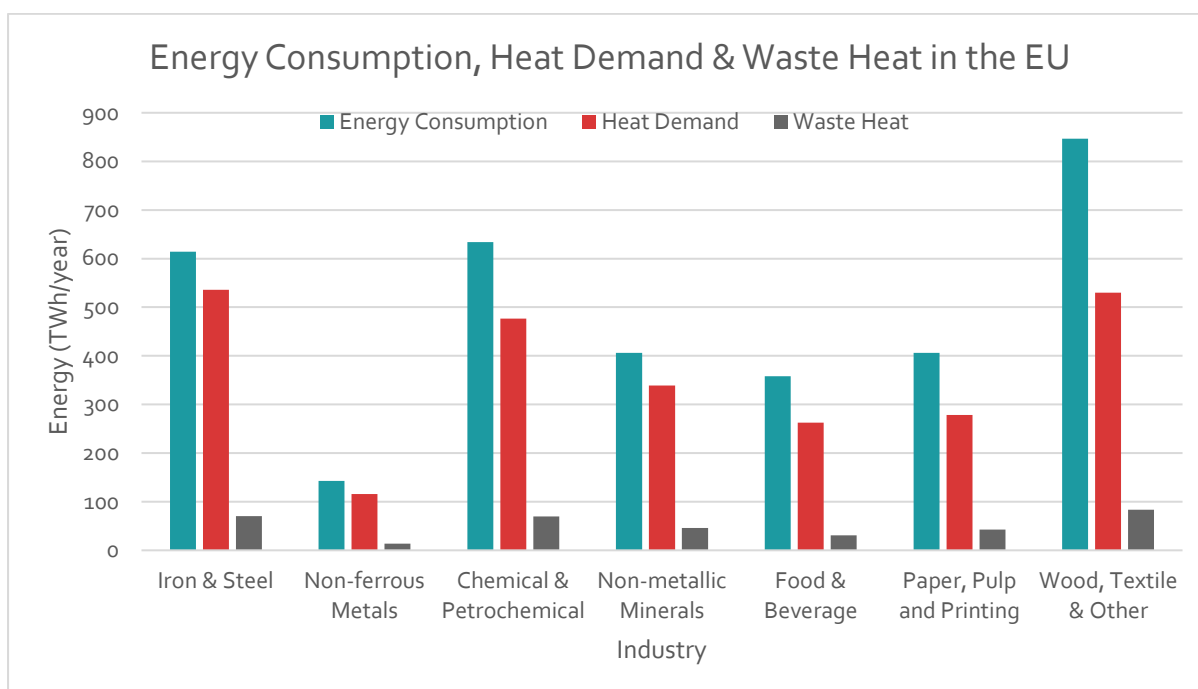
Figure 3-1: Energy consumption, heat demand and waste heat in the EU

The total energy consumed in 2017 across all industrial sectors in the EU is 3400 TWh. The two largest consumers are the Iron & Steel and Chemical & Petrochemical industries with both having an approximate 18% share of this total. Similar results are seen in the proportion of this energy that is used for heat and the surplus waste heat that is output from this. These two industries are estimated to each output 70 TWh of surplus waste heat annually across the EU. It should be noted that waste heat in the iron and steel industry is mainly at higher temperatures, about 60% of waste heat streams are over 1000°C, than the petrochemical industry, about 70% of waste heat is in the range 400-500°C. The rest of the waste heat streams in both industries are at lower temperatures.

The recoverable waste heat potential is calculated to be 187 TWh per year by method 1 and 167 TWh per year by Method 2.

Figure 3-2 shows a comparison of the results for total estimated recoverable waste heat potential in the EU by the two methods described across major industries in 2017. The two methods are shown to have reasonable correlation for most industries, with Iron & Steel and the smaller industries classed as Wood, Textile and Other Industries the exceptions to this.
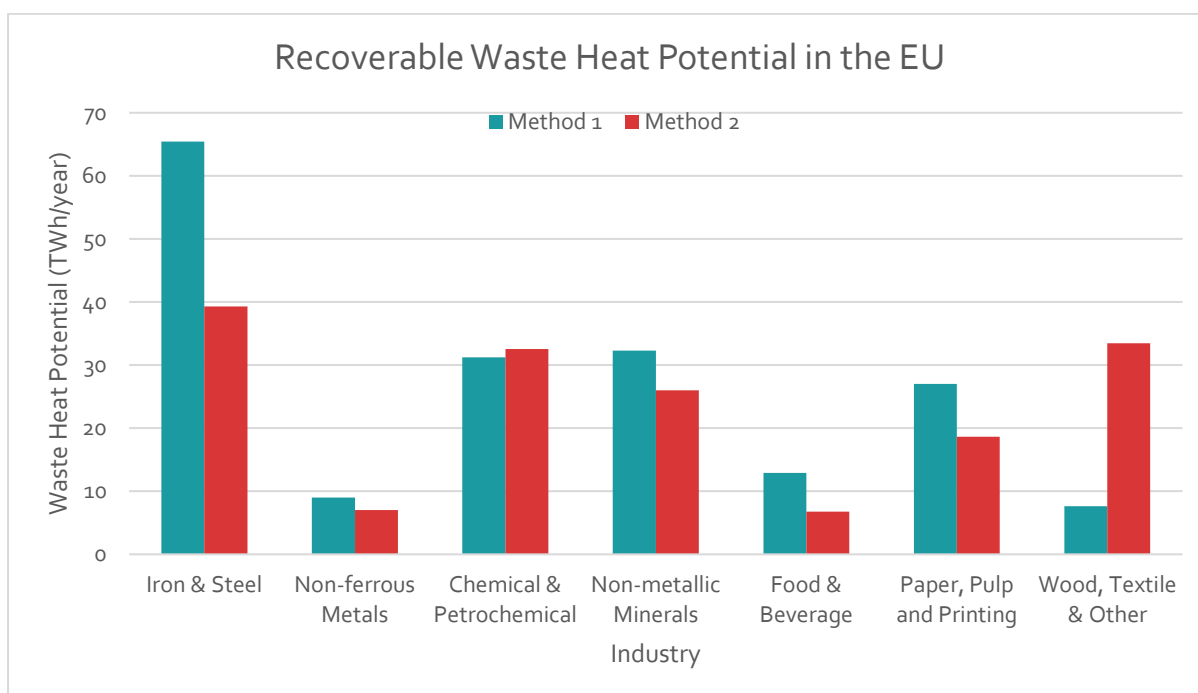
Figure 3-2: Recoverable waste heat potential in the EU

Method 1 calculates a total waste heat potential for Iron & Steel of 65TWh, which is 93% of the stated figure for total surplus waste heat available (as calculated by method 2). The effective start to end (energy consumption to recoverable waste heat potential) percentages for both methods are shown in Table 3-1. Note that these percentages are based on the reference country. Method 1 applies country specific energy factors that change the relative percentage for each country. There is a marked difference in the Iron & Steel figures with Method 1 being 183% of the corresponding figure for Method 2.

Table 3-1: Industrial sector specific waste heat & Carnot's potential percentages

Industry	Method 1 [%]	Method 2 [%]
Iron & Steel	11.69	6.4
Non-ferrous Metals	7.36	5.13
Chemical & Petrochemical	5.39	4.93
Non-metallic Minerals	9.51	6.4
Food & Beverage	4.62	1.89
Paper, Pulp and Printing	5.07	4.59
Other Industries	1.19	
Wood and Wood Products		2

Textile and Leather		2.72
Non-specific Industry		4.84

The differences in the Other Industries figure can be attributed to how the two methods deal with the problems of smaller industries where less information is available. The Method 1 considers all the smaller industries as separate in calculating the heat demand share of energy consumption before combining the totals and using a single waste heat factor to calculate the recoverable waste heat potential. The second method adds the consumption figures for four industries (transport equipment, machinery, mining & quarrying and construction) into the Other Industries category and uses one Carnot potential for these, whilst treating two smaller industries (Wood & Wood Products, Textiles & Leather) separately in the calculation of Carnot's potential. These have then been added to the Non-specific Industries for Method 2 to make an Other Industries category so the industrial sectors match those of Method 1.

Method 1 uses a single country study from 2002-2003 to provide waste heat fractions for each industry from which waste heat is calculated as a proportion of input energy and then applies a national energy intensity factor to this. This assumes that all industries in a country can assume the same energy intensity factor which may not be valid. To improve the accuracy of the result a number of more up to date studies of waste heat fractions in different industries and countries would be required.

Method 2 assumes uses the same waste heat fraction assumptions for each industry, irrespective of the country. This assumes that energy use and hence waste heat patterns are similar across the EU. This is a sensible assumption for this overall calculation but it would be useful to compare national studies to review the validity of this as it differs significantly from the national energy intensity factors assumed in Method 1.

3.2 Recoverable waste heat potential by industry and country

This section focuses on the differences between national waste heat potential and how this is affected by their mix of industries and the assumptions made in the waste heat calculations above. Appendix 2 contains plots of the waste heat potential calculated using both methods by industry and country to allow these comparisons.

