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An estimate of the ultralow waste heat available in the European Union

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Abstract

A large amount of low grade heat is wasted at temperatures below 100°C but its quantity remains mostly unknown. Therefore, the identification and quantitation of low grade heat availability enables further assessments on whether or not the recovery of this fraction of heat is convenient. By considering the countries composing the European Union (EU), this work quantifies the low grade heat from power generation and industrial sectors (mining, minerals, metals, chemicals, pulp and paper, food) with a particular focus on the faction of heat below 100°C. The analysis shows that, in the year 2018, $8{,}774.4 \cdot 10^6$ GJ (2,437.3 TWh) of heat was available in the EU below 100°C, with the power generation sector accounting for 95% of the total low grade heat emitted. In addition, around 96% of the waste heat was in the temperature range from 25°C to 80°C, being of ultralow grade. Similar conclusions were obtained in terms of exergy loss, which was essentially from the power generation sector, especially in the range of temperatures between 40°C to 60°C. These results suggest that ultralow waste heat is an untapped source of energy which can be conveniently exploited by the same point-source emitters, primarily in the power generation sector or in wider industrial areas where infrastructure is present.

Keywords: *Ultralow waste heat, Heat recovery, Thermal energy, Energy intensity, Process efficiency, EU energy resources*

1. Introduction

It is estimated that of the total primary energy sources which are consumed worldwide, 72% of the energy generated is lost [1]. Moreover, research into the industrial sectors has suggested that approximately 20–50% of the energy consumed by industry is also lost [2]. There are many sources of heat loss within the power generation and industrial sectors, but ultimately they all lead to the production of waste heat due to process inefficiencies [3]. Moreover, waste heat can be graded on temperature and this differentiation is critical. While the exact figures for heat grades can vary across the literature, generally high grade (>600°C), medium grade (240–650°C) and low grade (<240°C) are considered [2]. The heat grades convey the ability to successfully harness the waste heat. For instance, in the chemicals industry it would be straightforward to recover the energy from a high grade heat stream by using it to preheat another process stream via a heat exchanger. However, while the same task may still be possible with a medium or low grade stream, due to the lower temperature gradient, it is much harder to harness efficiently the waste heat when its temperature is only a few tens of degrees above the ambient temperature.

Although waste heat integration and process efficiency optimisation are widespread practices across the power generation and industrial sectors, energy losses are still incredibly high. Around 60% of waste heat lost is of low or ultralow grade [4]. Among the waste heat fractions, ultralow grade heat (heat at temperatures between ambient temperature and 80°C) is the largest. However, despite the large amount of energy available below 80°C, its recovery is so difficult and inefficient that it discouraged the attempts to assess it and exploit it in a useful way. For instance, the efficiency of a Carnot cycle operating between ambient temperature (25°C) and 80°C is around 0.16, and it drops down to 0.05 when moving from 80°C to 40°C. This implies that whichever cyclic process that uses ultralow grade heat ends up with rejecting the vast majority of heat input again into the surroundings instead of converting it into useful work. This thermodynamic aspect reduces significantly the potential of ultralow grade heat for generating work and sets a requirement for low-grade-heat-powered devices: they should convert heat into work at extremely high efficiency values, proximal to their maximum thermodynamic efficiency. This is not an impossible target. For instance, novel sorption materials for cooling have shown promising results [5], even if there is still a gap between the material properties and the possibility to harness them fully in practical engineering devices. Devices that are not deployed in closed thermodynamic cycles, such as power cycles or heat pump and refrigeration cycles, are not limited by the Carnot cycle's efficiency. These are often open separation processes where the thermodynamic limit is represented by the Gibbs energy of mixing. A number of these processes requires heat below 80°C (e.g. membrane distillation) and can show an energy demand close to the Gibbs energy of mixing, thus resulting in high separation efficiencies [6].

In addition to the mandatory requirements for high process efficiency, the second challenge of harnessing waste heat at temperature below 80°C consists in maintaining the highest temperature level possible during the multiple heat transfer operations. Heat transfer requires a temperature difference between the heat source and the heat carrier as well as the heat carrier and the final user. To save exergy in each heat transfer operation, the approach temperatures in each heat exchanger must be maintained minimal. Heat transfer with minimal approach temperatures implies heat exchangers with large surface areas.

If the technology was developed to harness the potential of ultralow grade heat, this could prove to be revolutionary for the consumption of energy. The ability to harness ultralow grade heat would significantly reduce the primary energy consumption across the power generation and industrial sectors.

The availability of ultralow grade heat has not been studied in great detail for many regions globally and the true potential of ultralow grade heat recovery from the power generation and industrial sectors is not fully understood. Only a few attempts of surveying waste heat available globally have been performed but with lack of detail on the ultralow grade heat fraction, which is often neglected or integrated within higher temperature levels. Rattner and Garimella [7] have reported that more than 1,500 PJ y^{-1} should be available in the USA from the power generation sector at temperatures below 50°C. An analysis on China's waste heat [8,9], focusing on waste heat emissions from three industrial sectors (cement, iron and steel, and glass), surveyed around 600 PJ y^{-1} below 150°C. Papapetrou et al. found that approximately 360 PJ y^{-1} is available in EU below 200°C from various industrial sectors [10], although the study disregarded the fraction of heat at temperatures close to ambient temperature. McKenna and Norman [11] and independent reports [12] assessed the presence of at least 100 PJ y^{-1} from the UK industry (not including the power generation sector) in the timeframe 2010–2014. Additionally, the worldwide waste heat potential study by Forman et al. found that 63% of all waste heat produced was at a temperature below 100°C [1]. It should be noted that this worldwide study also included the power generation sector, unlike [10].

Evidently, the availability of waste heat at temperatures below 80°C remains mostly underexplored, despite the agreement from literature that low grade and ultralow grade waste heat contribute significantly to the total waste heat picture. In this study, a method similar to the one applied by Rattner and Garimella to the USA is employed to estimate the availability of ultralow grade heat in the European Union [7]. Specifically, this study aims to analyse power generation and key industrial sectors from EU-28 countries in the year 2018. Because of the scattering of the information available, this work sometimes captures waste heat at temperatures above 80°C with the purpose of including those processes that emit waste heat at higher temperatures. Detailed breakdowns of waste heat potential categorised by temperature level are produced, which will help clarify where and how much ultralow grade heat could be harnessed in the EU.

2. Methods for surveying waste heat availability

Detailed studies specifically into the potential of ultralow grade heat have not been extensively carried out, however, multiple studies have attempted to determine waste heat potential across different regions of the world. Among these studies, methodologies and calculations to produce final waste heat estimations can vary significantly; some of these various methods are therefore reviewed and compared. Waste heat potential studies have been carried out on both the single process scale all the way to worldwide scale. Due to the vast differences in scope, these studies employ different methodologies to evaluate waste heat levels. An in-depth literature review was carried out by Brueckner et al. to classify the different methodologies by which waste heat potentials can be evaluated [13]. Two classifications of method were defined: top-down studies and a bottom-up studies.

A top-down approach refers to a study where general industry or process efficiency factors are employed and used across entire sectors [13]. This methodology enables large scale estimations to be made, such as entire countries. However, applying general efficiency data sets across entire countries will reduce the accuracy of the study. This is because not every process within a single subsector operates identically, so there will be efficiency differences, and, therefore, waste heat differences between different facilities. A top-down study was carried out to estimate the worldwide global waste heat potential [1]. An energy balance was established for each process being considered, and these balances were then extrapolated to a global scale. Although large assumptions have to be made in this specific methodology, it allowed worldwide waste heat estimations to be conducted, albeit with a higher degree of uncertainty, compared to a bottom-up methodology. A bottom-up methodology is when more in-depth process studies are carried out and then finally combined to create a full waste heat picture. For example, individual waste heat studies were carried out on cities in a particular German federal state [13]. These individual city-wide studies were then collated to form a waste heat picture for the whole state. The smaller scale allowed this approach to be more accurate, however this is a time-consuming methodology, therefore, less feasible for large scale analyses of entire countries.

The waste heat study of the EU by Papapetrou et al. applied a top-down methodology [10]. This study modified UK waste heat fractions from a previous literature work to represent the efficiencies of modern processes in the EU. Additionally, up-to date production data, at the time of writing, for each industry was also used. This EU study only considered industrial waste heat, neglecting the power generation sector. This method differs significantly from the Rattner and Garimella study of waste heat potential in the USA [7] that analysed the thermodynamic characteristics of processes representative of the main industrial sectors, and additionally the power generation sector. In this case, once energy intensities, efficiencies and waste heat fractions were established for each process, they were applied to up-to date production data for each industry. This methodology was a relatively precise top-down approach.

