A Bottom-Up Approach for Determining the European Heat Pump Potential

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Abstract
Waste heat from industrial processes is an undervalued resource, that if exploited, could result in large energy savings. Typically, the waste heat produced by processes is at too low a temperature level to be reused and is therefore discarded to the ambient. Industrial heat pumps are a rapidly developing technology that are able to upgrade the temperature of waste heat to be reused in the process, leading to a direct reduction of final energy use.

This study utilizes a newly developed bottom-up approach to determine the European industrial heat pump potential. Through application of knowledge on a multitude of energy intensive industrial processes, individual heat signatures containing information on heat quantities and temperature levels are assigned to various products. Production statistics, primarily sourced from the EUROSTAT Prodcom database are combined with the individual heat signatures to determine the European industrial heat pump potential.

This paper outlines the derived methodology as well as preliminary results on both process heat and waste heat quantities. From these, the potential for application of heat pumps to several industrial processes has been determined. The methodology is applied to a number of processes in the chemical, paper and pulp and food and beverage industries which combined, cover a large share of the European industrial heating demand.

Keywords: Waste Heat, Industrial Heat Pump, Heat Signature, Prodcom, EUROSTAT

1 Introduction
Increasing atmospheric CO_2 emissions, primarily driven by reliance on fossil fuels for energy consumption, are leading to adverse environmental effects such as global warming. There is a growing need to reduce greenhouse gas emissions and the associated negative environmental effects through a combined approach of reducing final energy consumption and a move to more sustainable energy sources such as solar and wind power. In 2014, energy use in industry was responsible for 11.5 EJ or 25.9% of the final energy consumption (FEC) of EU28 countries [1]. An overview of the industrial energy use by sector and country is seen in Figure 1 and Figure 2. Strong industrial sectors in Germany, France, Italy and the UK ensure these countries use large amounts of energy for various processes. The industrial energy usage is dominated by processes in the iron and steel (19% FEC) and chemical (19% FEC) industries, with the food and beverage (12% FEC), paper and pulp (10% FEC) as well as the non-metallic materials (12% FEC) also making up significant shares of the final energy consumption mix. The large proportion of final energy consumption attributed to industrial processes means that achieving energy efficiency and transitioning to more sustainable energy sources in industry are a requirement in order to achieve a low carbon economy for the future.

Within European industrial processes, demand for thermal energy (heating and cooling) accounted for 73 percent of final consumption in 2012 [2]. Indeed, heat is the primary driver for many industrial processes. Typically, after heat is used for driving processes, it is discarded to ambient as it is at too low a temperature to be reused. The potential of this waste heat that is a by-product of industrial processes is considered to be a relatively untapped energy source [3]. If the waste heat from the processing industry is recovered and re-used utilizing currently available or emerging technologies to produce heat, cold or electricity, the end result would be large savings in final energy consumption for the sector.

Technologies that are able to utilize the widely abundant waste heat from industrial processes are well described in the literature. Huang [4] distinguishes between indirect and direct technologies depending on the treatment of the waste heat source. Indirect recovery options are used to transfer the waste heat to other energy forms such as mechanical or electrical power (power cycle or heat engine technology), whilst direct utilization technologies recover energy to be reused within the process (heat exchange or heat pump). Further classification can be made to differentiate between active and passive technologies [5]. Active technologies are those where heat is converted to a higher temperature or another form of energy, whereas passive technologies are those whereby heat is utilised directly [5]. In most cases, industrial processes are designed to take into account passive reuse of waste heat in the process through elaborate heat exchange networks. There are limits to the amount of passive heat exchange in industrial processes as this can only be applied to recover heat if it is to be utilised at a lower temperature than the waste heat source. In order to fully exploit the potential for waste heat recovery in industry, integration of active technologies is essential.

Of the active technologies available, industrial heat pumps are a rapidly developing technology able to upgrade the temperature of a waste heat stream to be reused in the process with an input of electrical energy. Depending on the temperature difference between the waste heat and process heat streams, the electrical energy input is typically a factor of between 2 and 5 lower than the process heat output. Therefore, waste heat can be reused at higher temperatures than achievable with passive heat exchange whilst still resulting in reduction in final energy consumption of industrial processes. Increases in technology development from manufacturers, suppliers and research facilities, as well as falling capital costs of heat pumps and lower electricity prices for large industrial end users are growing drivers for the implementation of heat pumps for industrial waste heat use, providing heat at temperatures as high as 150°C. The focus of this study is therefore directed towards heat pump technologies and their applications for energy saving and market potential in industry.