Figure 3-3 below shows the total recoverable waste heat potential for each of the countries in this study. The relatively small differences between the two methodologies for most countries shows that there is good overall level of agreement between the estimates the two methods produce. There are some notable exceptions where the two methods don't agree well. Belgium, Finland and Sweden have significantly higher estimates for recoverable waste heat potential from Method 1 and the UK has a significantly lower estimate for recoverable waste heat potential from Method 1.
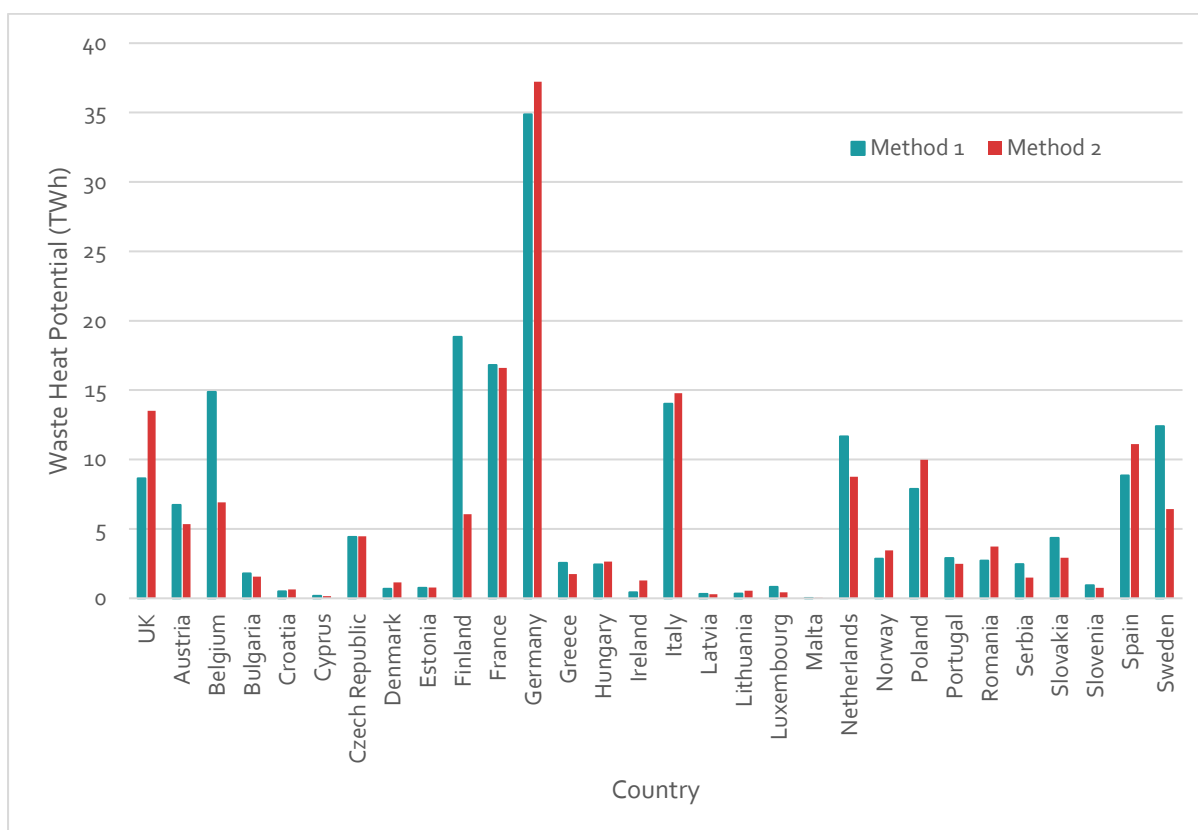
Figure 3-3: EU Waste heat potential per country

The start to end percentages shown in Table 3-1 for Method 1 combine the heat demand share of industry and the waste heat fractions from the two reference studies. Method 1 differs from Method 2 as it uses relative energy intensity per euro for each country to make a unique waste heat fraction for each country, (step 2 in the methodology). Most countries relative energy intensities are between 66% & 150% of the UK reference (50% more or less intense in pricing terms), but Belgium, Finland and Sweden are 223, 319 & 232 percent respectively. This explains some of the discrepancy seen between the methods for these countries.

Appendix 1 Table A-2 shows the energy consumption data from Appendix 1 Table A-1, expressed as a percentage of each countries total energy consumption. This shows that in cases where a country has a higher dependence on one industry there is an increased likelihood of significant disparity between the methods. Finland and Sweden for example have large percentages (56% & 49% respectively) of the total energy consumption is concentrated in the paper, pulp and printing industry.

The United Kingdom's lower percentage for the first method can be traced to the unusually high share of its industries that are classified as Other Industries. Table A-2 in Appendix 1 shows that for most countries Other Industries allocation has a percentage of total energy consumption in the range of 10-25%, whereas the UK has 43% of its industrial energy consumption classified under Other Industries. This means that the differences in how the Other Industries data are calculated between the two methods has a large effect on the UK's two estimates. The same reason is evident for disparity in Malta's two estimates with 72% of its industrial consumption classified in the Other Industry category (this is not easily discernible on Figure 3-3 due to the low estimates relative to other European countries).

Figures for each industry with contributions per country can be found in Appendix 2. Figures B-1:4 show that in the Iron & Steel, Non-ferrous Metals, Chemicals & Petrochemicals and Non-metallic Minerals industries, Germany has a leading position in terms of size and hence the largest recoverable waste heat potentials. Figure B-5 & Figure B-6, show that Germany also has large potential in the Food & Beverage and Paper, Pulp & Printing industries.

Appendix 2, Figure B-1 shows that Germany's Iron & Steel industries have a recoverable waste heat potential in the range 10-15 TWh and that several other European countries have significant potentials in the range of 2-5 TWh. These countries are Austria, Belgium, France, Italy, Netherlands, Poland, Spain and the UK.

Appendix 2, Figure B-2 shows that the recoverable waste heat potentials are much lower in the Non-ferrous metals industry with only two countries having a potential of one or more TWh per year. These are Germany with 1.3TWh and Norway with 1 TWh. France, Greece and Spain have potentials in the range 0.5 – 0.8 TWh.

Appendix 2, Figure B-3 shows that Germany has a significant recoverable waste heat potential in Chemicals & Petrochemicals in the range 7-9 TWh and the Netherlands is the next highest with a potential in the range of 4-5 TWh. Belgium, France and Italy also have potentials of approximately 2 TWh.

Appendix 2, Figure B-4 shows that Germany has a recoverable waste heat potential in Non-metallic Minerals of approximately 5 TWh. Italy has the next biggest potential at approximately 3 TWh with France, Poland, Spain and the UK in the range 2-3 TWh.

Appendix 2, Figure B-5 shows that France and Germany have the largest potentials in the Food & Beverage industry with an estimate of 1-2 TWh per year. Italy, Poland, Spain and the UK have potentials in the range 0.5-1 TWh.

Appendix 2, Figure B-6 shows that there are three countries that have large Paper, Pulp and Printing industries. Finland, Germany and Sweden have recoverable waste heat potentials in the range 2-4TWh from these industries. Appendix 2, Figure B-7 shows significant discrepancies between the two estimation methods for Other Industries as previously described.

The waste heat potential calculations above are based on overall energy consumption figures for industry groups and nations and it is not possible to understand from the data whether the industries tend to be many small heat users, such as a small dairy, or a few large ones, such as an integrated steel works producing several million tonnes of steel per year. This aggregated approach is useful for making full country estimates of waste heat potential but less useful when studying a single city or smaller region. The SO WHAT tool should help to overcome this lack of granularity to provide a clearer analysis of available waste heat on a scale that can highlight opportunities for exploitation.

4 Review of heat recovery application

4.1 Sector specific waste heat / cold factors

This section aims to provide an overview of the main energy consuming processes in industrial sectors. Examples as to how waste heat is commonly used or best practice in these industries is described as well as any industry specific barriers to the exploitation of waste heat. The list of industries and techniques described is not exhaustive and intends to provide good examples of waste heat recovery techniques rather than detailed figures for each sector. The sectors described below correspond with the sectors used for the calculations in Sections 2 and 3 of this report and energy data available from the Eurostat database.

4.1.1 Non-ferrous Metals

Non-ferrous metals are produced by a number of processes involving heat but each process route is specific to the metal and there is often more than one regular process route used for the refining of different types of ores.

Some of the available waste heat will be in the form of high temperature fume but the majority is from lower temperature (less than 200°C) heat sources (1). These lower temperature heat sources, usually fume extraction gases or cooling water, can most typically be exploited for space heating or using Organic Rankine or Kalina cycle machines to generate power. Examples of common processes and waste heat technologies applied are below.

Aluminium
Aluminium is produced by the electrolysis of bauxite (aluminium ore) that has been dissolved in a bath of molten cryolite at a temperature of over 900°C. This is known as the Hall-Héroult process. Although the process is high temperature the amount of waste heat is limited due to the relatively large distances between most of the sources and sinks and the transient nature of some of the sources.

Most of the waste heat sources are hot gas emissions from fume extraction systems at relatively low temperatures of 300°C or lower. Heat exchange in some of these gas streams is further complicated by the high dust loading of the streams and its potential fouling of heat exchangers.

Analysis shows that the waste heat in these flows may be used on an aluminium smelter site for space heating and for preheating of raw materials, both in primary smelting operations and in other auxiliary processes that support the smelting operation (9). This heat might also be used to drive Organic Rankine Cycle of Kalina cycle generators. Opportunities also exist to use process cooling water with a final temperature of 40°C to supplement space heating in offices and other accommodation on the aluminium plant with the use of a heat pump.

Zinc and Cadmium Ore Roasting
Zinc and cadmium ores are roasted on a fluidised bed in oxygen enriched air to convert sulphides in the ores to oxides. This is an exothermic process carried out at 900 to 1000°C. Temperatures in the roasting bed are maintained by cooling elements. It is common for the heat to be adsorbed in cooling coils and used to raise steam for power generation (2).

Sintering and Roasting Processes for Other Ores

Sintering and roasting of non-ferrous ores is common for refining from sulphites to oxides in preparation for electrolysis or other reduction processes (2). These processes are usually high temperature and there are opportunities for recovering waste heat from flue gases, either through recuperators for the pre-heating of process /combustion air or for raising steam.

4.1.2 Non-metallic Minerals

Non-metallic minerals include Cement, Lime, Gypsum and Ceramics. Production of these materials is energy intensive and the processes frequently require high temperatures.

Cement

Cement is one of the main ingredients of concrete, the most used building material in the world. In 2017 the EU produced approximately 175 million tonnes of cement (10).

Cement is produced by a process of calcining and sintering a mixture of ground calcium carbonate and oxides of silicon, aluminium and iron in a rotary kiln at temperatures of around 1450°C to form a clinker. This clinker is then ground and mixed with other ingredients, such as gypsum, to form Ordinary Portland Cement (OPC). Clinker normally constitutes at least 90% of OPC.

Cement kilns are large rotary kilns typically 3 – 5 m diameter and 30 to 60 m long. They are fired from one end by burners that may use a variety of fuels to produce typical flame temperatures of 1800 – 2000°C. The hot clinker is normally air cooled once it exits the kiln.

The exhaust gas from the kiln is regularly used to pre-heat the cement raw materials before they enter the kiln. This may be a multistage process with up to 6 cyclone preheater stages being used. In some plants calcining is partly carried out before the raw materials enter to rotary kiln as this can reduce the energy use through the process.

