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An estimation of the European industrial heat pump market potential

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ABSTRACT

This paper presents an estimation of the European (EU28) industrial heat pump market potential in terms of magnitude, sizing and number of units. This study is carried out in order to provide technology suppliers and manufacturers of industrial heat pumps perspectives for the technology. Potential heat pump applications in the food, paper, chemical and refining sectors are identified considering a maximum sink temperature of 200°C. This is achieved utilising a bottom-up methodology that uses detailed information from individual processes in the aforementioned sectors. Combining individual process data with typical plant capacities provides information on the heating capacities of heat pumps. The data is upscaled to European level, using production statistics relevant to the individual processes analysed. Since the database of processes is generic in nature and not fully covering the whole industrial sector, the results of this analysis provide a conservative estimate of the heat pump market potential. The results show a potential cumulative heating capacity of industrial heat pumps in EU28 of 23.0 GW, consisting of 4174 heat pump units which are able to cover 641 PJ/a of process heat demand. The largest number of heat pump units (%) can be found for heating capacities <10 MW, making up about 50% of the total market cumulative heating capacity. Clearly, there is a large market ahead for industrial heat pump manufacturers and suppliers.

1. Introduction

The European Union and its 28 member states (EU28) have strong ambitions regarding sustainable energy and the transition to a low carbon society by 2050. Close to 80% of current greenhouse gas (GHG) emissions are attributed to demand for energy [1], most notably in the form of electricity and heat, and as such there is a growing emphasis on the decarbonisation of these energy carriers. This is becoming increasingly important for the industrial sector, which according to the IPCC [2], is responsible for 32% of the global GHG emissions (direct and indirect). Despite a reduction in the energy consumption per unit added value (energy intensity) in the last decades, total industrial energy usage has increased due to disparately higher production output [3].

Fig. 1 shows an overview of the absolute and relative amount of final energy consumption (FEC) for various industrial sectors with EU28. The final energy consumption refers to all energy supplied to the various industry sectors and is a quantity indicating the consumption at the final place of energy use [4]. The strict definition of final energy consumption by Eurostat (data source, Fig. 1) includes only end use sectors and excludes energy used by the energy (transformation) sector. This paper differs slightly, in that oil refineries, usually considered part of the energy sector, is considered to be an additional industrial end-use sector and therefore, its energy use is attributed to final energy consumption.

Further examining the energy usage within industry, it is evident that heat is the dominant energy carrier. Indeed, demand for thermal energy in 2012 accounted for 73% of final energy consumption [5]. The large diversity of processes in industry mean that temperature requirements can range from well below 0°C to well above 1000°C. Low temperature process heat (<200°C) is typically demanded from processes which involve drying and dewatering, distillation, space heating, sterilization or cooking whilst high temperature heat (>500°C) is typically demanded from processes which involve cracking, reforming, reduction or smelting.

It has been suggested that the 80% reduction in GHG emissions by 2050 is only achievable through radical changes in the process operation of energy intensive industries [7,8]. The decarbonisation options at the forefront of the industrial transition are: the reduction in final energy consumption through process efficiency improvements and new processes, the reuse of waste heat, and the transition of energy and feedstock from fossil to renewable sources.

Many energy efficiency improvements implemented in industry over the past years are attributed to so called 'quick wins' [9]. Within the context of further efficiency improvements, the use of waste heat has

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Nomenclature

Abbreviations and Parameters

AFF	Avoided fossil fuel use (J)
CDE	Carbon dioxide (CO_2) emissions (t)
COP	Coefficient of performance (−)
E	Energy (J)
$\dot{E}$	Energy rate, power (W)
EF	CO_2 emission factor (t/J)
EU28	European Union 28 member states
FEC	Final energy consumption (J)
GHG	Greenhouse gas
n	Quantity for upper bound of summations (#)
N	Number of heat pump units (#)
PEC	Primary energy consumption (J)
PEF	Primary energy factor (−)
Q	Heat energy (J)
$\dot{Q}$	Heat flow rate, heating capacity (W)
T	Temperature (K, °C)
η	Efficiency factor (−)
β	Proportion of electricity generated from renewable sources (−)