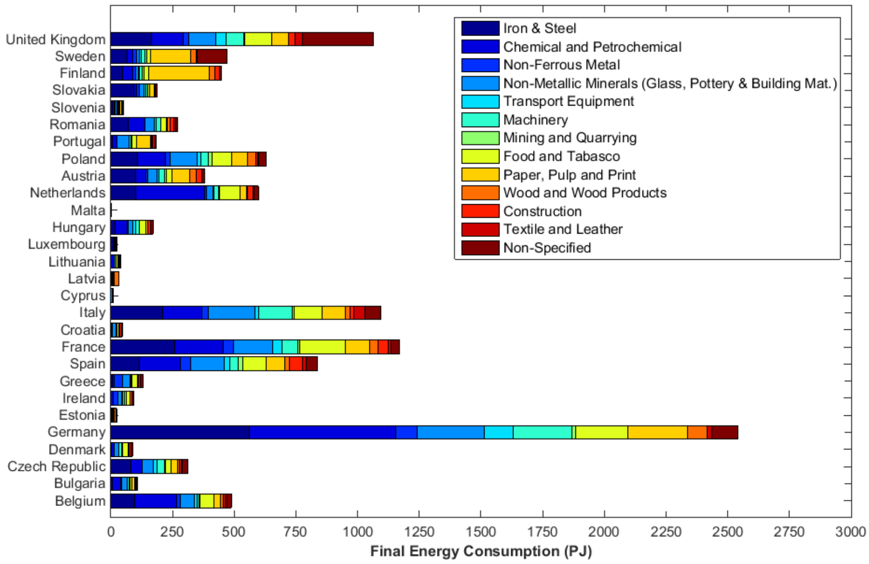

Figure 1: Final Industrial Energy Consumption for EU 28 Countries with individual sectors stacked [1]

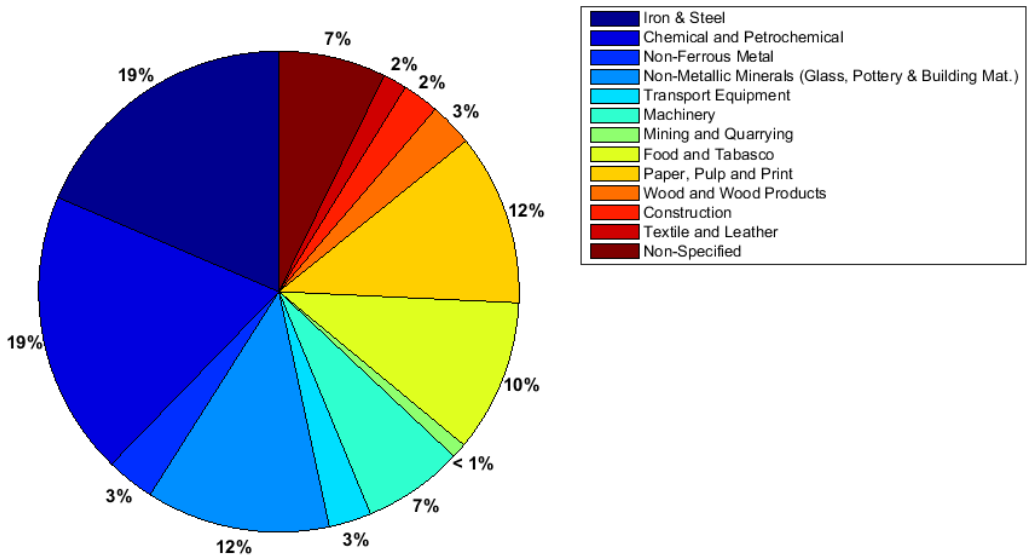

Figure 2: Share of Industrial Final Energy Consumption per Industrial Sector in EU28 Countries[1]

In order to determine the potential of heat pumps applied to industry, information is needed as to the characteristics (temperature, amount, media contained) of the process heat required as well as the waste heat supply in a multitude of industrial processes. Various methods have been described in the literature for collecting information including surveys, estimations, or utilising company mandatory reporting [6]. Further to this, a number of approaches have been described in the literature which can broadly be defined as either bottom-up or top-down [6]. For the given problem definition, it was decided the best approach for determining waste and process heat temperatures and quantities would be a novel bottom-up one utilising unique heat stream data from a multitude of industrial processes. In this way, not only can the total heat pump potential of EU28 countries be calculated, but also processes can be identified which are interesting for heat pump applications.

Combining the results of waste heat and process heat temperatures and quantities generated from the bottom-up approach with heat pump theory, leads to an estimation of the potential of the technology for a number of industrial processes. The unique methodology utilised to generate information related to process and waste heat temperatures and quantities is described in detail in the section which follows. Following this, an outlook of the characteristics of process and waste heat use in the paper and pulp, chemical and food and beverage industries is given for EU28 countries. The study is concluded through presentation of two case studies whereby the energy saving potential of heat pump technology is determined for the production of packaging paper as well for a distillation column in the production of styrene.

2 Methodology

On the basis of the problem definition and the information available to the authors, the European Product, Process and Energy (PPE) Database was initiated. For the database, a bottom-up approach was logical based on the problem definition and the knowledge of a multitude of processes available. Whilst this bottom-up process is laborious in nature, the resulting waste heat and process heat information obtained and collated are likely to be more representative of the European and regional scenarios than top-down, or other bottom-up approaches. The data structure of the database is seen in Figure 3 which follows.