The efficiency of cement kilns has improved significantly over the last 20 years. A modern kiln will use approximately 3300 MJ/t product with 55% of the energy being required to drive the process of clinker formation (11). The energy flows in a typical modern dry clinker cement kiln are shown in Figure 4-1.
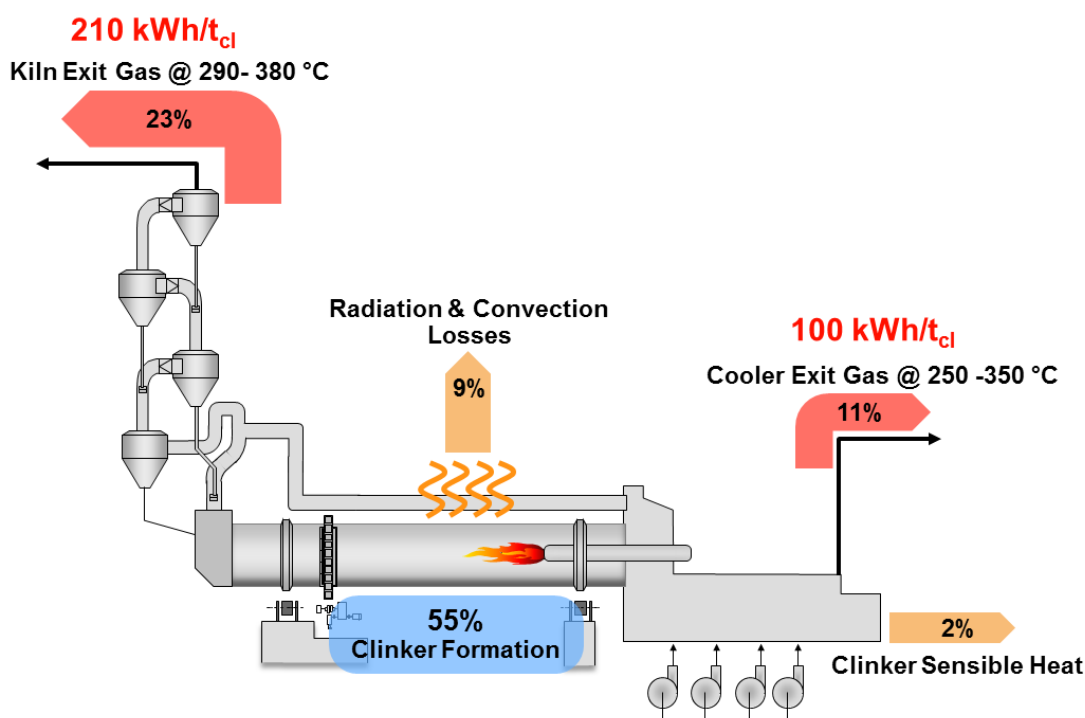
Figure 4-1: Energy output flows of a modern dry type clinker kiln (11)

The air from the clinker coolers has a typical temperature of 250 to 350°C and the exhaust from the kiln preheaters has a typical temperature of 280 to 380°C. These hot gases can be used to raise steam for electricity generation or through Rankine, Organic Rankine or Kalina cycle machines (12). It has been calculated that even in a modern plant using multistage preheaters there is approximately 0.3 GJ of available energy in the exhaust streams per tonne of clinker produced. Using waste heat in this manner is common in cement plants in China where it has been mandated as good practice by government.

Lime

Lime is used in the iron and steel industry, for water and flue gas treatment, as an agrochemical and in the paper, chemical and other industries. European Union lime production was approximately 24 million tonnes in 2016 (13)

Lime is produced by heating crushed calcium carbonate (limestone) to approximately 900°C in vertical or rotary kilns to produce calcium oxide or lime (14). This process is known as calcination.

Waste gases from the calcination process can be used for pre-heating the limestone being fed into the process in a similar manner to that done in cement manufacture.

Cooling air from cooling the lime may be used as warmed combustion air in the kiln. This is, in effect, a recuperation process using the hot product to pre-heat combustion gases.

Glass

Glass is produced by melting a mixture of sand, soda ash (sodium carbonate), limestone, dolomite and recycled glass in a furnace at a temperature of over 1500°C. The European Union produced approximately 35.4 million tonnes of glass in 2018 (15).

Just over 60% of European glass production is container glass. For container manufacture small pieces of molten glass are formed in automated machinery to produce jars, bottles and other containers. The largest user of glass containers is the food industry.

About 30 % of glass production is float glass. Float glass is produced by letting the molten glass from the furnace flow onto a bath of molten tin in an inert atmosphere. The glass is drawn across the surface of the tin as it cools and then lifted onto rollers for cutting and final cooling. This process produces large sheets of very flat glass for glazing.

It is normal practice to use recuperators to recover heat from glass furnace exhaust gases to preheat combustion air. Over half the energy in the furnace exhaust gases can be recuperated greatly increasing the energy efficiency of the process (11). Over 15% of the energy used in a glass kiln is lost through the furnace walls (11). Reducing these losses by increasing wall insulation is often not possible as this would increase the temperature of the furnace walls on the inside of the furnace increasing the rate at which they are corroded by the molten glass.

Float glass may be used as is for some applications. The largest amount is assembled into insulated units for building glazing, often with coatings applied first. Float glass may also be laminated and / or moulded for the manufacture of vehicle glazing.

Other types of manufacturing are used to make specialist glasses, glass fibres for communication systems and glass wools for insulation. These materials are typically produced in smaller volumes (factory producing less than 20 tonnes per day) but will still require high temperature processes for melting raw materials.

There are examples of energy recovery from glass manufacture using Rankine and Organic Rankine Cycle machines (16).

4.1.3   Chemical & Petrochemical

The petroleum refinery throughput in Europe (including non-EU countries) in 2017 was 686 million tonnes (17). This is approximately 90% of the oil demand for the region.

Crude oil is typically processed by first desalting to remove inorganic salts before being distilled into the fractions required. Typically the oil is heated before and after the desalting process using heat exchanged from hot distilled fractions and other streams before being heated to approximately 400°C by a furnace and fed into a distillation column that operates at atmospheric pressure.

Following distillation, reforming and hydrotreating processes are often used on lighter distilled fractions to produce gasoline, kerosene and diesel fuels. Heavy fractions may then be vacuum distilled and cracked in order to increase the fraction of lighter fuels in the final product or to produce isomers needed for plastics production. A diagram of this process is shown in Figure 4-2.
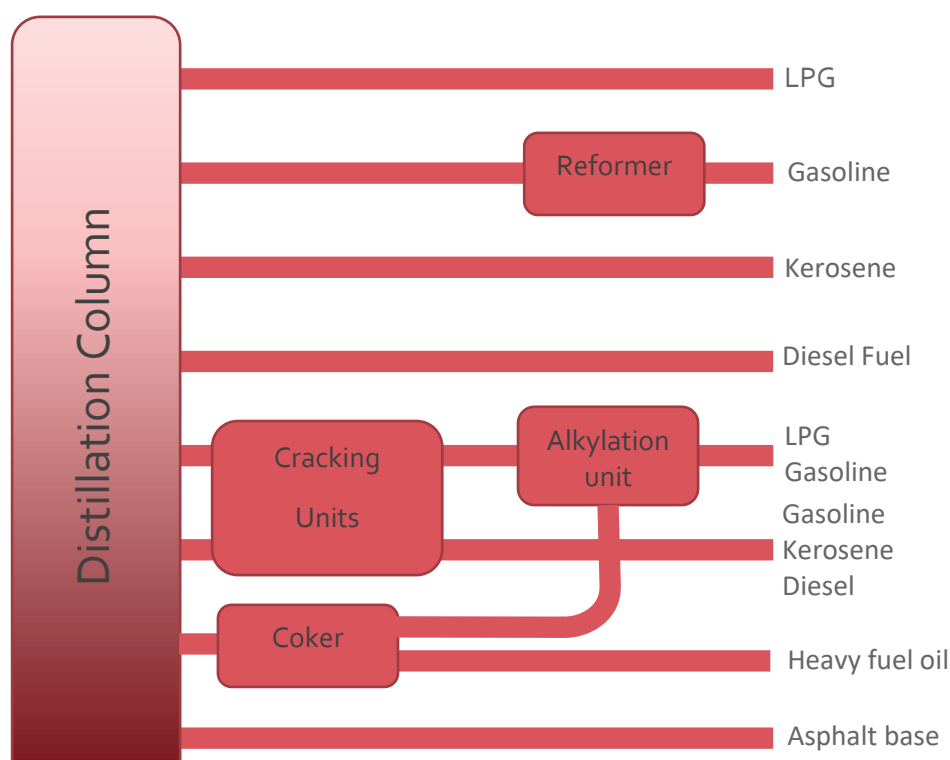
Figure 4-2: Diagram of oil refinery distillation process

Thermal cracking typically requires temperatures of 400 to 500°C, steam cracking requires reaction temperatures of approximately 850°C and catalytic cracking is carried out at 660 to 760°C.

The heaviest remaining oil fractions may then be processed in a coking unit. This releases some further lighter products for returning to distillation and petroleum coke is produced. This may then be calcined at approximated 1300°C to produce a coke with a very high (98-99.5%) carbon content that is commonly used for the manufacture of carbon components.

Waste energy streams from petrochemical refining are typically hot petrochemical products and waste steam at low or medium pressures. These are at medium (300-500°C) or low temperatures (<200°C). The hot streams are frequently used to heat incoming feedstocks using heat exchangers and waste heat is noted to be abundant in refinery processing (2).

Other bulk chemical manufacture includes the production of ammonia, sulphuric acid, cyanides, chlor-alkali and polymers.

These processes require significant amounts of energy and produce waste heat streams in the medium to low temperature ranges (2) (1).

4.1.4 Food & Beverage

The food and beverage industry uses numerous heat processes including baking, boiling, frying, drying, distilling, pasteurising and refrigerating. Most of these processes are classed as low temperature, i.e. temperatures lower that 260°C. Despite the relatively low temperatures in the industry energy recovery can still be usefully applied to reduce energy use.

The industry still has numerous opportunities for recovering heat from these processes. Low grade waste heat can be used for space and water heating or may be used to drive adsorption chillers for refrigeration.

There are also numerous opportunities to use heat pumps for upgrading low temperature waste heat from refrigerators or other low grade waste heat sources. It is reported that heat pumps have provided particularly good return on investment when used in beverage distillation applications (18).

Pasteurisation is commonly used to reduce the number of pathogens in foods. The process requires the food to be heated to a set temperature, usually less than 100°C, for a short set time. When pasteurising liquids, such as milk and beverages, it is common to use plate heat exchangers to warm the incoming product and chill the outgoing product. This can result in energy efficiencies of over 90% for the process (19).

Baking oven flues contain hot gases at temperatures that can be over 200°C. Heat exchangers can be used to heat combustion air entering the oven, reducing amount of energy required to heat the oven. Tube and plate heat exchangers can become fouled by particles in the oven exhaust so rotating plate heat exchangers may be more suitable as they can be designed to allow cleaning without interrupting production.

The exhaust gases from frying processes contain oil vapours that may foul extraction or heat exchange equipment making extracting the heat difficult. One solution is to recycle the frying vapours into the flame that is used to heat the frying oil (20). This both burns the chemical energy in the vapours for heating energy and supplies pre-heated air to the combustion flame. The exhaust from the fryer is also partially cleaned resulting in cleaner extraction systems.

Organic Rankine and Kalina cycle machines also present opportunities for the generation of electricity from low grade waste heat streams in the food and drink industry. They are particularly applicable to the low grade waste heat common in the industry (18).