Subscripts

1,2	Relating to individual scenarios presented
com	Combustible fuels
conv	Conversion
e	Electrical
fuel(s)	Relating to a combustible fuel
h	Heating
HPmarket	Relating to the calculated heat pump market
i	Index of summations
in	Input
j	Index relating to individual scenarios presented
Lorenz	Relating to an idealised Lorenz heat pump
LM	Log mean
mean	Mean (average) of dataset
median	Median of dataset
out	Output
P	Process
red	Reduction
ref	Reference scenario
W	Waste

been touted by many authors as being an underutilised or undervalued resource [10–12]. Indeed, after heat is utilised for driving industrial processes, it is generally discarded to ambient as it is at too low a temperature level to be reused. This waste heat can be contained in many media, including flue gasses, air or water steams and even radiative sources. The preferred solution would be to reuse this waste heat in the process where it originates, preventing lock-in situations whereby historical investment choices restrict further energy efficiency improvements.

One option for the decarbonisation of the low temperature industrial heat demand (<200°C), is large scale uptake of heat pump technology. Heat pumps are able to upgrade the temperature of a waste heat source to that of a given process with the input of either heat or electrical energy. In this way, the reuse of waste heat in the process is possible, resulting in large savings in energy consumption and associated CO_2 emissions. With the increasing share of renewable electricity generation, utilising an industrial heat pump powered by electricity is a robust choice for achieving a more sustainable industry. More specifically, the implementation of heat pumps could result in both significant energy efficiency improvements as well as the uptake of a sustainable energy source in the form of renewable electricity. It is a cross sectoral technology that is suited for both retrofit and greenfield applications.

The uptake of heat pumps in industry is currently limited for numerous reasons. One of the main reasons is that there are limited manufacturers of heat pump equipment which provide products which can supply higher temperatures required by the industry. Multiple manufacturers can provide products which supply heat up to 90°C [13]. Beyond this temperature, commercially available products are limited, with only a few pioneering manufacturers demonstrating sink temperatures in the range of 120°C – 165°C [13]. A number of research projects

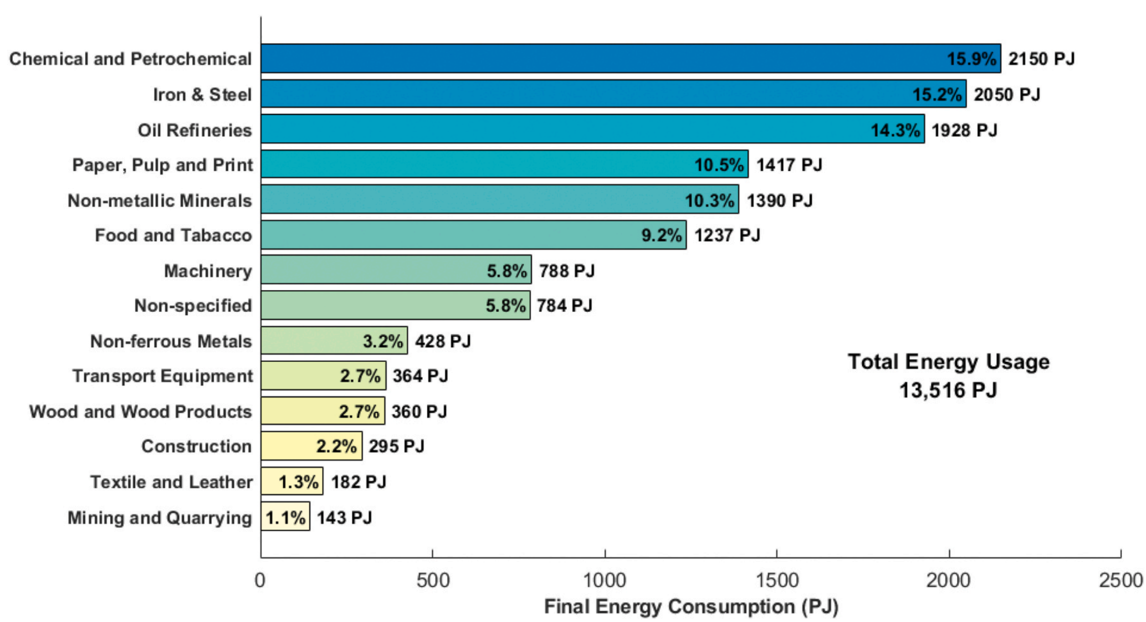

Fig. 1. Final energy consumption of various industrial sectors in EU28 (2016) [6].