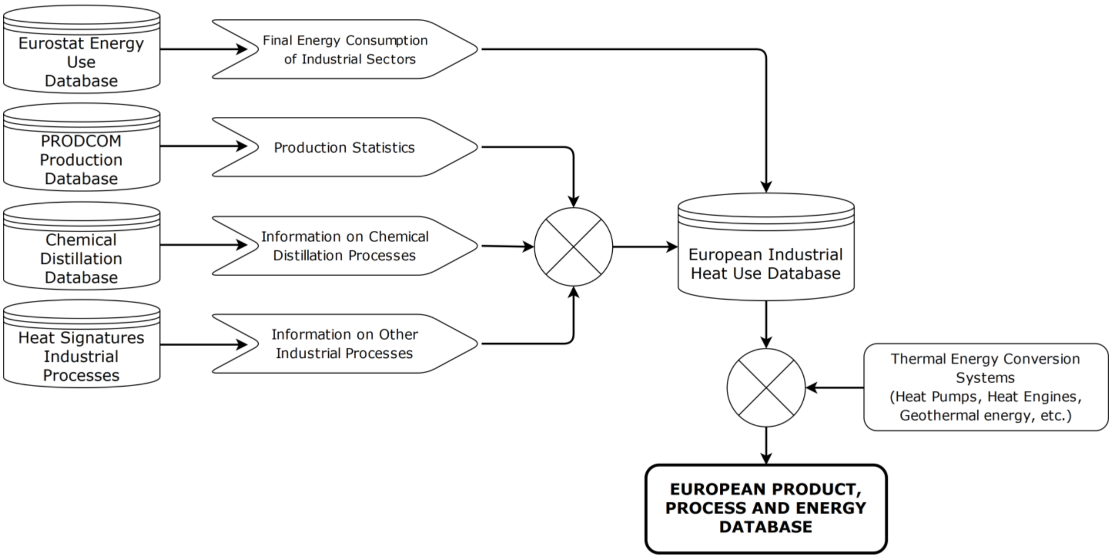

Figure 3: The Construction of the European Product, Process and Energy Database

The European PPE Database takes data from four primary sources of information as seen in the left side of Figure 3, which are then combined to give an overview of the industrial heating sector. To determine the energy saving potential of heat pump technologies, information relating to the waste heat and process heat streams of various industrial processes are needed. More specifically, the amount of waste heat produced as well as the process heat required at each temperature level is necessary. The distribution of the energy used over the different temperature levels is achieved by using so-called heat signatures, one signature describing the amount of waste heat as a function of temperature and a second signature describing the heat demand as a function of temperature. The waste and process heat quantities are derived relative to amounts of product produced with information sourced from data taken from industrial production facilities. Production statistics, sourced from the EUROSTAT Prodcom database [7] are used to determine produced quantities of products manufactured by processes contained within the heat signatures. These production statistics are then coupled with the individual heat signatures to give the total heat quantities at their respective temperature levels for all processes and sectors within EU28 countries. One limitation of this bottom-up methodology is it is assumed the heat signatures constructed are indicative of a number of process plants. Temperature levels and specific heat quantities may vary between plants and as such lead to discrepancies when extrapolating based on production quantities. However, in the context of determining the EU28 industrial heat pump potential, it is unfeasible to construct a heat signature of every process plant. The EUROSTAT Energy use database [1], which contains information on energy use for 13 industrial sectors in all EU28 countries is used to verify the results and determine the market energy coverage of the heat signatures for each sector. Following this, the energy saving and market potential of heat pumps can be determined once integrated into the processes defined by the database.

2.1 Construction of a Heat Signature

Construction of so-called waste and process heat signatures forms the basis of the European PPE Database. Waste heat streams were considered to be any form of heat (sensible/latent) in the process which are not directly used to drive the process and are therefore discarded to ambient. Similarly, process heat is considered to be any form of heat input (sensible/latent) to a given process utility and required for operation of the process. In both cases, heat can be contained in multiple media, which may include water, air or flue gases. Temperature of the utility is taken in the process, rather than that of an intermediate stream. The physical potential of these heat streams are recorded by noting the temperature of the heat and the quantity per produced product quantity (GJ/t). Some authors correctly indicate that technical and economic potential of heat should be considered [6], and as such the media in which heat is contained is specified. This allows heat stream sources which may be technically difficult or expensive to recover to be identified. In general, optimised processes containing many indirect heat recovery options (heat exchangers) to reduce the specific energy consumption of the process are preferred over non-optimised ones. This internal heat exchange within processes was not included in the construction of the heat signatures. The result of this is that rather than characterise the entire process, the generated heat signatures are residual in nature and are therefore more suitable for assessing the potential of active devices such as heat pumps.

The process heat and waste heat streams are considered separately when creating the individual signatures. The method for creating a heat signature of an arbitrary process is diagrammatically shown in Figure 4 and described in detail. A piecewise increasing function is created for each stream to be included in the database which is represented by a temperature range as a function of the change in enthalpy. The change in enthalpy of each successive stream is summated rather than have overlapping domains. After all streams have been identified, the resultant is a number of individual piecewise increasing functions over a given domain equivalent to the change in enthalpy of all streams in the process (left side, Figure 4). These individual piecewise functions are collated to become a single increasing function over the given domain (right side, Figure 4).