4.1.5 Paper, Pulp & Printing

The European paper and pulp industry produced 38.3Mt of pulp from virgin wood and 92.2Mt of paper and board in 2018 (21). European pulp production provides net of over 85% of the new pulp used in paper and board production in the region. Over 60% of European pulp is produced in Sweden and Finland. Recycled material makes up approximately half the raw material for paper and board production.

To produce pulp from virgin wood the wood logs are debarked and then chipped into small pieces. The pieces are then cooked and separated into individual fibres, i.e. pulped, by either a mechanical or chemical process. After screening cleaning and sometimes refining the fibres are mixed with water

to produce a slurry. Recycled paper is also pulped and de-inked before being mixed with virgin pulp at the refining stage.

To produce paper the pulp slurry is sprayed onto a wire screen which is drawn quickly through the pulp into the paper machine. Water drains out, and the fibres bond together. The paper is then squeezed between rollers to remove water and then dried by heated rollers. The finished paper is then slit into smaller rolls or sheets ready for use.

The main chemical pulping process in use for pulp making is the Kraft process. This process produces pulp with good strength properties. A diagram of the process is shown in Figure 4-3.

Chipped wood is cooked in a digester in a mixture of sodium sulfate and sodium hydroxide, known as white liquor, at approximately 170°C to degrade the wood fibres. The pulp fibres are then removed washed, screened, bleached and dried for paper making. The remnant chemicals, known as black liquor, are recovered.
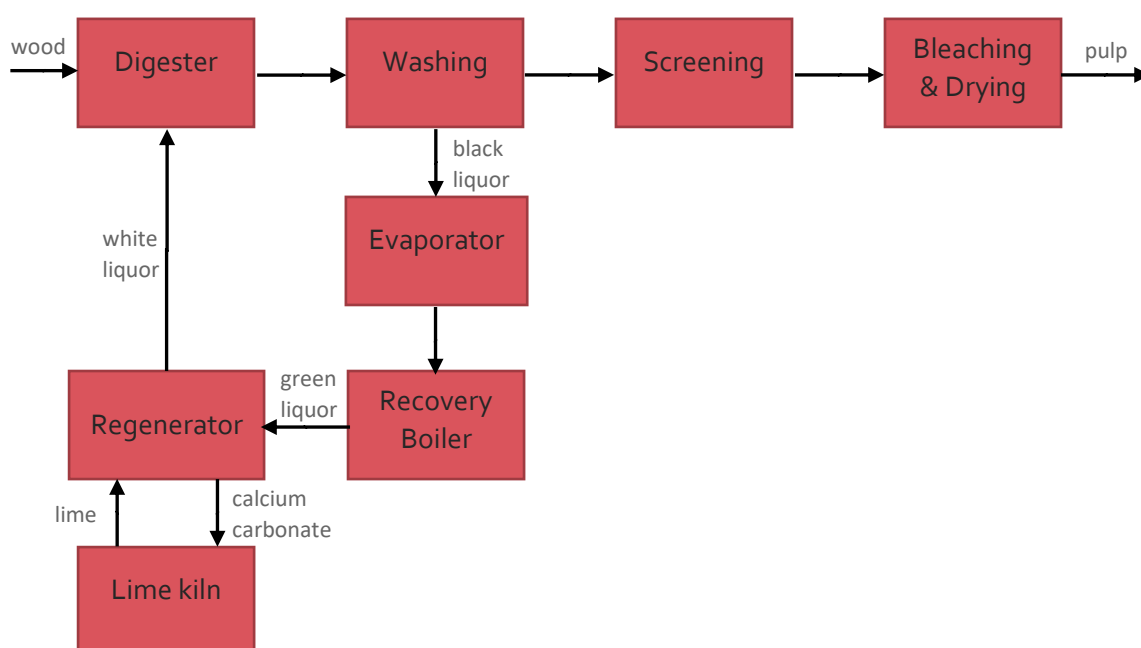
Figure 4-3: Diagram of the kraft pulp making process

The black liquor is recovered by first passing it through multistage evaporators, removing rosin soap as a by-product, until the liquor contains 65 – 80% solids. The liquor is then burned in a recovery boiler and the inorganic chemicals recovered are dissolved in water to form green liquor. The green liquor is mixed with lime (calcium oxide) which regenerates the green liquor to white liquor leaving a precipitate of calcium carbonate. The calcium carbonate is calcined to form lime in a lime kiln and the white liquor re-used at the start of the process.

The finished cooked wood chips are collected in a 'blow tank' releasing steam and volatiles, mainly turpentine, which are collected as by-products.

Bark and rejected pulp from the screening progress are often burned at paper mills to produce power and steam used in the processes. Coupled with energy from the energy recovery boiler this can allow the process to be self-sufficient or even a net generator of energy.

There are opportunities to recover energy from exhaust steam from the cooking and evaporating processes and from excess heat in the boiler and lime kiln flues (see Section 4.1.2).

Paper making machines require heat and dry air for drying the paper. There is the opportunity to use heat exchangers to heat air entering the drying process with outgoing air or with low grade steam.

4.1.6 Iron & Steel

The iron and steel industry in Europe produced 167.7Mt steel in 2018 (22). 58.5% was produced using the blast furnace and basic oxygen furnace (BF-BOF) route, where 80 – 90% of the finished product will be derived from virgin ores, and 41.5% using the electric arc furnace (EAF) route, where the majority of the finished product is derived from re-melted scrap and alloys. Figure 4-4 describes these two major process routes.

The BF-BOS process route, often referred to as the integrated route, starts with the production of coke and sinter or ore pellets for feeding into the blast furnace. The sintered or pelletised ores are then reduced in the blast furnace (BF) using coke and injected coal as both reductant and fuel to form liquid iron with approximately 4% carbon content.
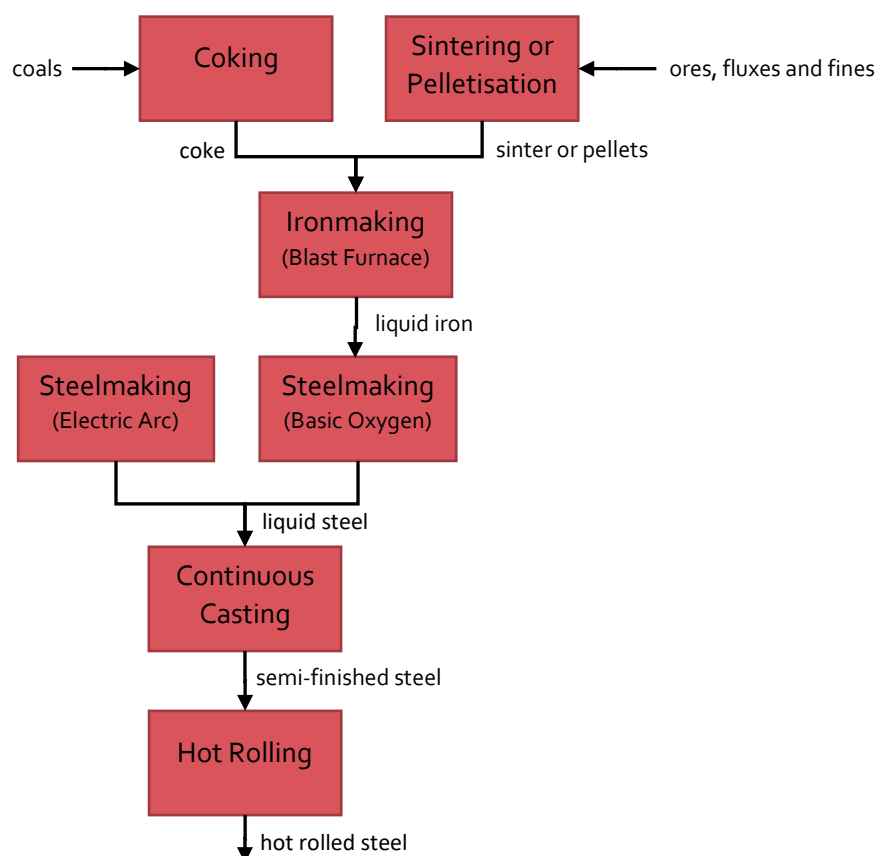
Figure 4-4: Diagram of iron & steel process route

The iron is refined to steel with a lower carbon content in the basic oxygen furnace (BOF) by blowing oxygen through the liquid iron. Scrap steel and alloying elements are usually added at this stage both to cool the process and increase final material yields. Further secondary steelmaking process are then often used to further refine and alloy the liquid steel.

The liquid steel is then cast into semi-finished products such as slabs, billets, blooms and ingots. In the EU more than 96% of steel produced is cast using a continuous casting process (22).

Once cast most steel is left to cool to ambient temperature although some is charged 'hot' or partially cooled reheat furnaces before being hot rolled into finished steel products.

Products are often further cold processed, coated or heat treated to achieve the final properties required by the application.

If made via the electric arc furnace (EAF) route then scrap steel is melted in an EAF before being further refined by secondary steelmaking processes and then cast and rolled in the same manner as BF-BOF produced steels. The electric arc furnace uses approximately 8 – 9 GJ less energy per tonne of liquid steel produced than the BF-BOF route (23). This reduced energy is in due to the energy already used to manufacture the EAF feedstock materials which are mainly scrap steel and granulated or pelletised iron.

Cavalier (23) notes that up to 25% of the EAF input energy may be recovered to raise steam for power generation but this is rarely practised due to the harsh environment of the fume system and the on-off batch nature of the process. Waste heat from the off gas system can also be used to pre-heat charged materials but requires significant investment in changed material handling equipment and exhaust systems.

A modern integrated steelmaking plant typically recycles process gases from coke, iron and BOF steelmaking processes to be burnt as an energy source and heat recovery is often used in a number of areas.

Steelmaking processes are by nature high temperature and produce a number of hot gas streams which are particularly suited to heat recovery (2). The energy from these streams is commonly recovered to either preheat combustion fuel and air or to raise steam. Kinetic energy is also commonly recovered from blast furnace exhaust gas flows using a low pressure turbine (24).

It has been calculated that there is 2.0 GJ/t of recoverable energy (24) from steel manufactured by the BF-BOS steel making process described above, assuming that relatively standard process technologies are used in combination with good heat recovery practices. The same study uses a pinch analysis to estimate that this could be increased to 2.5 GJ/t if heat recovery can be integrated across the production route. It is acknowledged that this may not be possible due to geographic constraints even on integrated steel works.

Steel production produces hot solid material, in the form of steel products, at high temperatures, over 700°C, from which very little energy is commonly recovered with most semi-finished steel products being allowed to cool before reheating for rolling and hot rolled material being allowed to cool following rolling with no heat recovered. This is in part due to the lack of cost effective practical technologies to enable heat recovery from these solids although projects to address this have been trialled or are ongoing (25).