Both the USA and EU waste heat studies discussed rely on various assumptions. In the EU study of waste heat potential, although waste heat fraction data was modified to represent modern efficiencies values, it was still fundamentally based on a waste heat study carried out for the UK only. Accuracy is therefore partially dependent on the reliability of the UK waste heat study. However, this was taken into account, as an uncertainty of 33% from the UK waste heat study was carried forward into the results of the EU study [10]. The waste heat study in the USA was highly influenced by the thermodynamic study of each process being considered. Since each industry's waste heat was estimated by one representative process, the analysis of energy intensity, efficiency and waste heat fractions are highly influential on the final waste heat values obtained. The US waste heat study attempted to select process thermodynamic data which was representative of industry, thus, where appropriate, the most abundant process in any given industry was selected. However, since it is important to not overestimate the amount of waste heat available, conservative approaches were sometimes more appropriate [7]. This is when the most efficient process technology for a given industry is used to determine waste heat for an entire industrial sector. Although the most modern, efficient process technologies may not be the most widely adopted in industry, they allow a conservative total waste heat value to be estimated. Moreover, since adoption of the most efficient technology is likely in the future, it may also serve as future proof of waste heat estimations.

3. Waste Heat Analysis in the EU

3.1 Methodology

To produce an estimate of the waste heat emissions in the European Union, a similar estimation method to the one used by Rattner and Garimella in their waste heat study of the US has been followed and applied to both power generation and industrial sectors [7]. Similarly to the US waste heat study, a detailed top-down approach was used to estimate EU waste heat emissions for the year 2018. Since the Brexit transition period lasted till the end of 2020, EU data comprised the United Kingdom (UK). When data for the specific 28 EU countries or in the year 2018 were not available, data were explicitly gathered and processed for the whole Europe or in previous years. The sectors being broadly considered were power generation and major industries. Specifically, the power generation sector included coal, oil, natural gas and nuclear, while the industrial sectors included mining, minerals, metals, chemicals, pulp and paper and food industries. It was reported that in 2018 these six major industries accounted for around 72% of sold production of EU total manufacturing activity [14].

For each individual sector, a process representative of the entire industry was analysed, and thereafter, annual production data were applied to determine a waste heat estimation. A thermodynamic analysis based on literature was carried out for each process. This allowed specific energy intensities, process efficiencies and waste heat fractions to be determined for the processes being used to represent each sector. Our analysis focused on the total waste heat available and did not distinguish how much heat is actually recoverable. Once key thermodynamic data were established, they could be used to estimate the waste heat potential. Statistics on the annual production rates for the industries being considered were generally obtained from EU statistics sources. In addition, waste heat temperature levels were mostly sourced from literature studies. Since the efficiency values selected to represent entire industrial sectors were highly influential on the final waste heat estimations, thermodynamic data were selected so that a conservatively low waste heat estimation was obtained.

3.2 Waste Heat – Power Generation

The total power generated in the European Union must be sufficient to meet the requirements of every avenue of society, providing for everything from industrial to domestic energy demands. It is apparent that the power generation sector will be one of the largest consumers of primary energy, thus it is expected to have one of the largest waste heat potentials. An energy data report by EUROSTAT provided a document of energy generation data from EU member states in 2018 [15]. The total EU energy generation in 2018 was $11{,}052 \cdot 10^6$ GJ (3,070 TWh). To determine the waste heat potential of the power sector, only electricity generation from coal, oil, natural gas, and nuclear sources were considered. Collectively, these four generation entries produced approximately 60% of electricity in the EU [15], as detailed in Table 1. Note that the “other” entry includes biomass and biofuels, geothermal and other renewable sources from which additional waste heat would be generated.

Table 1: Energy generation per source in the EU in 2018

Energy source		(%)
Conventional thermal	Coal	18.2
	Oil	1.1
	Natural gas	15.2
Nuclear		25.5
Renewable	Hydro	11.8
	Wind	12.2
	Solar	4.0
Other		12.0

Renewable energy is a significant contributor to the EU's electricity generation, accounting for 28% of total energy generation. However, the assumption was made that there were no significant waste heat sources in the renewable energy sector, thus it was not considered in the waste heat analysis. To determine the waste heat generated per source, the amount of energy being consumed was required. By using process efficiencies of energy generation representatives of industry standards, the energy consumption for conventional thermal and nuclear sources could be determined. The calculated energy consumption data are reported in Table 2 along with relevant references for process efficiencies.

Table 2: Process efficiency and energy consumption per source in the EU in 2018

Energy source	Energy generation (10^6 GJ)	Process efficiency (%)	Energy consumption (10^6 GJ)	Process efficiency reference
Coal	2,014.5	37.5	5,372.1	[16]
Oil	126.4	40.0	315.9	[17]
Natural gas	1,678.8	49.0	3,426.0	[17]
Nuclear	2,822.2	40.0	7,055.4	[18]

Using the process efficiencies and energy consumption values of Table 2, the waste heat could be calculated for each energy generation source. In the work by Rattner and Garimella [7] the authors provided a comprehensive thermodynamic analysis of power plants in the US, including process efficiencies, waste heat sources, fractions and temperatures. In this study, it was assumed that waste heat sources, fractions and temperatures would be the same for the power plants operating in the EU, however, with updated plant efficiencies.

In coal-fired power plants the waste sources are the exhaust gas, the wall losses and the condenser, with waste heat fractions and temperatures summarized in Table 3. The reference plants were assumed to be pulverized coal boilers as they represent by far the dominant technology. Amongst other technologies there are only three integrated gasification combined cycle (IGCC) plants in operation in the EU totalling 950 MW_e [19]. Although heat leakages, e.g. wall losses, can significantly contribute to the waste heat generation, they may be impractical to harness and a better insulation of walls may be a preferable strategy to improve the power generation efficiency of coal-fired power plants. It should be noted that the sum of waste heat fractions and the relevant process efficiency, e.g. 37.5% for coal, equal 100%. The overall estimated waste heat generation from coal-fired power plants in the EU was 3,357.5·10^6 GJ in 2018.

Table 3: Waste heat data from coal-fired power plants in the EU in 2018

Energy consumption (10^6 GJ)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
5,372.1	Exhaust gas	2.0	107.4	128.4	[7]
	Wall losses	19.4	1,042.2	70.0	
	Condenser	41.1	2,207.9	40.0	

In nuclear power plants the condenser represents the only source of waste heat [7]. There are various types of nuclear reactors in operation throughout the European Union with the advanced gas cooled reactor (AGR) being one of the most efficient ones (40%) [18]. To obtain the most conservative figures of waste heat from the nuclear power sector, this efficient reactor was used to represent the EU nuclear reactors. From Table 4 the overall waste heat generated from nuclear power plants in the EU was 4,233.3·10^6 GJ in 2018.

Table 4: Waste heat data from nuclear power plants in the EU in 2018

Energy consumption (10^6 GJ)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
7,055.4	Condenser	60.0	4,233.3	41.5	[7]

In oil-fired power plants exhaust gas and engine coolant are the main sources of waste heat with very similar waste heat fractions [7]. However, in this study, updated waste heat temperatures for the oil combustion process were sourced from [20,21]. Similarly to [7], the reference plants were assumed to be internal combustion engines given the lower share (36%) of the other technologies in operation in the EU including gas turbine cycles and combined cycle plants [22]. The overall waste heat generated from oil-fired power plants in the EU in 2018 can be estimated from Table 5 as 189.6·10^6 GJ.

Table 5: Waste heat data from oil-fired power plants in the EU in 2018

Energy consumption (10^6 GJ)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
315.9	Exhaust gas	29.9	94.5	600.0	[7,20]
	Engine coolant	30.1	95.1	82.0	[7,21]

Energy from natural gas in the EU is generated using various power cycles, as shown by the natural gas generation capacities for the EU [23]. These data cover the year 2016 and list natural gas-fired power plants including combined cycles, gas turbine cycles and differently categorised cycles. By dividing the capacity of each category by the total natural gas capacity, the percentage of each categories was determined. Given the lack of data for all EU countries, the split fractions were based on the UK natural gas generation capacities. In the US waste heat study by Rattner and Garimella [7], combined cycles, gas turbine cycles, steam turbine cycles and internal combustion cycles were considered with natural gas as an energy source. Since the energy generation by natural gas in the US and EU are similar, it was assumed that the differently categorised cycles were represented by steam turbine and internal combustion cycles.