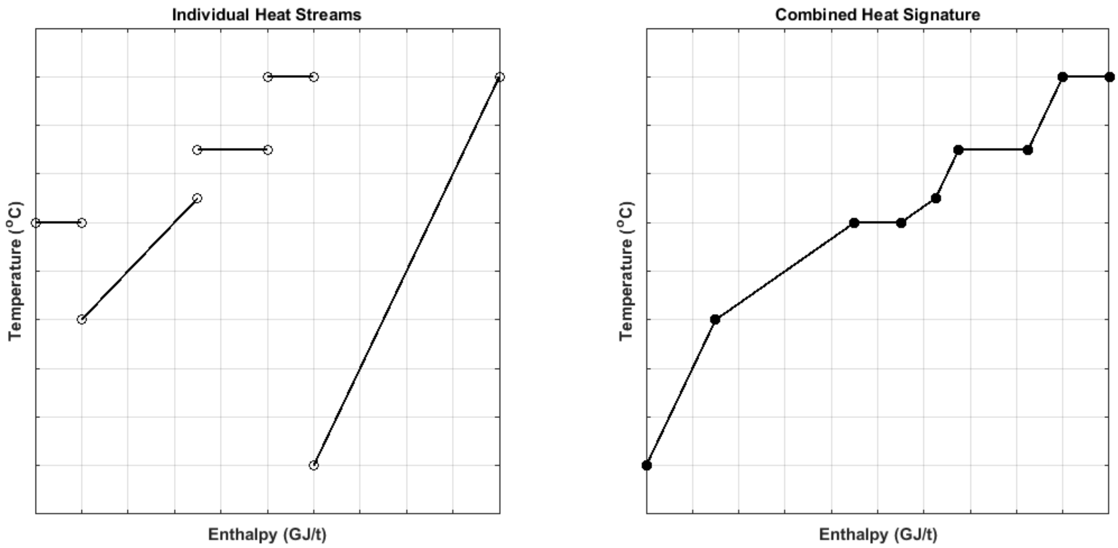

Figure 4: Construction of a process heat signature based on individual heat streams - increasing piecewise functions (left) to single continuous increasing function (right)

The resultant diagram is what is considered to be a heat signature of a given process. Combined with the production quantities from the Prodcom database [7], these figures give the total energy use for the given industrial processes in EU28 countries. Whilst details of individual streams are lost in the cumulative heat signatures presented, they provide a legible overview of all waste and process heat streams and are therefore useful in characterising the process. Multiple heat signatures within a sector, or from a number of sectors can also be combined to describe waste and process heat characteristics.

2.1.1 Heat Signatures from Chemical Distillation Database

The chemical and petrochemical industry is responsible for 19% of the European final industrial energy consumption [1] and should therefore be included within the European PPE Database. Distillation is the main separation technology and therefore energy user in the chemical industry and for this reason was chosen as the focus of the chemical industry heat signature.

For construction of heat signatures of chemical processes within the PPE database, required information on distillation processes was sourced from an external database [8]. Information within the database contained relevant temperature and heat quantities for a multitude of distillation columns specific to the Netherlands and is extrapolated to EU28 based on Prodcom production statistics. Heat pumps should be placed across the pinch point of the plant in order to maximize the energy saving potential of the process [4,9] and therefore distillation processes which failed to cross the pinch temperature of a process were excluded. The result was that 57 distillation columns covering the manufacture of 19 chemical products were included in the new PPE Database. A list of manufactured chemical products included and associated number of distillation columns for production of each chemical product is indicated in Table 1.

Table 1: Chemical Products from Distillation Columns in the PPE Database

Chemical Name	Number of Columns within Process	Chemical Name	Number of Columns within Process
Benzene	1	MDI	1
Bisphenol A	3	MTBE	1
Butadiene	2	Oxo Alcohols	7
1,4-Butanediol	3	Phthalic Anhydride	2
1-Butene	8	Propylene Oxide	4
Caprolactam	9	Styrene	3
Cumene	1	Urea	1
Cyclohexanone	2	Propylene Glycol	3
Ethylene Oxide	2	Isopropanol	1
Ethylene Glycol	3		

2.1.2 Heat Signatures of Industrial Processes

In addition to the chemical industry, the pulp and paper industry and the food and beverage industry were identified as ones suitable to heat pump applications due to their relatively low demand temperature to drive processes as well as having significant quantities of waste heat available. Together with the chemical industry, these industries are responsible for 41% of the total final industrial energy consumption [1]. Whilst the steel and building material industries were considered, the high demand temperature of these industries (200°C – 2000°C) are beyond the capabilities of current heat pump technologies and are therefore not considered in this analysis.

Heat signatures were constructed for a number of processes in the aforementioned industries and where possible, these were constructed from process flow charts of operational facilities. Heat signatures were available for Ammonia and Ethylene production and were therefore included separately from the distillation columns. The list of processes contained in the database is outlined in Table 2.

Table 2: Process Heat Signatures Contained in the PPE Database

Industry	Process
Paper and Pulp	Chemical Pulping Machine
	Tissue Paper Machine
	News Print Machine
	Graphic Board Machine
	Packaging Paper Machine
Food and Beverage	Milk Powder
	Whey Powder
	Beer Brewery
	Potato Processing
	White Sugar Production
Chemical Processing	Ammonia
	Ethylene
	Partial Heat Signatures from Table 1

2.2 Heat Pump Modelling

Through the use of the European PPE Database, the potential of both established heat pumps as well as theoretical concepts can be determined. The latter option provides the possibility to give a more relevant indication of the energy saving potential of heat pumps in general, rather than giving a value for a specific heat pump technology which may not be ideally suited to a given temperature range or application. However, the former option could be useful for a given manufacturer in determining the market potential of a given product. In order to give an estimation of the idealised heat pump potential for the processes contained in the European PPE Database, a simplified modelling approach was selected and coupled to the various heat signatures. This approach was based on the theoretical thermodynamic performance of a heat pump operating between two thermal reservoirs – the Carnot limit.