On integrated steel works 'hot connect' techniques, charging the reheat furnace with material that is not fully cooled, are used to reduce the amount reheating energy required. Some modern plants closely couple continuous casting plants to hot rolling mills to reduce the amount of cooling and reheating required, saving an estimated 1.9 GJ/t of steel produced (24). Both these processes are less flexible and not capable of producing the full range of steels required.

Although most, if not all, steelmakers will use heat recovery on parts of their process routes it is not common for up to date heat recovery solutions to be implemented across all steps of the process route. Financing heat recovery is often an issue for steelmakers together with the competing demands of whether available capital should be used for process upgrades, other energy saving solutions or heat recovery. Economic payback and capital availability rather than technical feasibility typically limit the adoption of heat recovery solutions.

There are several alternative iron & steelmaking processes such as direct reduction some of which have a reduced carbon footprint. These processes are not noted here as their use in the EU is currently very limited (less than 1Mt produced per year).

4.1.7 Power & Energy

Analysis of global waste heat potential has shown that 88% of the waste heat energy from electricity production is at temperatures less than 100°C and the rest is mainly in the range of 100-300°C (26).

This low-grade energy is mainly useful for space heating or recovery through Organic Rankine or Kalina cycle machines. This energy is often harnessed most effectively if power is generated by combined heat and power (CHP) stations providing both electricity and thermal energy.

CHP is often used to provide process heating and steam for industrial processes or heat for space heating through district heating schemes. CHP power stations may be powered by most fuels, including biomass, and are often used on oil refinery and paper pulp production plants.

Energy from Waste

Waste incineration to produce energy has been common worldwide since the early 20th century. Europe has a long history of using energy from waste both for district heating and combined heat and power plants (27).

Mass burn technology uses moving grate or fluidised beds to move waste through the incinerator. The aim is for the waste to spend a relatively long time in the combustion zone to ensure that it is completely destroyed. Temperatures in the incinerator are usually over 1000°C to prevent the formation of harmful dioxins but less than 1300°C as this adversely affects ash formation. The hot gases from the incinerator are used to raise steam for driving electricity generation and then lower grade heat may be used for heating water for space heating.

More modern energy from waste plants may use pyrolysis or gasification technology. These technologies heat the waste to a high temperature in the absence of air producing flammable gases and solid ashes. The gases can then be burned either in a gas engine or conventional boiler to produce electrical power and heat. Gasification technology is essentially similar to pyrolysis save that it is carried out at higher temperatures and produces mainly carbon monoxide and hydrogen gases that may either be burned or used as inputs for other industrial processes.

4.1.8 Other industries

Other industries not individually described above include transport and machinery manufacture, general manufacturing, textiles, mining and quarrying, construction and wood processing. Most of the waste heat steams from these industries are assumed to be at temperatures less than 200°C which tends to favour use in space or district heating applications or recovery through Organic Rankine and Kalina cycle machines.

The data obtained shows that this diverse range of industries account for approximately 20% of European energy consumption and so represent a major opportunity to exploit waste heat sources.

4.2 Specific waste heat / cold factors in demonstration countries

National geographies, policies, finance systems, history and culture have a large effect on the exploitation of industrial waste heat and the use of systems such as district heating and cooling. These are hard to quantify or make specific reference to as there are so many variations between countries, cities and regions within the EU. This section of the report aims to highlight some of the key features of national industries and the use of district heating within the demonstration countries of the SO WHAT project. It does not speculate as to the reasons for these differences but looks at macro scale information and how the SO WHAT project may be exploited.

4.2.1 Industrial energy use variation

Table A-2 in Appendix 1 shows the percentage of energy used in different industry sectors for every EU country in 2017. This can present some insight into the potential variations in the types of waste heat available in the demonstration countries in this project.

Belgium has nearly a third of its energy use reported to be in the chemical and petrochemical industries, nearly twice the EU average, and less than 9% of its energy use outside the main industry categories.

Italy has a mixed economy with similar percentages of its energy use as the EU average save for slightly lower chemical and petrochemical energy use and slightly more in the non-metallic minerals and other categories.

Industrial energy use in Portugal is dominated by the non-metallic mineral and paper and pulp industries representing 24.8% and 31.1% of the countries energy use.

Romanian energy use shows a mixed economy in line with EU averages save for slightly lower energy use in the paper and pulp industry and higher use in the food and non-metallic mineral industries.

Energy use in Spain is higher in the non-metallic mineral industries and proportionally spread fairly evenly across other industry sectors.

Sweden's energy economy is dominated by the paper and pulp industry that consumes nearly 49% of the industrial energy demand. Energy use for chemicals, petrochemicals and non-metallic minerals is significantly lower than EU average.

The UK reports that over 42% of its industrial energy use to be in 'other' sectors. Deeper analysis of the Eurostat energy database shows that a significant proportion of this is vehicle and machinery manufacture but there is still a large percentage classed as 'other'.

Applying the SO WHAT tool over this mix of industries and countries will ensure that it may be applied to any region to assist in the exploitation of waste heat.

4.2.2 District heating

District heating is a potential sink for industrial waste heat, particularly from lower temperature energy streams. Table 4-1 below shows the large differences in the reported use of district heating between demonstration countries in this project and the variation in heat sources used in these systems (28).

Table 4-1: District heating systems data by demonstrator country (28)

Country	Installed capacity (TWh)	% population served	% CHP generation	% waste heat non-RES	% waste heat RES	% other Renewable energy
Belgium	n/a					
Italy	10.1	6		2.7	8.2	21.4
Portugal	n/a					
Romania	52.4	23	90	0	0	2.0
Spain	0.5	0.5		0	0	29.7
Sweden	64.6	52	42	14.5	5.3	61.5
UK	n/a	2	80			

The data shows Belgium and Portugal to not report any district heating systems in this data from 2013, although it should be noted that does not mean that such systems do not exist in these countries. This project is being used as a tool by project partners in Antwerp, Belgium, and Porto, Portugal, to enhance buy-in to district heating networks.

The data shows that Romania has almost a quarter of its population served by district heating schemes with CHP power plants supplying the majority of the energy into them.

Where district heating is used in the UK it is also fed by a high percentage of CHP power plants.

Sweden has a particularly high penetration of district heating networks serving over half the population. The high percentage of renewable energy used in district heating schemes includes about 49% biomass and 6.5% from the use of heat pumps. The use of waste heat (not including CHP) is just under 20% of the energy input to these networks. The evolution of this energy mix and recommended practice are described by the Swedish Council for District Heating (29).

The SO WHAT tool might be help understand whether greater use might be made of waste heat in the Gothenburg lighthouse cluster in the project or whether this is already an ideal amount to be using. The tool may also be used, as part of this project, to determine the viability of introducing more industrial waste heat in to the district heating scheme in Constanta, Romania, Antwerp, Belgium and that proposed in Oporto, Portugal.

5 Recovery of waste cold

In researching the availability of waste cold very little information could be found quantifying the amount of cold energy available, save for estimation of the amount of energy used for refrigeration (30). There are also few methods to assess cold availability and use on a large scale such as those used in sections 2 and 3 of this report.

The main source of waste cold energy found in the literature is that released during the regasification of liquefied natural gas (LNG). Section 5.1 looks at this topic and makes a rough calculation as to the amount of energy that might be recovered.

District cooling networks can provide efficient cooling with reduced impact compared to distributed air conditioning and refrigeration systems. These are discussed in section 5.2.

The SO WHAT project aims to address some of the gaps in the analysis of cold and allow better full system understanding.

5.1 Regasification of liquified natural gas

Liquified natural gas (LNG) is transported from producing to consumer countries at a temperature of approximately -160°C. The regasification process releases a significant amount of 'cold energy' that may be harnessed.

Regasification energy may be harnessed to produce electricity by driving generators either by the direct energy of gas expansion or using Rankine, Brayton or Kalina cycle machines. It has been calculated that approximately 26% (31) (215 kJ per kg of gas) of the cold energy in the LNG may recovered using a combination of direct energy and Organic Rankine Cycle machines.

European LNG imports in 2018 were approximately 49 million tonnes and are expected to show an increase through 2019 (32). We can calculated that this represents a recoverable potential of 10.5 PJ (2.9 TWh) of energy. Although recovery of this energy is more common in Japan (33) only a single reference could be found to a European LNG terminal recovering energy to generate electricity at the LNG terminal in Huelva, Spain.

The cold from LNG regasification is used to improve the efficiency of some air distillation facilities and to cool the input to compressor systems in order to increase their efficiency (33). Others have proposed using the waste cold energy to produce liquid air (30) or dry ice (34) for use as a cold energy vector for cooling away from the plant or to use the cold in district cooling schemes.

5.2 District cooling systems

District cooling systems work in a similar manner to district heating systems, save that they provide chilled rather than hot water to consumers. Cold water is pumped to customers who require coolant for equipment or air conditioning. Such systems are used in an number of cities worldwide including the SO WHAT project lighthouse cluster in Gothenburg, Sweden (35).

Water cooling for district cooling is often provided by heat exhangers in sea, river or lake water or from the air. These renewable cooling resources are most abundant in winter. In warmer seasons it is common to use adsorption chillers using waste heat that would otherwise have been used in district heating networks in colder seasons. Conventional heat pump chillers are commonly added to the cooling capacity of the networks to ensure full system demand can be met.

The advantages of district cooling systems include reduced fossil fuel energy use where renewable cooling or waste heat can be used, reduced refrigerant leakage due to the reduced number of systems in operation and a reduction in the number of cooling towers and noise in densely populated areas served by the systems.

The SO WHAT tool could be used to highlight where cold is required and link this with sources of 'free' cold such as rivers or sources of waste heat that could be used to drive chillers. Increasing the understanding of the need for, and availability of, cold energy should increase the uptake of efficient district cooling networks. The lack of current tools to understand cold energy limit the ability to do this.

6 Barriers to waste heat / cold recovery

Economic and other barriers to exploiting industrial waste heat have been explored extensively and are summarised here. Most of the information discussed here comes from two UK government reports (36) (37) but other sources generally concur. Work package 3 of the SO WHAT project will build business models to help understand where these barriers are and strategies to overcome them.

The availability of capital to invest in heat recovery is limited and companies will often not place heat recovery as their investment priority. Where capital is available it is most commonly used to fund improvements to production processes to allow improved or new products. Capital that might be spent on waste heat recovery will also be directly compared to investments aimed at reducing primary energy demand which may be perceived as a preferred route to saving energy.

Companies often associate heat recovery technologies with high upfront costs and long payback periods of over 3 years. Unless in an industry where energy is a high percentage of operating costs long payback periods limit technology uptake. Grants or other economic interventions may help overcome some of these barriers.