To calculate the capacity splits per energy generation type in each category, the figures presented by Rattner and Garimella [7] were used. The latter reference was also used to determine process efficiencies, waste heat sources, fractions and temperatures. However, for the gas turbine cycles, process efficiencies and waste heat fractions were evaluated from the work by Fen and van der Berg [24] while the waste heat temperature from the engine coolant of the internal combustion was updated from the oil-fired power plants [21]. Table 6 reports the split fractions and process efficiencies as well as the waste heat sources, fractions and temperatures from natural gas-fired power plants in the EU. The sum of secondary splits equals the value of their primary split while, as already discussed, the sum of waste heat fractions and the relevant process efficiency equal 100%. It should be noted that in the present work process efficiencies in combined cycles (CC) are reported separately for the gas turbine (CC: GT) and steam turbine (CC: ST), in line with the convention adopted in [7] for having the same total heat input at the denominator. Thus, the relatively low individual generator efficiencies (35.3%, 20.1%) combine to yield a more familiar overall efficiency (55.4%) consistent with modern plants. Overall, the waste heat generated from natural gas-fired plants in the EU totalled $771.4 \cdot 10^6$ GJ in 2016 (Table 6).

Table 6: Split fractions, process efficiencies and waste heat data from natural gas-fired power plants in the EU in 2016

Total energy consumption (10^6 GJ)	Power cycle	Primary split (%)	Secondary split (%)	Energy consumption (10^6 GJ)	Process efficiency (%)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
3,426.0	***Total combined cycle (CC)***	93.3		3,196.5						[7]
	CC: GT		63.1	2,017.0	35.3	Exhaust gas	9.5	191.6	91.1	
	CC: ST		36.9	1,179.5	20.1	Condenser	35.1	414.0	29.0	
	Gas turbine	0.1		3.4	41.0	Exhaust gas	52.9	1.8	543.0	[7,24]
						Wall losses	6.1	0.2	50.0	
	Other natural gas	6.6		226.1						[7,21]
	Steam turbine		97.0	219.3	27.5	Exhaust gas	11.3	24.7	120.0	
						Condenser	61.2	134.3	38.1	
	Internal combustion		3.0	6.8	29.6	Exhaust gas	22.5	1.5	648.9	
						Engine coolant	48.0	3.3	82.0	

Using the waste heat figures calculated from the four energy generation sources being considered, a complete picture of waste heat from the power sector can be drawn. The overall waste heat generation in the EU was 8,551.8·10^6 GJ (2,375.5 TWh) in 2018. In addition, the vast majority of waste heat identified in the power sector was of ultralow grade (<80℃), as depicted in Figure 1.

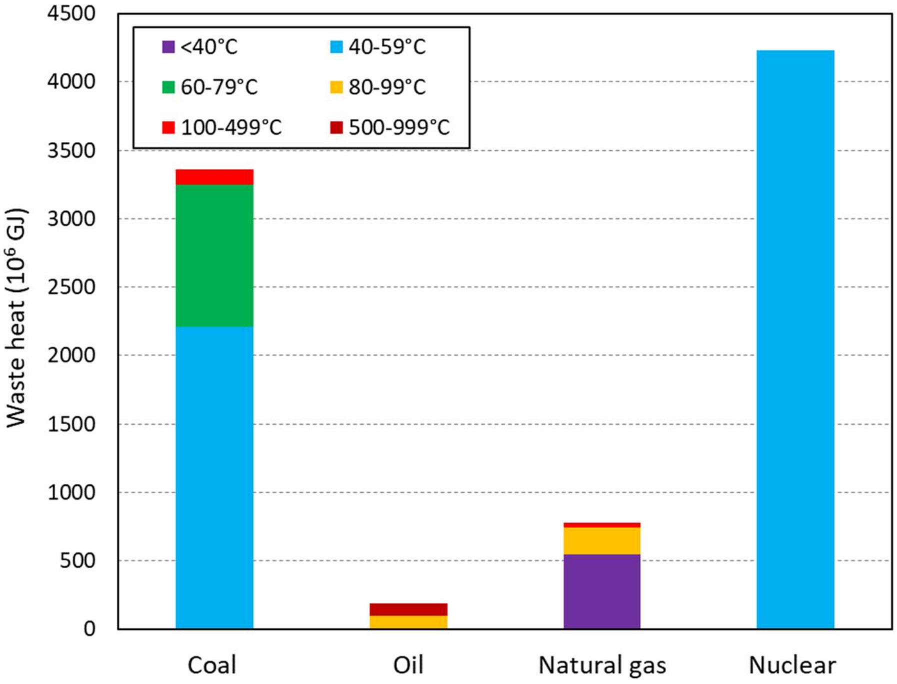

Figure 1: Waste heat generated in the power sector per energy source in the EU in 2018

3.3 Waste Heat – Industrial On-Site Power Generation

In the previous section the total power generated in the EU was based on the net electricity production, and as such the electricity used by industrial generators for their own consumption was not taken into account. Waste heat is primarily released in EU industry by combustion-driven machinery and on-site power generation. A technical article [25] estimated that in 2017 the net industrial on-site power generation in 13 EU analysed countries was 763.2·10^6 GJ (212 TWh), corresponding to more than 8% of the total power generation. More than two thirds of the electricity was generated by CHP systems while fossil fuels, primarily natural gas, accounted for around 60% of industrial on-site generation, followed by renewables, biomass, biofuels and waste [25,26]. Assuming representative natural gas-fired internal combustion engine data from Table 6 in line with [7], the waste heat from machinery and power generation could be estimated with values summarised in Table 7. As a result, additional 538.0·10^6 GJ of waste heat would be available from industrial on-site power generation at two temperature levels. Note that that only 366.3·10^6 GJ are below 100°C and can be classified as low grade waste heat.

Table 7: Waste heat data from industrial on-site power generation assuming internal combustion natural gas-fired power plants in the EU (13 countries) in 2017

Energy consumption (10^6 GJ)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
763.2	Exhaust gas	22.5	171.7	648.9	[7,21]
	Engine coolant	48.0	366.3	82.0	

3.4 Waste Heat – Mining Industry

In the current state the European Union mining industry serves as a relatively small contributor to the economy, however, the production of many metallic and mineral products is vital for the global output [27]. Moreover, mining is an energy intensive industry, therefore significant waste heat sources can be identified by analysing the mining operations. To assess the mining industry, production was split into four mining products including metals, industrial materials, coal and aggregates. The European Association of Mining Industries (Euromines) is recognised by most EU member states as a representative of the European mining industry [28]. Euromines production data for major metals and industrial materials in the EU are reported in Table 8 for the year 2018. Coal and aggregate production figures in the EU were sourced from literature [29,30]. The aggregates figure is from 2006 assuming a stable production in Europe [30]. Table 9 summarizes the mining production per category in the EU showing an overall production of 2,711.9 Mt in 2018.

Table 8: Metal and industrial material production in the EU in 2018

Metal	Production (Mt)	Industrial material	Production (Mt)
Aluminium	2.34	Baryte	0.26
Bauxite	1.82	Bentonite	2.87
Iron	19.60	Gypsum	26.05
Gold	3.48E-5	Diatomite	0.30
Tungsten	3.27E-3	Feldspar	9.71
Nickel	0.07	Kaolin	12.20
Copper	0.91	Fluorspar	0.24
Lead	0.21	Graphite	7.67E-3
Zinc	0.79	Magnesite	3.19
Silver	1.96E-3	Potash	3.72
Manganese	0.01	Salt	50.15
		Sulphur	4.91
		Talc	1.19

Table 9: Mining material production in the EU in 2018

Mining material	Production (Mt)
Metals	25.8
Industrial Materials	114.8
Aggregates	2,500
Coal	71.3

Mining operations can be broadly classified into two categories: surface mining and deep mining. According to literature, around 95% of non-metals, i.e. industrial materials, aggregates and coal, and 90% of metals produced globally are extracted by the surface mining process [31]. According to an EU publication, more than 50% of active coal mines in the EU are also surface mining-based [32]. Due to the dominance of surface mining as the most widespread operation, the waste heat analysis of mining in the EU has been based on surface mining. The energy intensity of surface mining process was found from the literature [33], therefore, a total energy consumption for the EU mining industry could be determined, as detailed in Table 10.

Table 10: Energy consumption from the mining industry in the EU in 2018

Surface mining production (Mt)	Surface mining energy intensity (GJ t^{-1})	Energy consumption (10^6 GJ)
2,711.9	0.09	244.1

Studies in the literature identified the key stages in the mining process and their percentages with respect to the total mining energy consumption [33,34]. Energy consumptions of the operational activities are summarised in Table 11 and include extraction, material processing and mineral processing. Data on process efficiencies, waste heat sources, fractions, generation and temperatures are also reported along with their relevant references. The power sources for the mining, transportation and processing equipment are dominated by electrical motors and diesel combustion engines [33,34]. A detailed waste heat generation split among the various mining operations can be found in Table 11. It is worth highlighting that the majority of waste heat originates from operations involving electrical motor-driven stationary machinery (47%) followed by diesel engine-driven mobile vehicles (27%), diesel engine-driven stationary machinery (19%) and other mineral processing (7%). Compared to stationary machinery it may be impractical to harness the waste heat from mobile vehicles.