The primary metric for determining the performance of the heat pump is the coefficient of performance (COP), defined as follows:

$$COP = \frac{\dot{Q}_{SINK}}{\dot{W}_{IN}} = \frac{\dot{Q}_{SINK}}{\dot{Q}_{SINK} - \dot{Q}_{SOURCE}}$$

$\dot{Q}_{SINK}$ = Process heat output from heat pump
$\dot{Q}_{SOURCE}$ = Waste heat input to heat pump
$\dot{W}_{IN}$ = Electrical work input to heat pump

For a cycle containing strictly internally reversible processes, there is zero entropy production. It follows from this that the theoretical maximum (Carnot) COP of a heat pump cycle operating between two thermal reservoirs is:

$$COP_{CARNOT} = \frac{T_{SINK}(K)}{T_{SINK}(K) - T_{SOURCE}(K)}$$

T_{SINK} = Temperature heat is rejected from the heat pump
T_{SOURCE} = Temperature that heat is transferred to the heat pump

In reality, real cycles contain many sources of irreversabilities which significantly reduce this value. For a more realistic indication of heat pump performance, a temperature difference of 10°C between the waste and process heat streams and the heat pump source and sink temperatures respectively was imposed which is representative of the temperature difference required to facilitate heat transfer. An efficiency, relative to the resulting Carnot COP is further utilised to give a more realistic indication of the performance of the cycle. It is indicated by van de Bor [10] that dividing the Carnot efficiency by a value of two gives a reasonable estimate of the performance of a conventional compression heat pump cycle and therefore the value of 0.5 is taken in this study. The COP of a heat pump operating within a given industrial process is therefore given by the following equation:

$$COP_{THEORETICAL} = 0.5\frac{T_{SINK}(K) + 10}{(T_{SINK}(K) + 10) - (T_{SOURCE}(K) - 10)} = \frac{\dot{Q}_{SINK}}{\dot{W}_{IN}}$$

3. Results and Case Studies

Within this section, results are presented to provide an outlook as to the characteristics of waste heat available and process heat usage in the chemical, paper and pulp and food and beverage industries within the of EU28 countries. Furthermore, case studies are presented to determine the energy saving potential of heat pumps applied to selected industrial processes.

3.1 European Industrial Heat Signatures

Combining the processes contained in the European PPE database results in cumulative heat signatures for both waste heat and heat demand, which characterise the heat quantity as well as the temperature level of the collated processes in the paper and pulp, chemical and food and beverage industries. These industrial heat signatures are displayed graphically in Figure 5 which depicts the heat demand and Figure 6 which depicts waste heat in industrial processes. Further information relevant to the relative industrial sectors which make up these figures is tabulated in Table 3.

The heat demand of industrial processes contained within the European PPE database amounts to 1118 PJ whereas the waste heat totals 916 PJ. Conservation of energy suggests that process heat and waste heat quantities should be equal. Discrepancies can be attributed to a number of factors, including but not limited to; technically non-recoverable heat, such as that stored in solid materials, endothermic or exothermic reactions which may take place in the process as well as radiative and convective heat losses to atmosphere or missing process information. The EU market energy coverage based on the 4709 PJ [1] of the paper and pulp, chemical and food and beverage industries which make up the sectors within PPE database was found to be 23.7% for heat demand and 19.5% for waste heat. The paper and pulp industry was found to have the highest market share of 46.9% heat demand and 43.2% waste heat, as the five paper processes (or slight variances of those) contained in the database manufacture almost all produced paper products. Whilst market coverage for the chemical industry was low, in most cases only partial heat signatures consisting of distillation columns were available as opposed to the entirety of the processes. Within the food and beverage industries, lower (<10%) values for market energy coverage are attributed to the lack of processes in the current iteration of the database. Further to this, electricity consumption (26.5% FEC paper and pulp, 29.6% FEC chemical industry, 34.8% FEC for food and beverage [1]), which is not usually utilised for industrial heating purposes, is included in the final energy consumption figure and therefore acts to reduce the value of the market coverage of the heat signatures. Despite these variances, it is clear the resulting heat signatures give a strong indication of the industrial heating characteristics in these sectors and allow potential of heat pump devices to be calculated.