Scale is often a strong factor in calculating the economics of waste heat recovery. Smaller sized machines to generate electricity from waste heat may not be economic to maintain or justify additional infrastructure and generation on too large a scale may require additional regulatory permits or expensive large scale infrastructure.

There is often a lack of confidence in the energy payback promised by heat recovery equipment suppliers. Demonstration projects and independent case studies may reduce this perception barrier, particularly for companies with less proceduralised energy approaches.

It is sometimes perceived that there is a risk to product quality in adding heat recovery technologies, particularly where product quality depends on correct and precise heating schedules. Companies are often reluctant to make any alternation in heating mechanisms for fear it could change the product quality. Demonstration projects or independent feasibility studies are thought to be useful tools to overcome these issues.

Energy efficiency is often a low priority for companies compared with other commercial or corporate priorities. It is important to encourage companies to commit more resource to this and to empower energy managers with tools to identify and build business cases for energy recovery.

Element Energy (37) have estimated that of approximately 11 TWh of annual technical waste heat potential in the UK approximately 7 TWh is commercially economically viable to exploit, rising to 8 TWh if a socially discounted economic rate is assumed. Projects with a payback time of less than 2 years account for approximately 5 TWh. This analysis shows that even assuming short payback terms of 2 years nearly half the potentially recoverable waste heat is commercially exploitable. It would seem reasonable to assume that the economics of recovering waste heat will be similar across the EU, with small adjustments based on differing local financing criteria.

The viability of energy recovery is often questioned due to the assumption that it will require complex agreements with other partners that may restrict the ability of the heat producer to be flexible in their production schedules. Element energy (37) show that most heat sinks available for the use of waste

heat are on the same site as the heat source and when economically viable schemes are considered very few opportunities exist 'over the fence' with other industries. If this is emphasised when first exploring waste heat use then it may be easier to engage industries into fully considering what options may be viable.

One factor that may reduce the uptake of district heating schemes is the risk of industrial waste heat resources disappearing if factories close or are reconfigured. Research to assess this risk (38) shows that the risk of terminated heat delivery was increased where heat volumes are small or where heat pumps are used for recovering low temperature waste heat. It was found that risk of losing a heat supplier was only 7% after 20 years and only 5% if the higher risk heat sources were removed from the analysis. This shows that industrial waste heat generally provides a robust, long term heat source for district heating systems, provided that the barriers to investment may be overcome.

7   Conclusions

Two different methods have been used to calculate the waste heat potential in the EU both producing comparable results. Method 1 is a top down calculation that estimates heat use and waste heat from national and industry studies and applies these over the EU using calculated national energy intensity factors. Method 2 is a bottom up calculation that estimates surplus energy output from industries based on the technologies they employ and then calculates the waste heat potential for each industry and applies this to industry energy consumption data for each country.

Both methods make broad assumptions that key studies from a single country can be applied across the EU. This is sensible for an overall calculation such as this but takes little account of local differences in industry practice.

The recoverable waste heat potential is calculated to be 187TWh per year by method 1 and 167TWh per year by method 2.

The two methods show significant variation between industries and countries due to the effects of different assumptions and generalisations made by the methods.

These overall calculations provide an overall estimate for waste heat potential but lack the granularity describing the size of waste heat sources and do not reflect the waste heat potential of a single city or region. The SO WHAT tool will enable smaller scale views of waste heat potential to be built up enabling understanding and exploitation.

Approximately 2.9TWh of electricity might be generated per year from the recovered cold energy of liquid natural gas regasification in the EU. The technology to do this is proven but take up is very limited in the EU.

There is very little data available on sources of waste cold save for LNG regasification. The SO WHAT tool will enable mapping of these sources so that that may be more effectively exploited.

Waste heat is produced at different temperatures and in different energy vectors (gases, steam, liquids and solids) for different processes and producers. For energy recovery to be successful it is important to appropriately match waste heat sources and sinks. The SO WHAT tool will enable this process, improving the ease of waste heat exploitation.

It has been shown that the majority of sinks for recovered waste heat from industrial processes can be found on the same site in which the waste heat is generated and that most of the waste recoverable waste heat produced by industry may be recovered economically.

Capital availability and perceived risk of implementation are often the largest barriers to implementing energy recovery. The SO WHAT tool will enable better understanding of costs and risks to improve the exploitation of waste heat.

The perceived risk of loss of any single waste heat input to a district heating system are small and can be mitigated by the use of multiple waste heat sources feeding into a system.

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A Appendix 1 – EU industrial energy consumption

Table A-1: European union energy consumption by country and industrial sector 2017 (TWh)

	Iron & Steel	Non-ferrous Metals	Chemical & Petro-chemical	Non-metallic Minerals	Food & Beverage & Tobacco	Paper, Pulp and Printing	Wood and Wood Products	Textile and Leather	Other inc. Non-Specific
Austria	25.5	2.6	12.5	10.2	8.0	21.1	7.4	1.0	20.5
Belgium	29.7	3.6	46.8	15.5	17.7	8.6	2.7	2.1	12.4
Bulgaria	1.4	1.9	10.2	6.6	2.6	2.6	0.7	0.8	4.8
Croatia	0.1	0.2	1.9	4.3	2.3	0.8	0.9	0.3	2.9
Cyprus	0.0	0.0	0.1	1.8	0.4	0.0	0.0	0.0	0.3
Czech	21.2	1.2	12.2	13.3	6.9	7.0	2.5	1.5	21.6
Denmark	1.0	0.0	3.4	5.8	7.4	0.8	1.3	0.2	6.8
Estonia	8.5	0.0	0.4	1.0	0.7	0.8	0.8	0.1	1.5
Finland	13.6	2.8	11.7	3.8	4.8	72.6	6.8	0.3	13.4
France	62.8	13.0	48.3	39.2	56.9	27.9	6.9	3.8	90.2
Germany	168.0	27.4	175.8	78.0	59.4	66.2	21.7	5.5	131.8
Greece	1.5	10.1	1.4	7.9	4.9	0.6	0.3	0.4	8.8
Hungary	7.7	1.5	13.4	6.3	7.2	2.8	1.1	0.5	14.3
Ireland	0.0	5.8	2.9	5.3	5.5	0.3	2.0	0.2	7.3
Italy	52.9	8.1	42.5	48.8	33.2	26.6	5.6	13.5	69.8
Latvia	0.0	0.0	0.3	1.5	0.9	0.1	5.4	0.1	0.9
Lithuania	0.0	0.0	4.9	1.6	2.3	0.4	1.1	0.4	1.8
Luxembourg	3.5	0.0	0.5	1.6	0.2	0.1	0.2	0.4	0.9
Malta	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.5
Netherlands	30.4	3.1	85.0	6.8	24.8	6.9	0.6	1.1	21.2
Norway	8.6	21.5	15.9	4.1	4.9	5.4	1.7	0.1	8.2
Poland	41.4	5.7	32.2	34.8	23.8	20.4	12.2	1.4	30.8
Portugal	2.1	0.3	4.6	13.1	5.3	16.4	1.3	3.5	6.1
Romania	15.8	3.4	15.5	11.8	6.7	2.0	3.8	1.9	13.5
Serbia	6.8	0.9	5.5	4.4	4.8	1.3	0.4	0.9	5.3
Slovakia	24.2	3.1	4.3	5.4	1.6	5.6	0.6	0.3	7.0
Slovenia	1.8	2.0	1.9	2.2	0.8	2.0	0.5	0.2	3.6
Spain	38.0	13.2	34.0	39.3	29.4	20.5	7.3	3.5	42.0
Sweden	19.7	3.8	7.1	4.0	4.2	65.5	7.0	0.3	23.1
UK	28.3	7.4	39.0	27.6	30.3	21.1	2.4	6.2	120.1
Industry Totals	614.4	142.5	634.3	406.0	358.0	406.2	105.1	50.4	691.1

Table A-2: European union energy consumption by country and industrial sector 2017 (% of country total)

	Iron & Steel	Non-ferrous Metals	Chemical & Petro-chemical	Non-metallic Minerals	Food & Beverage & Tobacco	Paper, Pulp and Printing	Wood and Wood Products	Textile and Leather	Other inc. Non-Specific
Austria	23.4	2.4	11.5	9.4	7.4	19.4	6.8	0.9	18.9
Belgium	21.3	2.6	33.6	11.1	12.7	6.2	2.0	1.5	8.9
Bulgaria	4.4	6.0	32.4	20.9	8.4	8.1	2.3	2.4	15.2
Croatia	0.6	1.4	14.1	31.7	16.9	5.8	6.3	2.2	21.1
Cyprus	0.1	0.3	2.6	67.3	16.8	1.1	0.2	0.2	11.5
Czech	24.3	1.3	13.9	15.3	7.9	8.0	2.9	1.7	24.7
Denmark	3.9	0.0	12.9	21.8	27.6	2.9	4.7	0.7	25.5
Estonia	61.7	0.1	3.1	7.1	4.9	6.1	5.6	0.7	10.8
Finland	10.5	2.2	9.0	2.9	3.7	56.0	5.2	0.2	10.3
France	18.0	3.7	13.8	11.2	16.3	8.0	2.0	1.1	25.9
Germany	22.9	3.7	24.0	10.6	8.1	9.0	3.0	0.7	18.0
Greece	4.2	28.1	3.9	22.0	13.7	1.6	0.9	1.2	24.5
Hungary	14.0	2.8	24.5	11.5	13.2	5.1	1.9	0.9	26.2
Ireland	0.0	19.7	10.0	18.2	18.8	1.0	6.7	0.6	24.9
Italy	17.6	2.7	14.1	16.2	11.0	8.8	1.9	4.5	23.2
Latvia	0.2	0.1	3.3	16.5	9.8	0.7	58.6	1.0	9.8
Lithuania	0.2	0.0	39.1	12.5	18.1	3.5	8.9	3.0	14.7
Luxembourg	46.3	0.0	7.0	21.8	3.3	0.8	3.1	5.5	12.2
Malta	0.0	0.0	7.5	1.3	10.3	3.8	0.3	4.6	72.2
Netherlands	16.9	1.8	47.2	3.8	13.8	3.8	0.3	0.6	11.8
Norway	12.2	30.7	22.6	5.8	6.9	7.6	2.4	0.1	11.6
Poland	20.4	2.8	15.9	17.2	11.8	10.1	6.0	0.7	15.2
Portugal	4.0	0.7	8.8	24.8	10.0	31.1	2.4	6.6	11.5
Romania	21.3	4.5	20.8	15.9	9.0	2.7	5.1	2.5	18.2
Serbia	22.4	3.0	18.3	14.4	15.9	4.4	1.2	3.0	17.4
Slovakia	46.5	5.9	8.2	10.5	3.2	10.7	1.1	0.6	13.4
Slovenia	12.2	13.1	12.7	14.9	5.1	13.1	3.6	1.6	23.7
Spain	16.7	5.8	15.0	17.3	12.9	9.0	3.2	1.5	18.5
Sweden	14.6	2.8	5.3	2.9	3.1	48.6	5.2	0.2	17.1
UK	10.0	2.6	13.8	9.8	10.7	7.5	0.9	2.2	42.5
Industry Totals	18.0	4.2	18.6	11.9	10.5	11.9	3.1	1.5	20.3