are developing heat pumps which aim to demonstrate sink temperatures in the range of 160°C – 200°C [14–16], although implementation in the market is expected to take some years. In many cases, the lack of product development at higher temperatures is likely attributed to lack of knowledge by heat pump manufacturers regarding industrial applications and market size. This paper specifically aims to address this issue and provide manufacturers with perspectives for the technology, by providing an estimate of the industrial heat pump market potential in EU28 in terms of cumulative heating capacity and number of units, whilst also presenting information on typical sizing and temperature levels.

Whilst there have been limited studies which have attempted to quantify the application potential of industrial heat pump technology, an overview of the market containing all aforementioned details is absent. Wolf and Blesl [17] conducted a study focused on quantifying the entire industrial heat pump market on a European level. This study was however restricted in that the heat pump sink temperature was limited to 100°C. The focus was primarily on the calculation of bulk energy saving and CO_2 abatement potential (both economic and technical). The combined top-down and bottom-up methodology utilised for calculating waste and process heat amounts and temperature levels, led to the calculation of a final energy consumption reduction potential of 1717 PJ in the sectors investigated. Kosmadakis [18], also presented a study whereby the potential of industrial heat pumps was estimated focusing on applications in the temperature range of 100°C – 200°C. Process and waste heat quantities were derived separately, but in general consisted of aggregated values grouped into temperature level and broad application. The heat pump potential was calculated on this aggregated level, estimated to be 102 PJ in EU industries. In both studies, there was an absence of information relating to the characteristics (temperature level, heating capacity, performance) of individual heat pumps which made up the market.

This study adds to the work conducted in previous heat pump market studies through utilisation of a bottom-up methodology for calculating the industrial heat pump market potential in EU28. The bottom-up methodology ensures that data relating to individual heat pump applications are retained, which can then be collated to give a complete market overview. The focus of the study is directed towards electrically driven heat pumps with a maximum sink temperature of 200°C. This market potential could be covered by heat pump technology developed in research and demonstration projects in the longer term. A supplementary result is provided on the market potential for applications with sink temperatures up to 150°C which can be covered with pioneering technology from heat pump manufacturers now and in the near future. However, it is hoped that by focusing on temperatures (200°C) higher than current available technology, it will provide manufacturers incentive to develop products for this market.

2. Heat pump concept

The concept of a heat pump is presented in this section. Firstly, the thermodynamic concept and relevant equations are presented, followed by details on the factors which influence industrial heat pumps achieving both energy and CO_2 savings.

2.1. Heat pump theory

The thermodynamic working principle of an industrial heat pump driven by electricity is seen in Fig. 2. A waste heat source from a given process ($\dot{Q}_W$) is input into the device at low temperature (T_W). With the input of electrical power ($\dot{E}_e$), the temperature of the waste heat source is upgraded to produce high temperature (T_P) process heat ($\dot{Q}_P$) at the heat sink. The performance of a heat pump is defined by the coefficient of performance (COP) defined as the ratio of heat output to electrical power input and indicated in Equation (1):

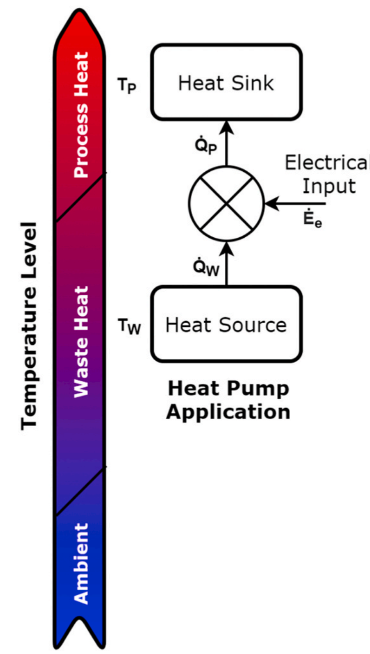

Fig. 2. Thermodynamic representation of a heat pump applied to an industrial process.