Table 11: Split fractions, process efficiencies and waste heat data from the mining industry in the EU in 2018

Total energy consumption (10^6 GJ)	Mining operation	Primary split (%)	Secondary split (%)	Energy consumption (10^6 GJ)	Process efficiency (%)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
244.1	***Extraction***	27		65.9						
	Drilling		5	12.2	39.1	Exhaust	35.5	4.33	400.0	[7,34]
						Coolant	10.6	1.29	85.0	
						A/C	6.0	0.73	130.0	
						Other	8.8	1.07	25.0	
	Blasting		2	4.9	N/A	N/A	N/A	N/A	N/A	N/A
	Digging		8	19.5	39.1	Exhaust	35.5	6.93	400.0	[7,34]
						Coolant	10.6	2.07	85.0	
						A/C	6.0	1.17	130.0	
						Other	8.8	1.72	25.0	
	Ventilation		9	22.0	83.5	Motor	16.5	3.62	20.0	[35]
	Dewatering		2	4.9	83.7	Motor	16.3	0.80	80.0	[36]
	Crushing		1	2.4	39.1	Exhaust	35.5	0.87	400.0	[7,34]
						Coolant	10.6	0.26	85.0	
						A/C	6.0	0.15	130.0	
						Other	8.8	0.21	25.0	
	Material processing	33		80.5						
	Haulage		24	58.6	39.1	Exhaust	35.5	20.79	400.0	[7,34]
						Coolant	10.6	6.21	85.0	
						A/C	6.0	3.51	130.0	
						Other	8.8	5.15	25.0	
	Conveyors		5	12.2	85.0	Motor	15.0	1.83	40.0	[37]
	Hoisting		3	7.3	37.5	Motor	62.5	4.58	40.0	[38]

Rail transport		1	2.4	39.1	Exhaust	35.5	0.87	400.0	[7,34]
					Coolant	10.6	0.26	85.0	
					A/C	6.0	0.15	130.0	
					Other	8.8	0.21	25.0	
Mineral processing	40		97.7						
Crushing		4	9.8	39.1	Exhaust	35.5	3.47	400.0	[7,34]
					Coolant	10.6	1.03	85.0	
					A/C	6.0	0.59	130.0	
					Other	8.8	0.86	25.0	
Grinding		32	78.1	31.0	Motor	69.0	53.89	45.0	[39]
Separation		4	9.8	0.0	Reboiler	100.0	9.76	525.0	[40]

Using the waste heat figures calculated from the surface mining process in Table 11 the overall waste heat generation in the EU was 138.4·10^6 GJ (38.4 TWh) in 2018. Also in this case more than 50% of waste heat identified in the mining industry was of ultralow grade, as depicted in Figure 2.

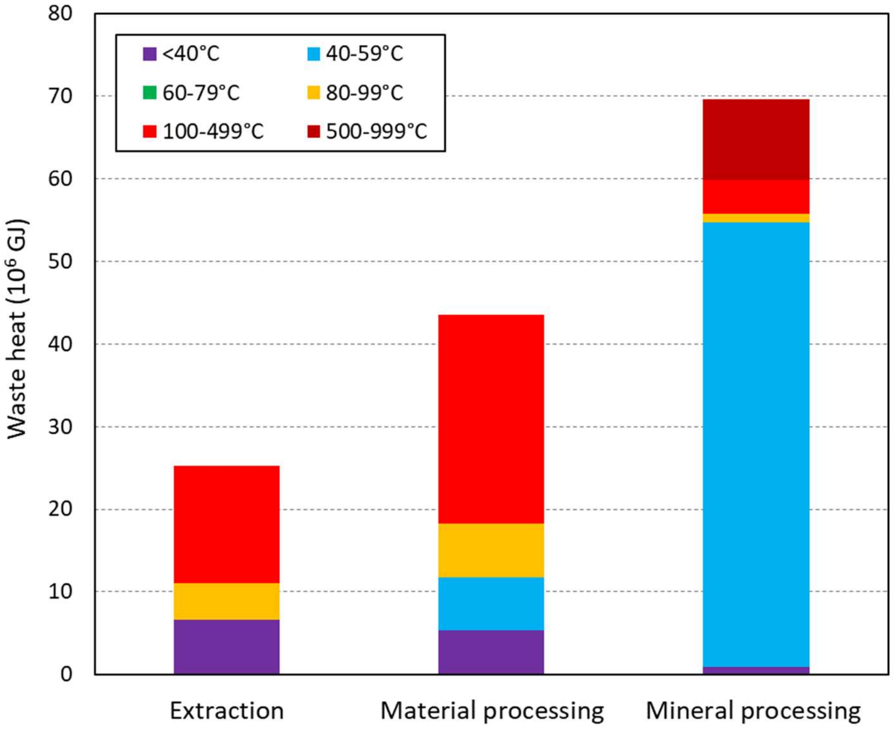

Figure 2: Waste heat generated in the mining industry per mining operation in the EU in 2018

3.5 Waste Heat – Minerals Industry

In the US waste heat study [7] the minerals industry was analysed based on the mineral products consuming most of energy. Those products were cement clinker, glass, lime and ceramics. Within this industry the kilns are by far the major sources of energy consumption, thus they were the focus of the waste heat assessment. In this work the same approach as [7] was followed for the cement clinker, glass and lime in the EU. After sourcing from literature mineral productions in 2018, energy intensities, waste heat fractions and temperatures, energy consumption and waste heat generation were calculated with values summarized in Table 12. Data for the production of lime was from 2016.

Table 12: Energy consumption and waste heat data from cement clinker, glass and lime industry in the EU in 2018

Mineral product	Mineral production (Mt)	Energy intensity (GJ t^{-1})	Energy consumption (10^6 GJ)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
Cement clinker	179.8	3.4	611.3	Kiln	30.0	183.4	1,400.0	[7,41–43]
Glass	36.5	8.0	292.0	Kiln	70.0	204.4	1,400.0	[7,44–46]
Lime	23.9	4.25	101.6	Kiln	39.0	39.6	900.0	[7,47–49]

The ceramic industry has two main sources of thermal energy consumption: the firing process in the kiln and the drying process in the oven. Energy intensities per square metre of ceramic tile produced and waste heat temperatures were taken from a study about the ceramic tile industry [50]. The EU production was obtained from a world report on the production of ceramic tiles updated to the year 2017 [51]. Typical kiln and oven efficiencies, and, thus waste heat fractions, were found in the literature [52]. It was assumed that the ceramic industry could be represented by the production of the ceramic tiles industry. Accordingly, energy consumption and waste heat generation were calculated and reported in Table 13.

Table 13: Energy consumption and waste heat data from ceramic tiles industry in the EU in 2017

Mineral product	Mineral production (10^6 m^2)	Energy intensity (GJ m^{-2})	Energy consumption (10^6 GJ)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
Ceramic tiles	1,362	0.0233	31.7	Kiln	40.0	12.7	950.0	[50–52]
		0.0115	15.7	Oven	40.0	6.3	190.0	

Overall, the waste heat generation in the EU from the minerals industry was $446.4 \cdot 10^6$ GJ (124.0 TWh) in 2018. The waste heat temperatures in the mineral production are very high, with the exception of the ceramic tiles drying oven (190°C). This industrial sector is therefore not of great importance with respect to the analysis of ultralow grade waste heat in the EU.

3.6 Waste Heat – Metals Industry

The European Union plays a significant role in the global metals industry. The EU is one of the largest producers of steel in the world, with a share of 11% of annual global production [53]. While the EU's impact on the non-ferrous industry is smaller, they still contribute significantly to the global production of aluminium, copper, nickel, cobalt and lead [54]. To assess the waste heat generation in the metals industry, ferrous and non-ferrous industries have been analysed separately.

The ferrous metal industry refers to the production of steel, of which many different alloys exist. Most importantly, iron ore is the major metallic component of the steel industry. To determine the waste heat from the ferrous metal industry, the total EU steel production in 2018 was assessed in conjunction with a steel refinery. The World Steel Association was used to obtain the EU's 2018 steel production, which was found to be 168.1 Mt [55]. Publications from the European Commission and the European Steel Association (EUROFER) identified the production split between the two main processes, namely the basic oxygen furnace (BOF) process and the electric arc furnace (EAF) process, as 55% and 45% of the overall EU ferrous capacity, respectively [56,57].

The BOF process is a very common and mature steelmaking process which uses raw materials of coal, limestone and iron ore. Coal is initially coked in a coking oven, thereafter the coke and other raw materials are sintered. Next is a blast furnace, where the sintered product is melted, and impurities are removed. The BOF furnace then converts the molten mixture into a molten steel alloy, which can be cast and then rolled [58].