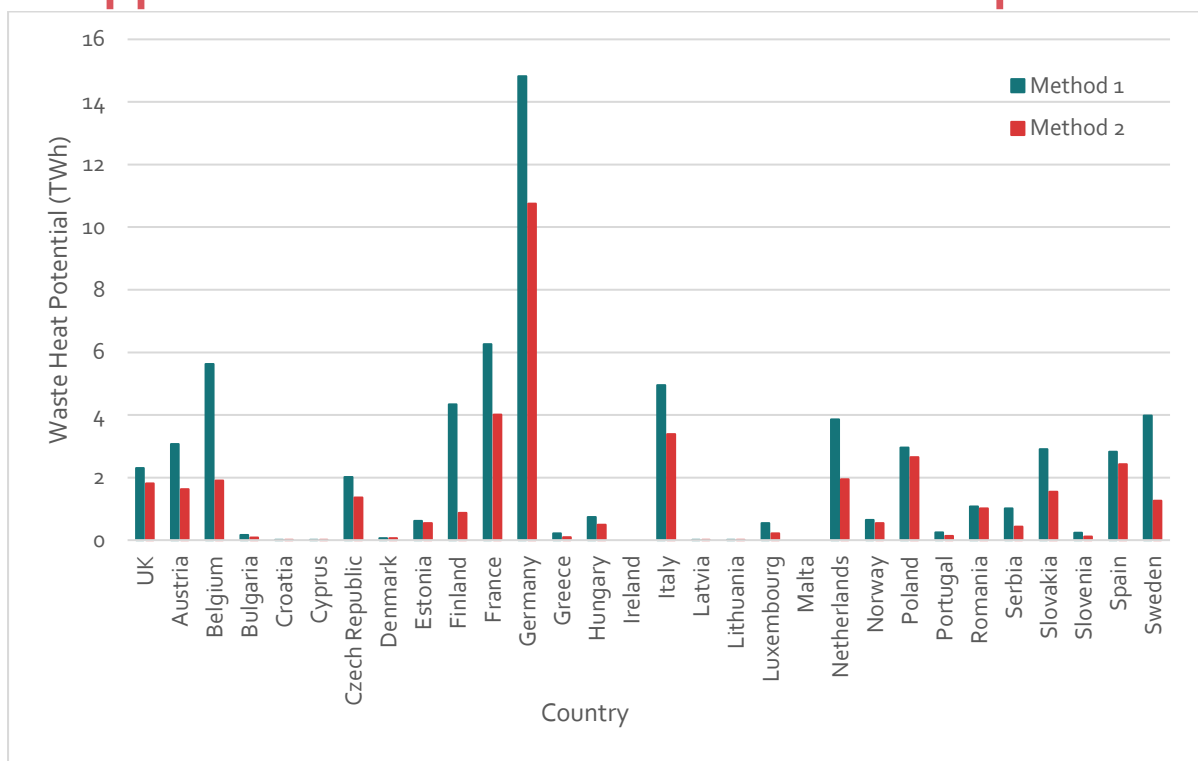# B Appendix 2 – Calculated EU waste heat potential

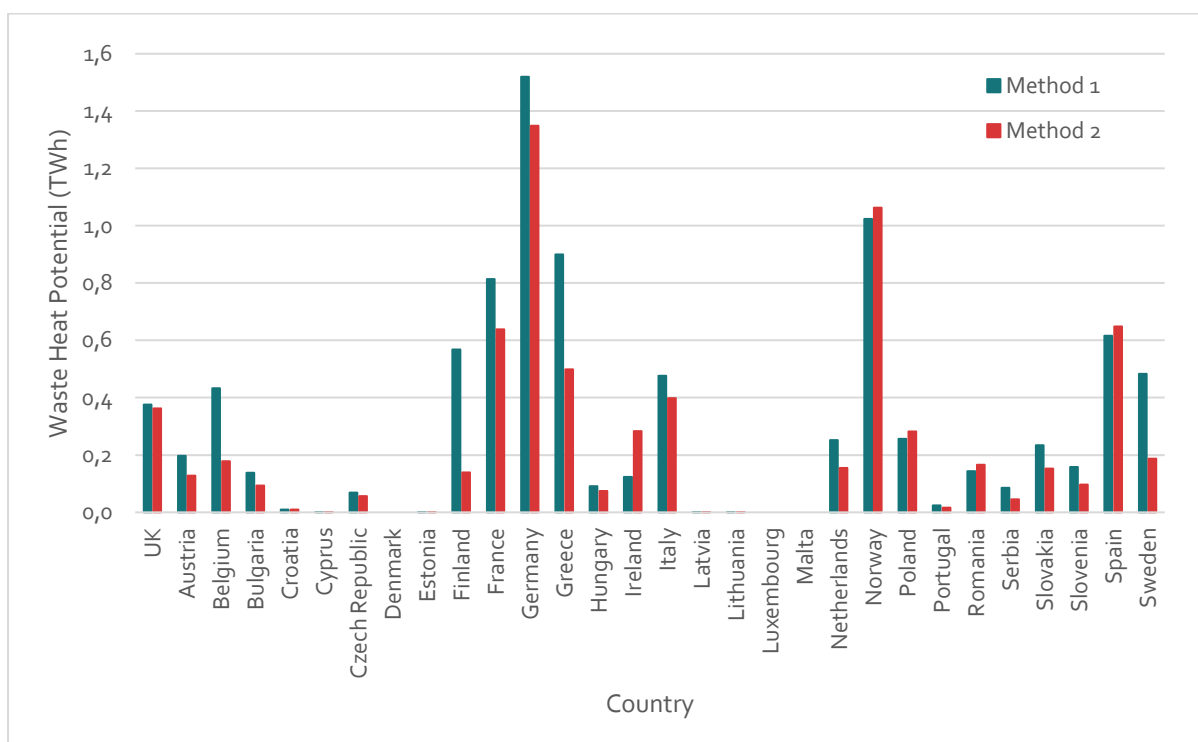Figure B-1: Waste heat potential of iron and steel industry by country

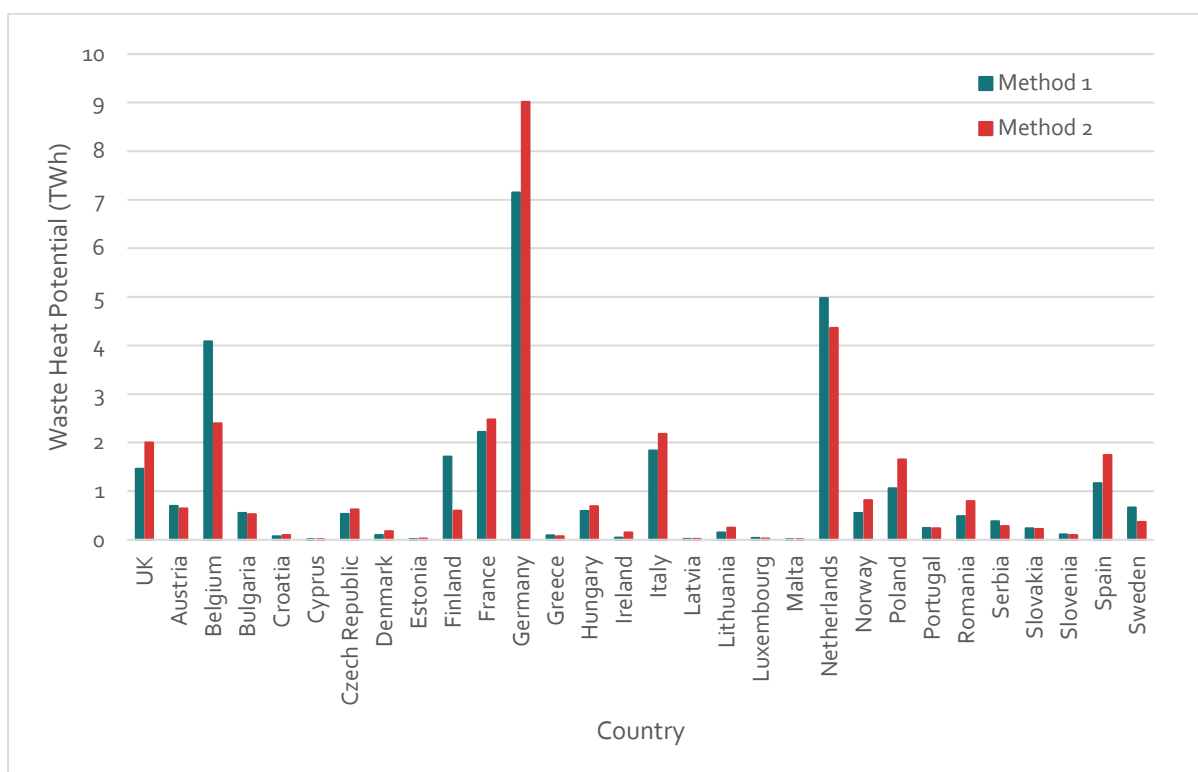Figure B-2: Waste heat potential of non-ferrous metals industry by country