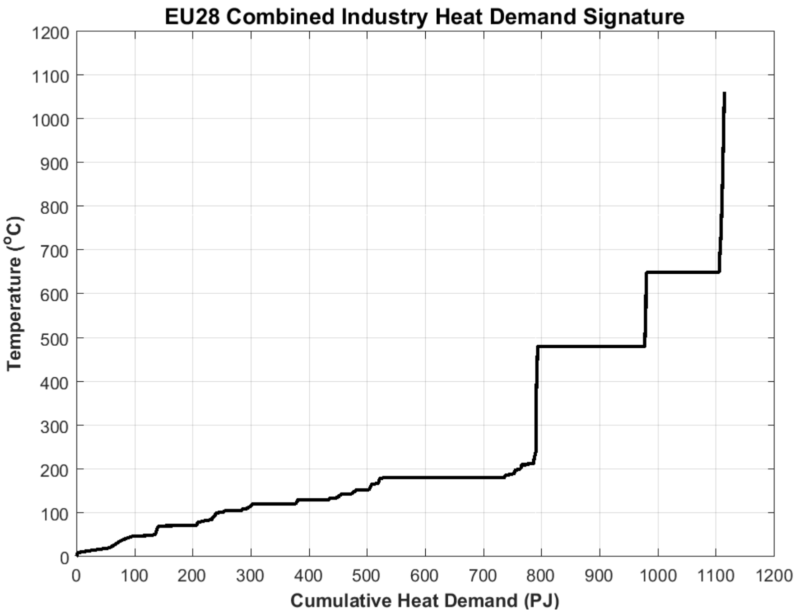

Figure 5: EU28 Industrial Process Heat Demand

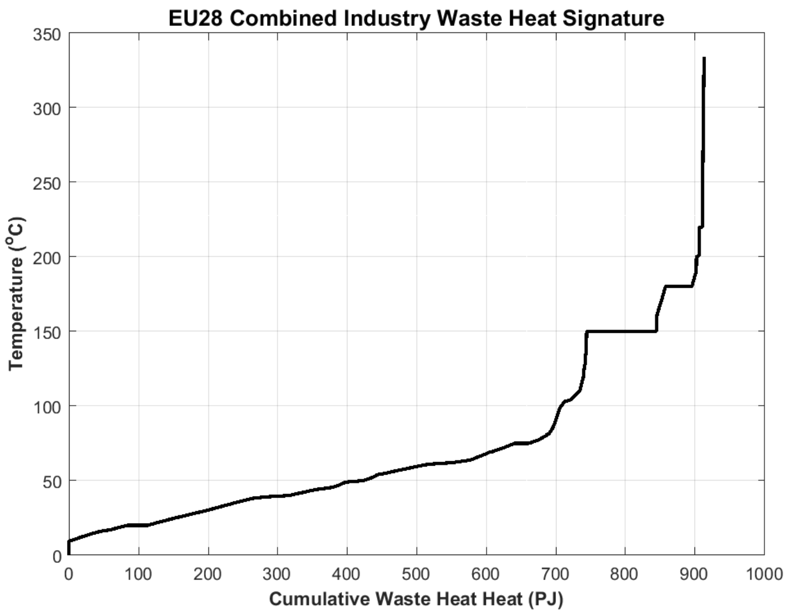

Figure 6: EU28 Industrial Waste Heat Supply

Table 3: Market Energy Coverage of Various Sectors in PPE Database

	FEC (PJ) [1]	Heat Demand PPE Database (PJ)	Waste Heat PPE Database (PJ)	Heat Demand PPE Database (% Sector FEC)	Waste Heat PPE Database (% Sector FEC)
Paper and Pulp	1326	622	573	46.9%	43.2%
Chemical	2203	393	267	17.8%	12.1%
Food and Beverage	1180	103	76	8.8%	6.4%
Total	**4709**	**1118**	**916**	**23.7%**	**19.5%**

Initial scoping of the suitability for heat pump applications in the defined sectors can also be conducted from inspection of Figure 5 and Figure 6. Current heat pump technology has the potential to reach temperatures of 150°C, with delivery temperatures of 200°C within reach. Process heat demand for temperatures up to 200°C is calculated to be 766 PJ from the PPE database (16.3% of FEC) in EU28 countries for the given sectors. Waste heat in the same temperature interval is found to be 905 PJ (19.2% of FEC). These numbers indicate that there is a large demand for process heat in the range of temperatures suitable for heat pumps and furthermore, there is sufficient heat available as input for this technology.

3.2 Case Studies

Within this section, two cases which are suitable for heat pump applications have been selected and identified for further analysis; one process within the paper manufacturing industry and one within the chemical industry.

3.2.1 Paper Production

Production of paper within a European context contributed a large share, 12%, of the EU industrial final energy consumption [1]. Of the five paper production processes within the PPE database, the heat demand and waste heat signatures for the manufacture of packaging paper accounted for the largest share of the final energy consumption in the sector within EU28 countries. The heat demand from the packaging paper process covered a cumulative 233 PJ whilst the waste heat supply covered a cumulative total of 211 PJ based on a sold volume of 32.4 MT paper product. Details of the streams which make up the heat signatures are presented in Table 4 which are combined to generate the heat signatures as presented in Figure 7.

Analysis of the waste and demand heat gives indication as to the most suitable locations for implementation of a heat pump in the process. Within the process, the pre-dryer and after-dryer segments are physically separated, however both sections essentially identical. In these sections the paper sheet is guided over cylinders which are heated from the inside using steam that is approximately 180°C. The primary purpose of the cylinders is to guide the web of paper through the machine, as well as to provide the heat of evaporation needed to dry the web. The water evaporated in this section is transferred to the environment using a process ventilation system. Fresh process ventilation air is heated utilizing a combination of process recovery as well as steam of 130°C. The dryer sections are covered by a hood allowing the process to take place at air conditions of approximately 85°C with a dew point of 64°C.

The heat content of the saturated air at 85°C, as denoted by the Pre-Dryer Ventilation and the After-Dryer Ventilation in Table 4, has a large sensible and latent heat content when cooling down to 54°C. This large source of waste heat which is otherwise discarded to ambient, is an ideal source that can be upgraded by a heat pump to be reused in the process. In determining a suitable sink for the drying section of the process, steam is required at temperature levels of 180°C for the cylinders, and 130°C for the preheating of air in both the pre drying and after drying section. Using a heat pump to lift the temperature from the ventilation heat source to higher than 180°C is beyond the capabilities of any current heat pump technology. Furthermore, the large temperature lift, coupled with Carnot heat pump limitations imply that the efficiency will be low. Producing steam at a temperature of 130°C is however, a feasible option that should be explored.