The EAF process is more recent and has scrap steel as a feed, therefore many of the BOF process stages to refine the raw materials are not required. Scrap metal is fed straightaway to the electric arc furnace and, thereafter is cast and rolled [58]. Energy intensities for the operations involved in BOF and EAF steelmaking processes were sourced from the International Energy Association (IEA) and a study on the energy intensity of steelmaking in the US and China [59,60]. Another study into the waste heat recovery in a steel refinery concluded that 26.1% of the total refinery energy consumption was potentially recoverable via waste heat. It was therefore assumed that, for all process operations, 26.1% of energy consumption had the potential to be recovered [61].

Table 14 reports energy consumption and waste data from the ferrous metals industry in the EU in 2018. References for the waste heat temperatures are provided in the last column of Table 14.

Table 14: Energy consumption and waste heat data from ferrous metals industry in the EU in 2018

Steel process	Process operation	Steel production (Mt)	Energy intensity (GJ t^{-1})	Energy consumption (10^6 GJ)	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat temperature reference
BOF	Coking	92.5	4.2	388.3	26.1	101.3	1,100.0	[59]
	Sintering		1.9	175.7		45.8	350.0	
	Blast furnace		13.7	1,266.6		330.3	1,500.0	
	BOF furnace		0.8	74.0		19.3	1,600.0	
	Casting		1.4	129.4		33.8	700.0	
	Rolling		2.7	249.6		65.1	1,200.0	[62]
EAF	EAF furnace	75.7	6.2	469.0	26.1	122.3	1,600.0	[63]
	Casting		1.4	105.9		27.6	700.0	[59]
	Rolling		2.7	204.3		53.3	1,200.0	[62]

For the analysis of the non-ferrous metals industry, the five most produced non-ferrous metals were considered including copper, aluminium, nickel, cobalt and lead. Table 15 summarizes the non-ferrous metals production in the EU along with the year of estimation and the relevant reference. An overall production of 5.55 Mt was obtained.

Table 15: Non-ferrous metals production in the EU

Non-ferrous metal	Production (Mt)	Year of estimation	Reference
Copper	2.60	2016	[64]
Aluminium	2.10	2018	[65]
Nickel	0.40	2014	[66]
Cobalt	0.01	2016	[67]
Lead	0.44	2016	[68]

It was assumed that the refining of non-ferrous metals included the operations of sintering, blast furnace, induction furnace, casting and rolling. The use of coal is for the refining of iron ore, thus coking was not part of the non-ferrous metal refining. An induction furnace is a relatively modern technology which is being employed to produce non-ferrous metals and reduce energy intensity of production. Energy intensity for an induction furnace was sourced from literature [69]. In addition, it was assumed that the recoverable waste heat potential of 26.1% from the steelmaking refinery can be applicable to the non-ferrous metals industry as well [61]. Waste heat temperatures for the non-ferrous metals industry were based on copper, since its annual production rate is the highest among the non-ferrous metals. Similarly to the ferrous metals, Table 16 reports energy consumption and waste data from the ferrous metals industry in the EU in 2018. References for the waste heat temperatures are provided in the last column of Table 16.

Table 16: Energy consumption and waste heat data from non-ferrous metals industry in the EU in 2018

Process operation	Non-ferrous metal production (Mt)	Energy intensity (GJ t^{-1})	Energy consumption (10^6 GJ)	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat temperature reference
Sintering	5.55	1.9	10.5	26.1	2.8	350.0	[59]
Blast furnace		13.7	76.1		19.8	1,500.0	
Induction furnace		0.36	2.0		0.5	1,100.0	[70]
Casting		1.4	7.8		2.0	700.0	[59]
Rolling		2.7	15.0		3.9	500.0	[71]

From Tables 14 and 16 the waste heat generation in the EU in 2018 was 798.8·10^6 GJ for the ferrous metals industry and 29.0·10^6 GJ for the non-ferrous metals industry, with a total of 827.9·10^6 GJ (230.0 TWh) for the overall metals industry. The waste heat temperatures in the metals production are very high, with 350°C being the lowest temperature in the sintering operation, therefore well above the ultralow grade heat range. A visual summary of the waste heat generated in the overall metals industry per process operation is exhibited in Figure 3.

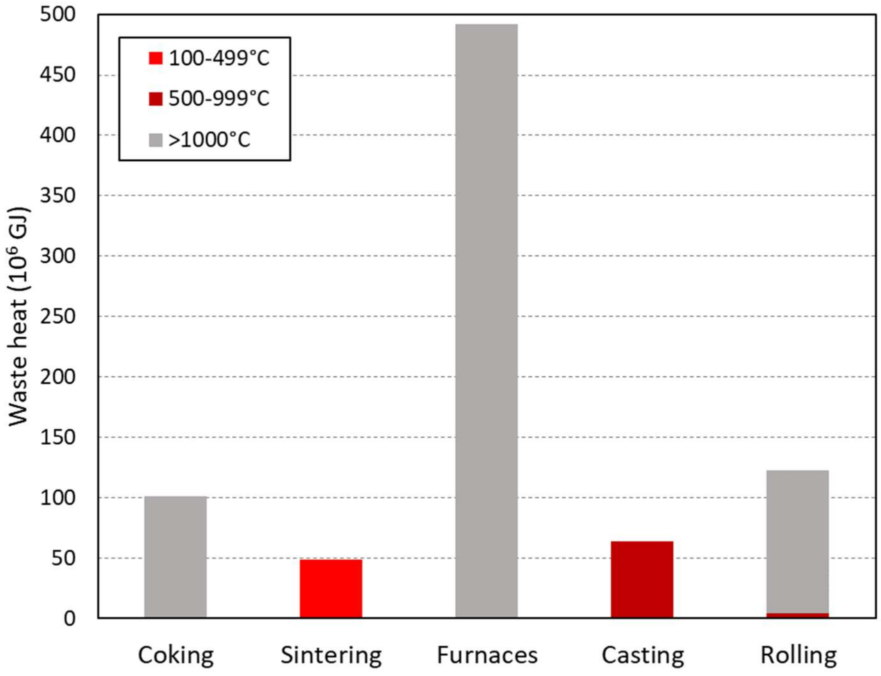

Figure 3: Waste heat generated in the metals industry per process operation in the EU in 2018

3.7 Waste Heat – Chemicals Industry

The chemicals industry in the European Union is another essential sector of the economy. Rattner and Garimella assessed the US waste heat potential from chemicals industry and found that most chemical processes emit high temperature waste heat [7]. In this study it was aimed to focus only on those chemical processes emitting heat at the lowest temperatures. According to [7] these processes are those producing sodium carbonate (soda ash) and latex rubber.

In the EU soda ash production is dominated by the Solvay process, which accounts for approximately 91% of soda ash production [72]. Therefore, it was assumed that only the Solvay process is used for the production of soda ash and this applies across the EU. The Solvay process consumes energy at an average rate of up to 11.1 GJ t^{-1} of soda ash produced [73,74]. The total soda ash production in the EU was sourced from the chemicals companies Solvay (FR), Sequens (FR), Ciech (PL), Tata Chemicals (UK), Sisecam (TR) and Eti Soda (TR). In 2018, the total installed plant capacity in the EU was 10.7 Mt [72] with a utilization rate of 86% [75]. Therefore, 9.2 Mt of soda ash were produced that corresponds to the 16% of the global production of 57 Mt in 2018 [76].

Because the Solvay soda ash method is not an electricity-intensive process, the consumption of energy is mainly for the production of steam. Some processes are now using combined cycles power plants (Brayton cycle plus Hirn cycle) to deliver the heat and power needed to the process [76]. The major waste heat source is therefore the low grade heat from the combined cycle with an upper efficiency assumed at 65% [77]. This is a conservative value of efficiency which leaves only 35% of the primary energy as waste heat at a temperature of 40°C [78]. Energy consumption and waste data from the soda ash industry in the EU in 2018 are reported in Table 17.

Table 17: Energy consumption and waste heat data from soda ash industry in the EU in 2018

Soda ash production (Mt)	Energy intensity (GJ t^{-1})	Energy consumption (10^6 GJ)	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)
9.2	11.1	102.1	35.0	35.7	40.0

The latex rubber industry is the second sector of the chemicals industry emitting ultralow temperature waste heat. Latex refers to two products: the natural rubber obtained from trees and a type of synthetic rubber polymer. This study assumed that latex refers to the synthetic rubber industry only. In 2018, 16% [79] of the global synthetic rubber production equal to 15.3 Mt [80] was produced in the EU, totalling 2.45 Mt. The energy intensity of this industry can vary significantly depending on the final product. This analysis took the average value of 5.5 GJ t^{-1} from raw products such as rubber sheets, bar and concentrated latex for which the energy intensity varies from a minimum of 0.6 GJ t^{-1} to a maximum of 10.4 GJ t^{-1} [81]. Electrical energy shares an average of 54% the total, while heat accounts for an average of 44% across the three products [81]. The analysis assumed that electricity is used in the electrical components of the process at 45% efficiency [82] and heat is totally consumed in the process without any waste. Waste heat temperature of the latex rubber industry was taken as 40°C from [7]. Table 18 details the energy consumption and waste data from the latex rubber industry in the EU in 2018.