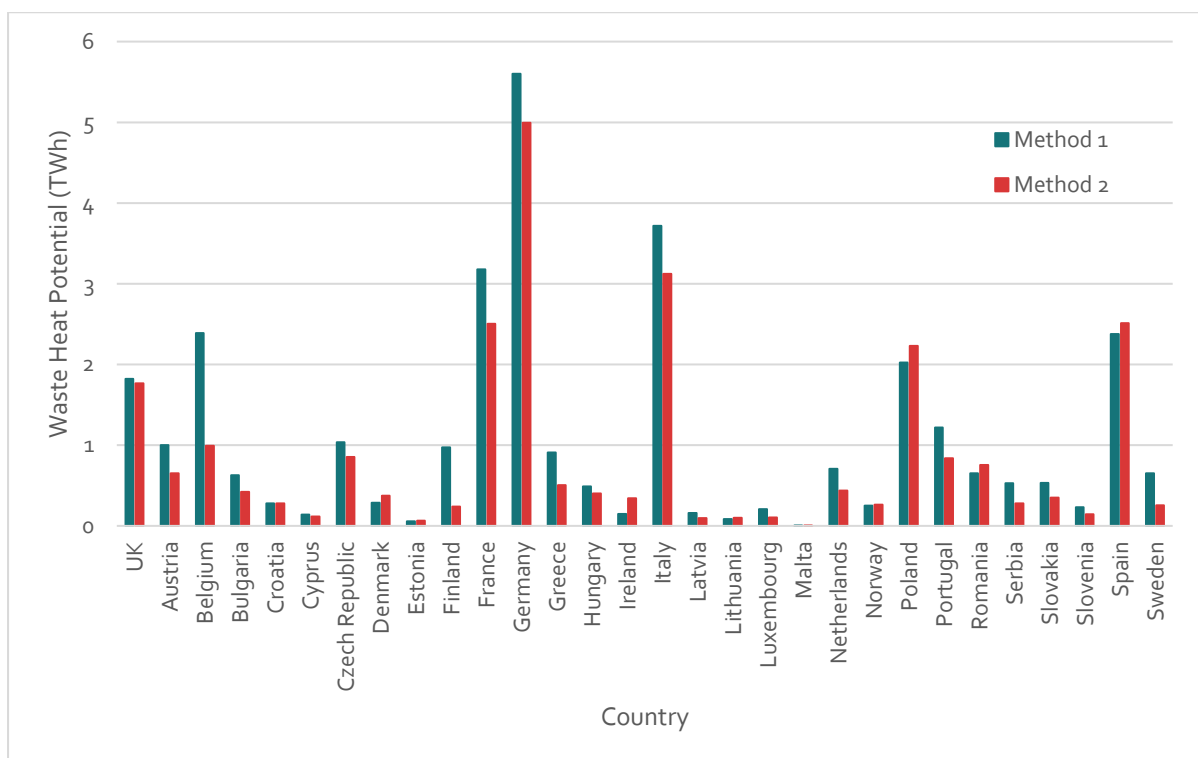*Figure B-3: Waste heat potential of chemical & petrochemical industry by country*

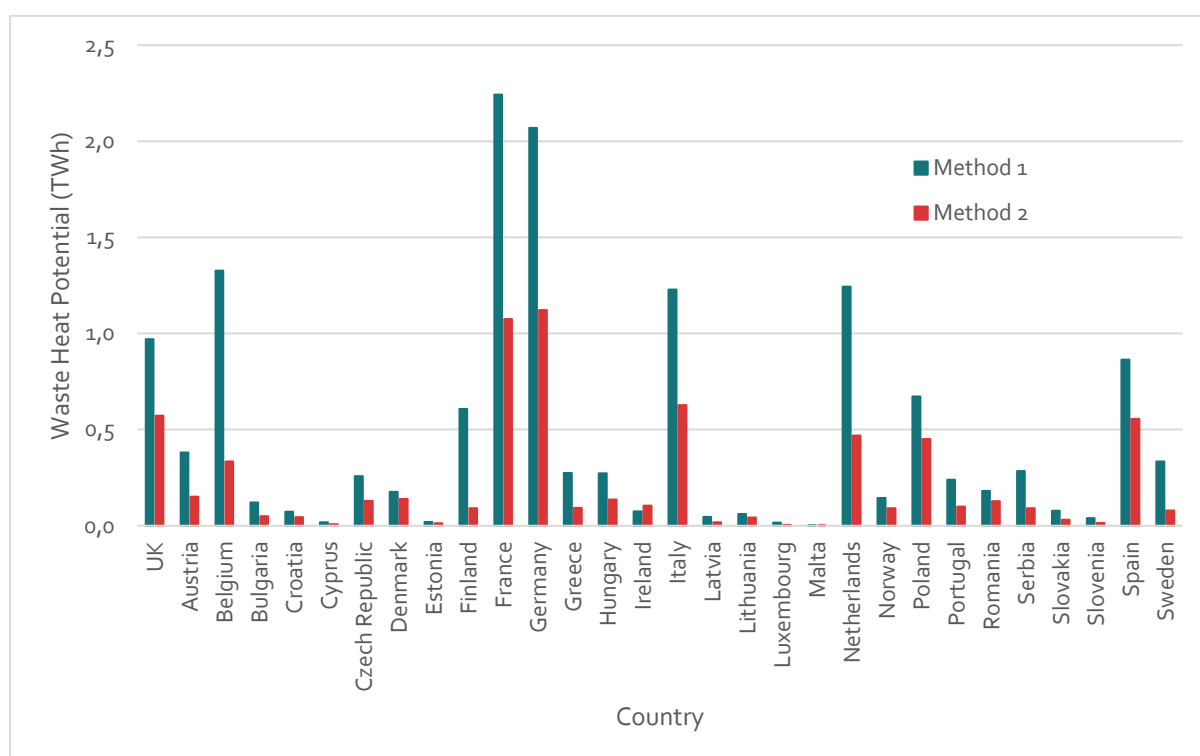*Figure B-4: Waste heat potential of non-metallic minerals industry by country*

Figure B-5: Waste heat potential of food and beverage industry by country
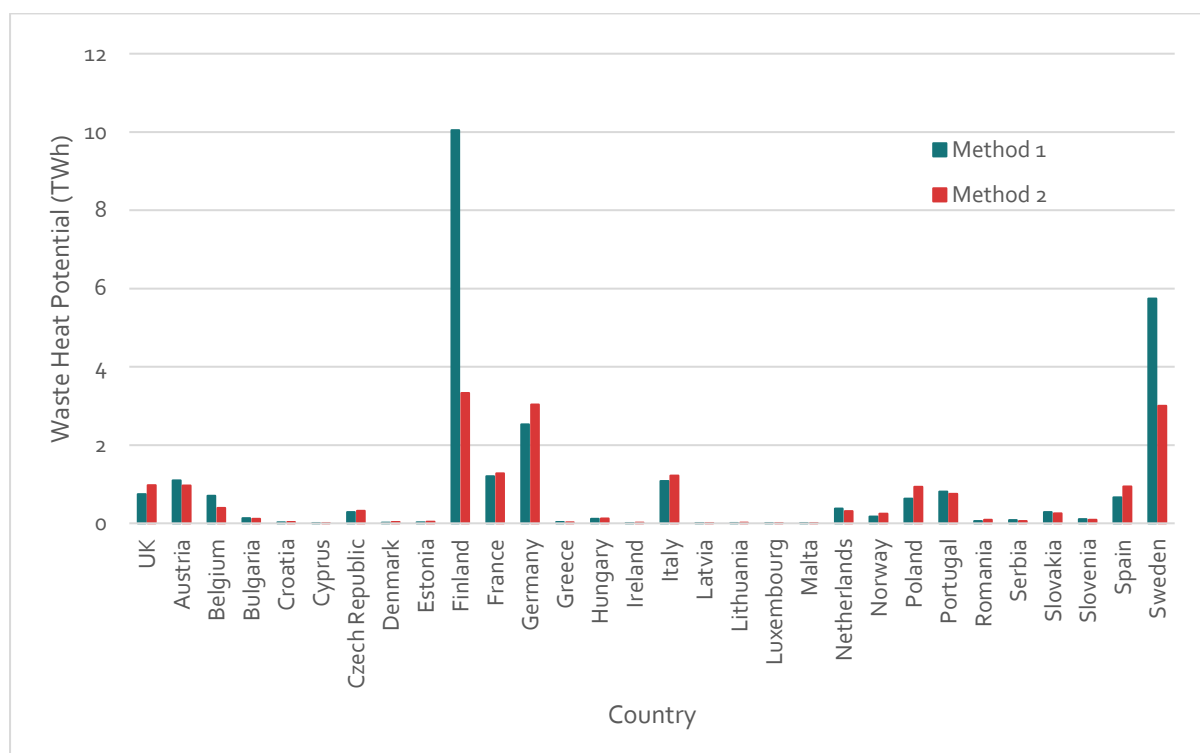

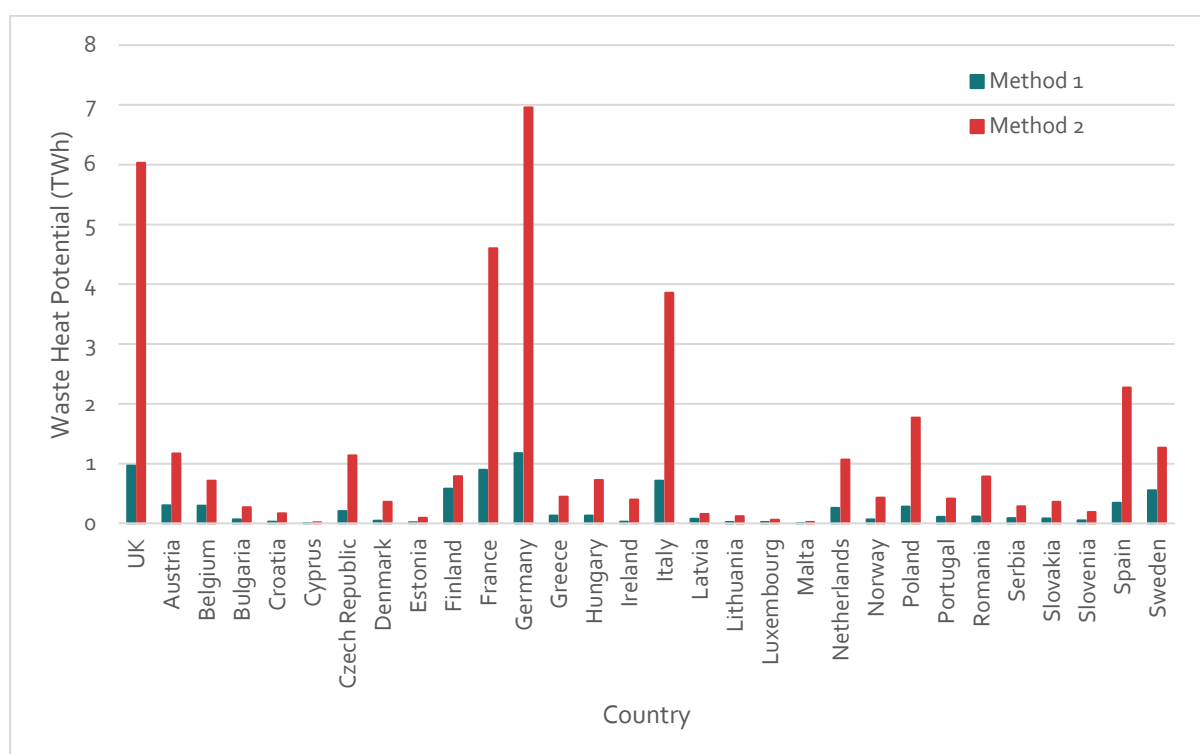*Figure B-6: Waste heat potential of paper pulp & printing industry by country*

Figure B-7: Waste heat potential of wood, textile & other industries by country