Table 4: Packaging Paper Machine Net Heat Signature Input

	T_{min}	T_{max}	Heat Demand (GJ/Tonne)
Process Water			
Process Water	13°C	52°C	1.1
Circulation Water	46°C	50°C	0.7
Process Air			
Pre-Dryer Ventilation	78°C	85°C	0.3
After-Dryer Ventilation	78°C	85°C	0.3
Comfort Air			
Machine Room Ventilation	9°C	20°C	1.4
Steam Condensate			
Steam Box	130°C	130°C	0.2
Pre-Dryer Air Heating	130°C	130°C	0.1
After-Dryer Air Heating	130°C	130°C	0.1
Starch Cooker	130°C	130°C	0.2
Pre-Dryer Cylinders	180°C	180°C	1.6
After-Dryer Cylinders	180°C	180°C	1.2

	T_{min}	T_{max}	Waste Heat (GJ/Tonne)
Process Water			
Process Water	22°C	46°C	0.5
Process Air			
Vacuum Pump Exhaust Air	20°C	55°C	0.6
Pre-Dryer Ventilation 1	64°C	85°C	0.14
After-Dryer Ventilation 1	64°C	85°C	0.11
Pre-Dryer Ventilation 2	54°C	64°C	0.96
After-Dryer Ventilation 2	54°C	64°C	0.79
Comfort Air			
Machine Room Ventilation	9°C	43°C	2.4

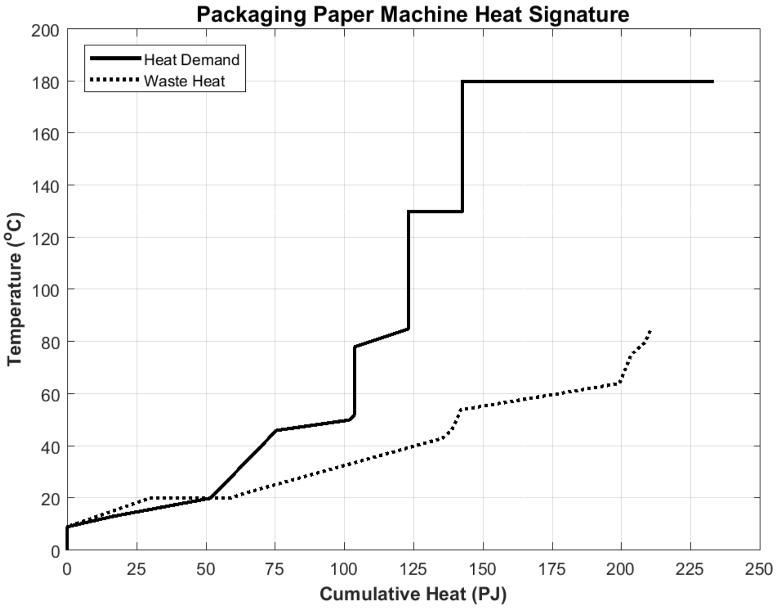

Figure 7: Heat Demand and Waste Heat Signatures of Packaging Paper Manufacturing Process in EU28

Utilising the process described in section 2.2, the potential reduction in FEC is calculated for integration of a heat pump into the aforementioned packaging paper production process. The results of the analysis for this application are seen in Table 5. The results are split into the pre-dryer and after dryer sections. Whilst the heat demand in both cases is the same, differences in sensible waste heat quantities in the pre-dryer and after-dryer sections result in differing heat pump source temperatures and therefore differing COPs. Overall, the potential reduction in FEC for EU28 countries through application of heat pumps to this process was in the order of 4.10 PJ or 0.31% of FEC in the pulp and paper sector. It is evident that there still exists large amounts of latent heat in the pre-dryer and after-dryer ventilation systems which is not utilised as the waste heat stream is not cooled below the dew point in both the pre-dryer and after-dryer sections. Modification of the process to allow lower steam pressures to be fed to the pre-dryer and after dryer cylinders should be considered to allow this reduction in energy consumption to be significantly higher, however the technical feasibility of this would need to be examined.

Table 5: Energy Saving Potential of Heat Pumps in Packaging Paper Production

	Heat Demand (PJ/year)	COP	Electrical Work Input (PJ/year)	Reduction in FEC (PJ/year)
Pre-Dryer	3.24	2.77	1.17	2.07
After-Dryer	3.24	2.68	1.20	2.03

3.2.2 Chemical Distillation

The European PPE Database contains 57 distillation columns used for the manufacture of 19 products in the chemical industry. Figure 8 shows a typical distillation process and compares this with a heat pump assisted distillation process. A reverse Rankine cycle compression heat pump is depicted in this figure for illustration only and is therefore interchangeable with other heat pump cycle technologies. Distillation columns are well suited to heat pump applications as there is a large heat input to the reboiler section at the bottom of the column and a corresponding large heat rejection from the condenser at the top of the column. It can be seen that for the heat pump assisted distillation process, heat from the condenser that would otherwise be rejected to ambient, is pumped to a higher temperature level using the heat pump and then fed into the reboiler. In this manner, a large amount of energy savings can be achieved.