Table 18: Energy consumption and waste heat data from rubber latex industry in the EU in 2018

Latex rubber production (Mt)	Energy intensity (GJ t^{-1})	Total energy consumption (10^6 GJ)	Electrical energy consumption (10^6 GJ)	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)
2.45	5.5	13.5	7.3	0.55	4.0	40.0

In 2018 the EU generated an overall waste heat of $39.7 \cdot 10^6$ GJ (11.0 TWh) from the ultralow grade heat chemicals industry at 40°C.

3.8 Waste Heat – Pulp and Paper Industry

With a production of 38.3 Mt in 2018 [83], the pulp and paper industry is a large industrial sector in the EU, contributing every year approximately 180 billion euros to the economy [84]. To produce paper products, wood chips first have to be processed into a pulp, which is thereafter turned into paper. There are various pulp making processes but the most used are the Kraft bleached, Kraft unbleached and thermomechanical process (TMP). TMP is a mechanical pulping process while the Kraft processes are both chemical [85]. Of the total 38.3 Mt, 27% (10.3 Mt) was assumed to follow the TMP and 73% (28.0 Mt) the chemical processes, according to the data reported in [86].

Process operations and energy intensities were taken from [7]. The Kraft unbleached process was assumed as representative of both chemical processes. This is a conservative assumption since its energy intensity is lower than the Kraft bleached process. Energy consumptions from the pulping processes in the EU in 2018 are reported in Table 19. The overall figure resulted in $280.6 \cdot 10^6$ GJ of energy consumed.

Table 19: Energy consumption per process operation from pulp industry in the EU in 2018

Pulp process	Process operation	Pulp production (Mt)	Energy intensity (GJ t^{-1})	Energy consumption (10^6 GJ)
Kraft unbleached	Washing & preheating	28.0	0.26	7.3
	Chemical production		0.6 2.0	16.8 56.0
	Chemical pulping		2.6	72.8
	Evaporators		3.7	103.6
Thermo mechanical	Washing & preheating	10.3	0.24	2.5
	O_2 delignification & bleaching		2.1	21.6

Once pulp is produced, it is then fed to the paper making process, where a variety of grades and types of paper can be manufactured. Pulp and paper making processes are often co-located [86]. According to [7] there are two main paper making processes: the Kraft paper process for freesheet, packing paper, bristol, industrial papers, corrugating medium, liner and other boards; and newsprint paper process for newsprint and groundwood. In 2018, 92.2 Mt of diverse paper types were manufactured in EU [86]. Of this amount, only 5.5% corresponding to 5.1 Mt was from newsprint paper process, with the remaining 87.1 Mt from the Kraft paper process [86]. Also in this case the US waste heat study [7] was used to obtain process operations and energy intensities. Table 20 details the energy consumption from the paper industry in the EU in 2018. In that year the EU consumed $631.2 \cdot 10^6$ GJ of energy for the paper industry.

Table 20: Energy consumption per process operation from paper industry in the EU in 2018

Paper process	Process operation	Pulp production (Mt)	Energy intensity (GJ t^{-1})	Energy consumption (10^6 GJ)
Kraft	Stock preparation	87.1	1.3	113.2
	Paper rolling & drying		3.0	261.3
			0.7	61.0
			1.0	87.1
	Wastewater processing		0.9	78.4
Newsprint	Stock preparation	5.1	0.9	4.6
	Paper rolling & drying		2.6	13.3
			0.6	3.1
			0.9	4.6
	Wastewater processing		0.9	4.6

The total energy consumption for both pulp and paper industry in the EU in 2018 was $280.6 \cdot 10^6 + 631.2 \cdot 10^6 = 911.8 \cdot 10^6$ GJ. Similarly to the chemicals industry, this heat is usually produced in CHP plants at a combined electricity and heat efficiency of maximum 92% with an electricity to heat ratio ranging from 0.4 to 1.1 [87]. This leaves 8% as waste heat fraction at ultralow temperature of approximately 40°C that corresponds to $72.9 \cdot 10^6$ GJ of energy. However, an additional amount of ultralow temperature waste heat is present throughout the pulp and paper production process. This fraction is difficult to intercept since it is dispersed heat from various process equipment. Nevertheless, there are a few steps in the pulp and paper production processes where some fractions of waste heat can be recovered. TMP is the least energy intensive pulping method and has been used to represent the entire EU pulp and paper industry in order to obtain a conservative value of additional ultralow waste heat recoverable. In the representative TMP plant investigated by Brown et al. [88] 5% the supplied heat is released at 51°C in the white water tank. Assuming a conservative electricity to heat ratio of 1.1 (48% of heat, 52% of electricity), this adds $21.9 \cdot 10^6$ GJ of ultralow waste heat at 51°C. Waste heat data from the pulp and paper industry in the EU in 2018 are summarized in Table 21, showing an overall ultralow grade waste heat generation of $94.8 \cdot 10^6$ GJ (26.3 TWh).

Table 21: Waste heat data from pulp and paper industry in the EU in 2018

Total energy consumption (10^6 GJ)	Waste heat source	Waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)
911.8	CHP plant	8.0	72.9	40.0
	TMO white water tank	2.4	21.9	51.0

3.9 Waste Heat – Food Industry

The analysis of ultralow waste heat in the food industry is split into the major food production categories: cereals, fruit and vegetables, dairy, meat and sugar. The vast array of food products available across the EU inevitably means that many manufacturing processes have not been considered. Information on the production rates of the food categories are from Eurostat, the official statistical office of the European Union. All production data from 2019 are reported in Table 22 along with their relevant references.

Table 22: Food production in the EU in 2019

Food Product	Production (Mt)	Reference
Cereals	274.0	[89]
Fruit & vegetables	120.6	
Dairy	211.2	[90]
Meat	43.7	[91]
Sugar	17.6	[92]

The energy intensities for the major food processing operations were sourced from [93] and were associated to the waste heat temperatures disclosed in [7]. In the food industry, electricity is sourced from the grid, therefore, only the heat fraction was taken into account. The heat input is used in the diverse processes mostly in phase-change operations [93]. Each specific manufacturing process uses its own specific higher grade heat and releases lower grade heat that is a fraction of the input heat. As these data are rarely available, the current analysis neglected the heat released from the stack of industrial boilers and focussed only on the heat that can be recovered from the process. Table 23 details the average energy intensities, energy consumption and waste heat data from the food industry in the EU in 2018. References on the waste heat fractions from the heat inputs are reported in the last column of Table 23. The total waste heat generation from the food industry was $260.8 \cdot 10^6$ GJ (72.4 TWh), out of which $232.9 \cdot 10^6$ GJ of ultralow grade.

Table 23: Energy consumption and waste heat data from food industry in the EU in 2019

Process operation	Average energy intensity (GJ t^{-1})	Energy consumption (10^6 GJ)	Heat waste heat fraction (%)	Waste heat generation (10^6 GJ)	Waste heat temperature (°C)	Waste heat data reference
Grain milling	33.2	9,096.8	1.4	127.4	50.0	[7,93,94]
Canning of fruit/veg	5.4	651.2	1.6	10.4	120.0	[7,93,95]
Dairy pasteurization	5.6	1,182.7	3.5	41.4	72.0	[7,93,96]
Canning of meat	25.0	1,092.5	1.6	17.5	140.0	[7,93,95]
Sugar refining	13.8	242.9	27.8	64.1	95.0	[7,93,97]

3.10 Total Waste Heat in the EU

The key figures of waste heat generated and temperature levels from the power generation and major industrial sectors in the EU are summarized in Table 24. The power generation sector showed a much higher waste heat potential of $8{,}551.8 \cdot 10^6$ GJ in 2018 compared to the sum of industrial sectors ($1{,}808.0 \cdot 10^6$ GJ). Out of the total waste heat, the ultralow grade fraction (<80°C) was much higher for the power sector accounting for 93.9% compared to the industrial sectors where it accounted for only 20.8%. However, it should be noted that the two largest industrial contributors, namely minerals and metals industries, generated waste heat at a temperature level well above 100°C, as depicted in Figure 4. Overall, in 2018 the EU generated a total waste heat amount of approximately $10{,}360 \cdot 10^6$ GJ corresponding to 2,878 TWh. It should be remembered that additional $538.0 \cdot 10^6$ GJ of waste heat would also be available from industrial on-site power generation.

Table 24: Waste heat potential per temperature level from power generation and industrial sectors in the EU in 2018

Temperature range (°C)	Waste heat (10^6 GJ)						
	Power generation	Industrial sectors					
		Mining	Minerals	Metals	Chemicals	Pulp & Paper	Food
<40	548.3	12.9	0.0	0.0	0.0	0.0	0.0
40-59	6441.4	60.3	0.0	0.0	39.7	94.8	127.4
60-79	1,042.2	0.0	0.0	0.0	0.0	0.0	41.4
80-99	290.0	11.9	0.0	0.0	0.0	0.0	64.1
100-499	132.2	43.6	6.3	48.6	0.0	0.0	27.9
500-999	97.8	9.8	52.3	67.3	0.0	0.0	0.0
>1000	0.0	0.0	387.8	712.0	0.0	0.0	0.0
Subtotals	8,551.8	138.4	446.4	827.9	39.7	94.8	260.8
		1,808.0					
Grand total	10,359.9						

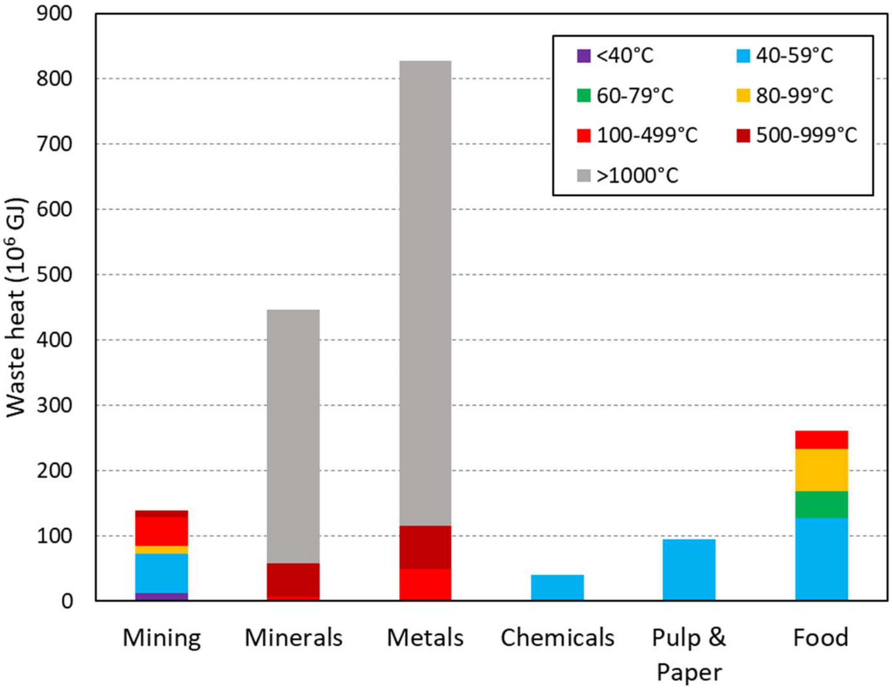

Figure 4: Waste heat generated in the major industrial sectors in the EU in 2018

4. Discussion

The analysis of EU power generation and industrial sectors found that in 2018, 8551.8·10^6 GJ (2,375.5 TWh) of waste heat was available from power generation and 1808.0·10^6 GJ (502.2 TWh) from various industrial sectors as well as 538.0·10^6 GJ (149.4 TWh) from industrial on-site power generation. By analysing the total waste heat (Table 24), 25.0% of waste heat emissions from industry were below 100°C. This is comparable with other studies in the literature such as the waste heat study by Papapetrou et al., who found that one third of industrial waste heat was below 200°C [10]. However, the same study reported a total industrial waste heat of 300 TWh y^{-1}, which is smaller than the value of 502.2 TWh y^{-1} obtained in this work. Although all results varied slightly, the major differences between this work and the analysis by Papapetrou et al. [10] were in the food, minerals and the mining industries.

For the power generation sector, around 97% of waste heat identified was found to be below 100°C, and around 94% of waste heat was classified below 80°C. In comparison to other studies in the literature, the worldwide waste heat study by Forman et al. found that 88% of waste heat from the power generation sector was below 100°C [1]. While both results concluded that the majority of power generation waste heat originates at low temperatures, the percentage obtained in this work was higher. This may be explained by considering the contribution of nuclear power to the waste heat estimation. All waste heat from the nuclear sector was at 40°C and in total it contributed to approximately 50% of the entire power sector waste heat. According to the Nuclear Energy Institute, NEI, seven of the top 15 nuclear power producing countries are in the EU, with France being the second largest producer in the world [98]. It is, therefore, likely that the percentage of waste heat below 100°C was higher due to the strong influence of nuclear power.

Of the total waste heat estimation in this study, $8{,}408.4 \cdot 10^6$ GJ (2,335.6 TWh) of waste heat below 80°C was identified, which corresponds to 81.1% of the total waste heat. However, care should be taken as this percentage is not representative of the entire industry waste heat. This is because the waste heat analysis in this study was specifically focused on ultralow grade waste heat, thus the results are far more representative of it in comparison to higher waste heat grades. For example, the chemicals industry, as shown by Rattner and Garimella, is a significant contributor to higher waste heat grades, specifically in the production of plastics and petrochemicals [7]. However, only chemical processes producing ultralow grade waste heat were considered in this study, thus a large proportion of the chemicals industry was not considered in the waste heat estimation. It is therefore likely that the percentage of total waste heat categorised as ultralow grade would be lower if a study including all higher waste heat grades was carried out. The worldwide waste heat analysis by Forman et al. found that 63% of all waste heat produced was below 100°C, which is still a large proportion of the waste heat spectrum [1].

To estimate the ultralow grade waste heat potential, assumptions had to be made, specifically that the waste heat from each sector could be modelled from a single process commonly employed in that industry. This methodology is acceptable considering the final waste heat value is an estimate, however, the waste heat values were very dependent on the thermodynamic analysis of the processes used to represent industrial sectors. For example, pulp and paper production can be carried out using a variety of different process configurations, but a combined heat and power TMP process was used to estimate waste heat for this industry. It was chosen due to its highly efficient operation, allowing a conservatively low estimation to be made. However, since it is likely not the most abundant pulp and paper production method in the EU, it may not have been fully representative of the industry. Additionally, across the nuclear power sector, various reactor types are in operation in the European Union, but an efficient AGR was used to achieve a conservative waste heat estimation.

The results in Table 24 highlight that the largest fraction of waste heat in EU is in the range of temperatures between 40°C and 80°C from the power generation sector. This waste heat of ultralow grade amounts to $7{,}483.6 \cdot 10^6$ GJ (2,078.8 TWh), 72.2% of the total waste heat surveyed in this study and 89.0% of the waste heat fraction at temperatures below 80°C released by the combined industrial and power generation sectors. The results in Table 24 can also be analysed in terms of exergy by taking into account an average Carnot efficiency in the temperature range and 298.15 K as the reference temperature (cold temperature). Table 25 shows the distribution of the exergy across the temperatures from power generation and industrial sectors in the EU in 2018. Focussing on the power generation sector, the largest fraction is available in the temperature range between 40°C and 59°C (70.9%), with an additional 19.6% located between 60°C and 79°C. These results clearly show an opportunity for the power generation sector to adopt sustainable technologies that can recover these fractions of waste heat. The values in Table 24 refer to the recovery of waste heat with cyclic processes. The recovery with non-cyclic technologies, i.e. waste heat recovery in separation processes, can in principle make available even larger fractions of the total waste heat reported in Table 24.

Table 25: Exergy from waste heat per temperature level from power generation and industrial sectors in the EU in 2018

Temperature range (°C)	Average Carnot efficiency	Exergy (10^6 GJ$_{ex}$)						
		Power generation	Industrial sectors					
			Mining	Minerals	Metals	Chemicals	Pulp & Paper	Food
<40	0.025	13.5	0.3	0.0	0.0	0.0	0.0	0.0
40-59	0.076	489.3	4.6	0.0	0.0	3.0	7.2	9.7
60-79	0.130	135.4	0.0	0.0	0.0	0.0	0.0	5.4
80-99	0.178	51.6	2.1	0.0	0.0	0.0	0.0	11.4
Subtotals		689.8	7.0	0.0	0.0	3.0	7.2	26.5
			43.7					
Grand total		733.5						

4.1 Ultralow temperature waste heat utilisation

In the introduction, the following two requirements were identified for devices powered by ultralow temperature waste heat: *(i)* cyclic and non-cyclic processes must operate at an efficiency close to their thermodynamic limit to exploit the waste heat exergy content almost in full; *(ii)* the approach temperatures in each heat exchanger must be maintained minimal implying large heat transfer surface areas. While a wise design can address properly the second requirement, the first requirement is intrinsic of the process thermodynamics and favour some processes over others.