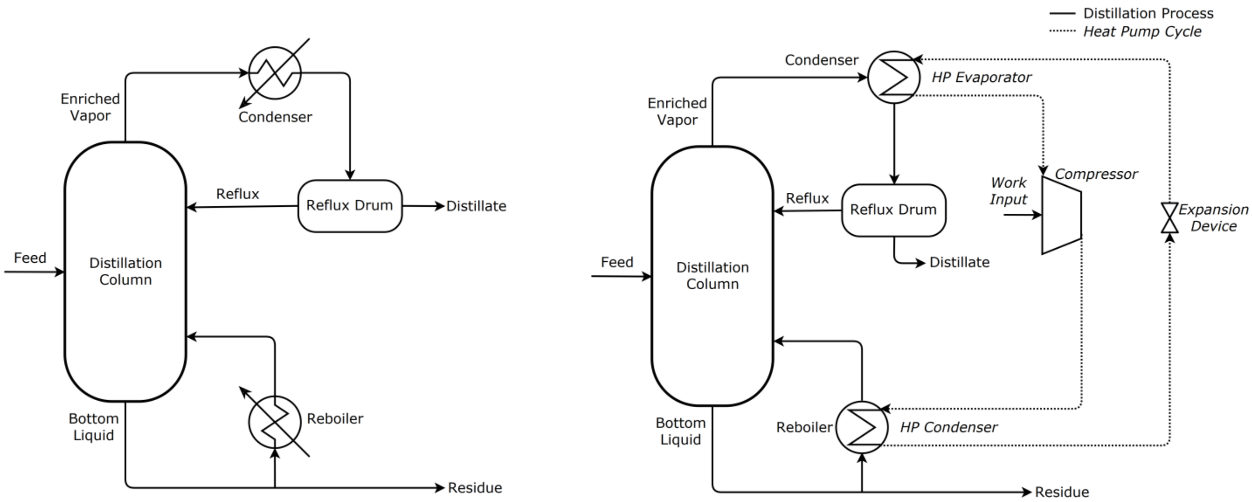

Figure 8: Standard Distillation Column Process (Left) and a Distillation Column with an Integrated Reverse Rankine Cycle Compression Heat Pump (Right)

Within this case study, we consider the manufacture of Styrene and the integration of a heat pump over a distillation column within the process. Styrene is a widely used monomer within the polymer industry. It is manufactured from an energy intensive process involving the dehydrogenation of ethylbenzene and has an approximate manufacturing energy requirement of 6.3 GJ/tonne [11]. The sold volume of Styrene in EU was reported to be 3.14 MT in 2014 resulting in an estimated energy use for production of 19.7 PJ annually. This equated to approximately 0.9% of energy use in the EU28 chemical industry [1].

Table 6: Ethyl-Benzene Recycle Distillation Column Parameters

Reboiler Duty	2.160 GJ/tonne
Reboiler T_{in}	101°C
Reboiler T_{out}	102°C
Reboiler Utility	Low Pressure Steam
Condenser Duty	1.728 GJ/tonne
Condenser T_{in}	47°C
Condenser T_{out}	45°C
Condenser Utility	Cold Water
Process Pinch Temperature	90°C

Within the European PPE Database, the Ethyl-Benzene Recycle Column was identified as being suitable for the integration of a heat pump. Information and critical parameters relating to the distillation column can be seen in Table 6. The column is particularly suitable for a heat pump application due to the relatively low reboiler temperature (101°C to 102°C) and the moderate temperature difference between the reboiler and condenser (57°C). Furthermore, the pinch temperature of the process is between the condenser and reboiler temperature, the main requirement for determining the eligibility of a heat pump over the distillation column.

Utilising the process described in section 2.2, the potential reduction in FEC is calculated for integrating a heat pump into the aforementioned chemical distillation column. The results of the analysis are seen in Table 7. The COP of the heat pump concept was calculated to be 2.50, rather low in respect to heat typical heat pumps. Overall, the savings in FEC from implementation heat pumps in this single distillation column were in the order of 4.07 PJ/year, equivalent to 0.18% of FEC in the chemical industry.

Table 7: Energy Saving Potential of Heat Pump Assisted Distillation Column

	Heat Demand (PJ/year)	**COP**	**Electrical Work Input (PJ/year)**	**Reduction in FEC (PJ/year)**
Ethyl-Benzene Recycle Distillation Column	6.78	2.50	2.71	4.07

4. Conclusions

This study investigated the energy saving potential of heat pump technology applied to various processes in the pulp and paper, food and beverage and chemical industries. A bottom-up approach was utilised to create so-called heat signatures containing information as to the quantity and temperature level of waste and process heat in a multitude of processes. Heat signatures were created for a total of 12 industrial processes, with an additional 19 partial heat signatures of processes in the chemical industry containing information on distillation columns within these processes. Combining the heat signatures with European production statistics sourced from the EUROSTAT Prodcom database, resulted in the European PPE Database. Specific cases were selected within the PPE database and presented in order to determine the energy saving potential of heat pumps applied to these processes.

Results were presented, giving a general overview of the cumulative heat signatures contained in the European PPE database. The combined heat signatures of the paper and pulp, chemical and food and beverage industries covered an estimated 23.7% for process heat demand and 19.5% for waste heat supply of the 4709 PJ final energy consumption [1] within these sectors. Overall, it was found that there was large amounts of waste heat available (905 PJ) and process heat demand (766 PJ) in the temperature range relevant to current heat pump technologies, indicating the potential for application in the paper and pulp, chemical and food and beverage industries is large.

Specific cases were selected and presented to illustrate the energy saving potential of heat pumps applied to the chosen processes. A case was presented for a heat pump applied to the production of packaging paper. Large quantities of waste heat were available, however only small amounts of process heat was required in the temperature range applicable to heat pump technology. It was calculated that the reduction in the EU28 final energy consumption was 4.10 PJ/year or 0.31% of energy in the pulp and paper industry based on the heat signature used to characterise the process. It was suggested that modification to the process should be considered to increase the potential applications of heat pumps to that given process. A second case study was presented for the case of a distillation column utilised in the production of Styrene. For the particular column, the reduction in the EU28 final energy consumption was found to be 4.07 PJ/year or 0.18% of energy in the chemical industry. Whilst in both cases the relative reduction in FEC is low, the energy savings that can be achieved in each case is specific to a given process. It is indeed obvious that when considering the entirety (57) of the distillation columns as well as all 12 industrial processes within the PPE database, that the energy saving potential of heat pump technologies will have a significant impact in achieving energy efficiency in industry.

5. References

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