The attempt of this section is to highlight some promising processes that have demonstrated the achievement of the efficiency required. The maturity of these processes is diverse as they are in many cases emerging processes currently at development stage that might or not become part of the portfolio of technologies in the future society. Although rich, this overview is not exhaustive since it aims at showcasing some of the emerging opportunities to exploit ultralow grade waste heat:

- *Processes for heat transformation:* Heat transformation devices move heat across the temperature scales and include heat pumps and chillers. Recent activities encompass 4th generation ultralow temperature district heating networks [99] to supply electrical heat pumps that upgrade heat at any higher temperature. Thermodynamic assessments have shown that such arrangements can achieve high second law theoretical efficiency ranging up to 60% [100] and possibly higher if the temperature is controlled within few tens of degrees [101]. Actual demonstrations are limited to a few documented cases [102] that, however, highlight the advantage of coupling ultralow temperature heat with heat pumps to use surplus of electrical energy. Ultralow temperature heat-powered adsorption heat transformation is a technological option [103] that meets the cooling demand. The technology can exploit heat at temperatures <80°C for the production of cold in diverse temperature ranges from -18°C to 15°C depending on the working pair adsorption material/adsorbed fluid in use [104]. The second law performance is primarily related to the thermodynamic and kinetic properties of the working pair. Figure 5 reports the second law efficiency, expressed as ratio between the Coefficient of Performance (COP) of the adsorption material and the COP of the corresponding three temperatures Carnot Refrigeration Cycle ($COP_{Carnot\ 3T}$) [105], that have shown in some conditions performances close to the thermodynamic limit (ratio approaching unity).

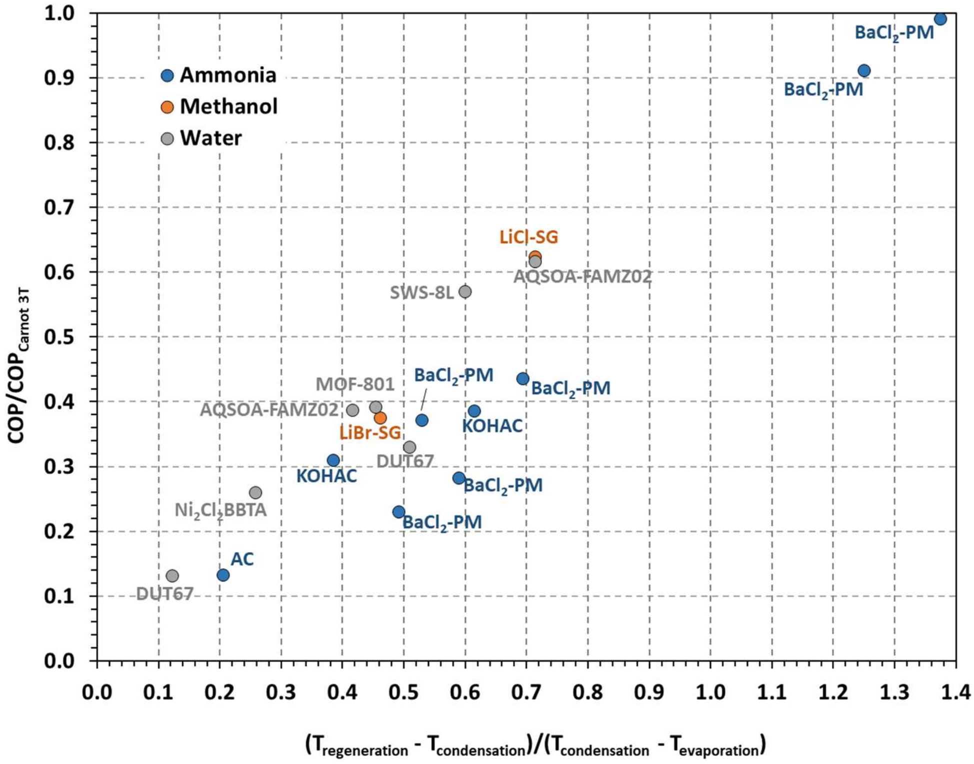

Figure 5: Second law efficiency of adsorption refrigeration materials expressed as ratio between the COP calculated from equilibrium data and the COP of a three temperatures Carnot Refrigeration Cycle. Data for DTU67 in [106]; AC in [107]; Ni_2Cl_2BBTA in [108]; KOHAC in [109]; AQSOA-FAM02 and LiBr-SG in [110]; MOF-801 in [111]; $BaCl_2$-PM in [112]; SWS-8L in [113]; LiCl-SG in [114].

- *Processes for separation and purification:* The operation of practical membrane distillation and adsorption desalination devices has been demonstrated with heat from 70°C down to only few degrees above the ambient temperature [115]. Direct contact membrane distillation could operate at 30°C [116] and adsorption desalination with heat at only 5°C above the ambient temperature [117].
- *Processes for electricity generation:* Heat at temperatures below 80°C can be turned into electricity by looping one salinity gradient electricity generating process (e.g. reverse electrodialysis, pressure retarded osmosis, capacitive mixing) with one low-grade-heat-driven purification process (e.g. multi-effect distillation, adsorption desalination, membrane distillation) [118]. Each of the combinations returned different theoretical second law efficiencies under diverse configurations, making their comparison difficult on an even basis.

An efficiency of 16.5% was achieved in a demonstrative reverse electrodialysis-multi-effect distillation installation [119]. Calculations have shown that the reverse electrodialysis-multi-effect distillation can reach a maximum efficiency of 24% [120]. When multi-effect distillation is replaced by adsorption desalination, the second law efficiency can increase up to 44.6% [121]. Although the values are low, the large improvement in efficiency obtained by replacing the regeneration techniques shows that there is hope for heat to power concepts working at higher efficiency.

5. Conclusions and Future Outlook

Recovery and utilization of ultralow grade heat faces significant challenges that prevent its deployment. One of the major challenges is the identification and quantitation of ultralow grade heat availability. The amount of energy available is rarely monitored, its generation is often de-centralised and requires devices, including heat storage, which in the best case scenario exist only at low technology readiness level. This work addressed this challenge by surveying waste heat with a special focus on ultralow grade heat (<80°C). The analysis focused on the year 2018 and identified the largest fraction of waste heat in EU at temperatures between 40°C and 60°C from the power generation sector. This waste heat at ultralow grade amounts to $6{,}441.4 \cdot 10^6$ GJ (1,789.3 TWh) and corresponds to 75% of the total waste heat from the power generation sector and 73% of the waste heat fraction at temperatures below 100°C released by the combined industrial and power generation sectors. In addition, this is also the largest exergy fraction, amounting to 71% of the total exergy wasted in the power generation sector.

The total waste heat surveyed by this study is equivalent to a maximum loss of exergy of $733.5 \cdot 10^6$ GJ_{ex} (203.7 TWh_{ex}) that could be theoretically recovered with technologies operating at efficiencies close to the theoretical maximum. However, the recovery of waste heat with non-cyclic technologies, i.e. waste heat recovery in separation processes, can in principle make available even larger fractions of the total waste heat emitted. The results reaffirm that the recovery of ultralow grade waste heat is a viable and advisable option for point-source waste heat emitters such as power stations or when an infrastructure such as low grade heat network is available. The analysis presented here applied a conservative approach. Therefore it provides a lower end to the amount of ultralow grade waste heat actually present in the EU. It must also be noted that although the major industrial sectors were analysed in this study, some large sectors with potentially high waste heat emissions were not considered. These include transportation, construction and residential sectors [7]. By analysing these EU waste heat sectors in future works, a higher waste heat potential could be produced.

In the close future the waste heat availability will be strongly influenced by the EU political decisions in the energy sector, particularly in the upcoming electricity supply. As the “Clean Energy for All Europeans” package set a renewable energy target of 32% of gross final consumption by 2030, it is expected that the share of renewables in electricity will exceed 50% [122]. Furthermore, according to the World Energy Outlook [123], wind power is set to become the European Union’s leading source of electricity around 2025, overtaking gas and nuclear and poising for rapid growth with country-level targets targeting at least a tripling of installed capacity by 2030. Thirteen member states have also plans to phase out all coal-fired power plants while Germany, Belgium and Spain have announced in 2019 they intend to phase out their nuclear power plants [123]. At the same time it is likely that combined cycle power plants will increase their electrical efficiency, up to 65%, through engineering improvements in gas and steam turbines [124]. Nevertheless, the higher renewable energy share will need storage, including heat storage (power-to-heat) [125], fostering the spread of 4th generation low temperature district heating [126]. As a result, in the next two decades the availability of low grade heat in the EU is likely to stand, despite the changes in the energy systems.

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