$$COP = \frac{\dot{Q}_P}{\dot{E}_e} \tag{1}$$

For an ideal heat pump, operating between process and waste heat streams with constant heat capacities and varying temperatures (temperature glides), the maximum theoretical COP is known as the Lorenz COP and is given by Equation (2). The definition of the log mean temperatures of a stream is given in Equation (3). For a heat stream which has no temperature glide, the log mean temperature can be replaced by the constant temperature of the waste heat source or process heat sink.

$$COP_{Lorenz} = \frac{T_{P,LM}}{T_{P,LM} - T_{W,LM}} \quad T \text{ in } K \tag{2}$$

$$T_{LM} = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in}}{T_{out}}\right)} \quad T \text{ in } K \tag{3}$$

In practice, thermodynamic processes contain numerous losses which reduce the actual COP to a fraction of the Lorenz COP value. An efficiency term (known as a second law or exegetic efficiency), which relates the actual COP to the maximum Lorenz COP is given in Equation (4).

$$\eta_{Lorenz} = \frac{COP}{COP_{Lorenz}} \tag{4}$$

The concept of an industrial heat pump can be realised by numerous thermodynamic cycles, with the Reverse Rankine (vapor-compression) cycle the most well-known. This paper will not address the details of the different technologies. The interested reader is referred to the work of Arpagaus et al. [13] for an excellent review on this topic. For the various heat pump cycles and technology, efficiencies relative to Lorenz (η_{Lorenz}) vary in practice and depend on a number of operating factors, however values of 50% have been reported and utilised in the literature as giving a reasonable indication of typical well-designed large-scale heat pump performance [19,20]. Based on this, typical values for the COP of numerous industrial applications would be expected to be in the range of 2 – 5 depending on the relative temperatures of the source and sink. In the works of Arpagaus et al. (Fig. 8) [13] it is shown for numerous industrial heat pump units, that typical COPs are within the aforementioned range.

2.2. Energy and CO_2 saving potential

When considering the energy savings from the application of a heat pump, reductions in the primary energy are of greatest interest. The primary energy consumption (PEC) represents the total energy demand, including the final energy consumption (see section 1), as well as upstream losses in the transformation (i.e. fuel to electricity) and distribution of energy [21]. The CO_2 savings are subsequently calculated on basis of the reduced primary energy consumption.

The primary energy and CO_2 savings that arise from the application of a heat pump are dependent on numerous factors, the main being:

i. The COP achieved by the heat pump in operation
ii. The energy source which the heat pump replaces
iii. The generation sources of the electricity system in which the heat pump operates

Fig. 3 shows a simplified energy flow diagram, which illustrates the transformation from primary energy to process heat for traditional process heating without a heat pump (left) and when a heat pump is utilised (right). The primary energy factor (PEF) is a measure of the units of primary energy needed to generate a single unit of process heat or electricity and is an important metric when considering primary energy saving potential of a heat pump. The heating primary energy factor ($PEF_h = PEC/Q_P$), considered when evaluating the primary energy consumption without a heat pump, is usually close or equal to unity indicating that it is of secondary importance for determining primary energy saving potential. The electrical primary energy factor ($PEF_e = PEC/E_e$) is of greater importance. Calculation of the PEF_e on a country, regional or European level is not trivial and numerous methods are described for calculating this value [22,23]. Despite this, the use of fixed values are common, such as in the European Commission Energy Efficiency Directive (EED) [24] which bases reductions in primary energy consumption on a PEF_e value of 2.1 unless another number can be justified. The increased uptake and higher proportion of renewable electricity generation will imply that PEF_e values will decrease significantly in the future towards an ideal value of 1.0. When examining Fig. 3, it is indeed obvious that reductions in the PEF_e will result in increases in primary energy savings when implementing a heat pump.

3. Determining the European industrial heat pump market potential

The application of a heat pump requires the availability of waste heat (source) and the demand for process heat (sink). Ideally, these should be located in the vicinity of each other, preferably within the same process. Furthermore, the heat capacity of both source and sink should be of similar magnitude, with both streams being available at the same time period. To determine whether a heat pump can be applied, information is needed about the temperature profiles of both the waste heat supply and the process heat demand.

In general, there are two approaches to estimate both process heat demand and waste heat availability: a top-down approach and a bottom-up approach. The top-down approach usually starts with the total energy use of a sector and determines which part is used for heating purposes. Thereafter, this heating demand is divided across temperature intervals based on a fraction of the total heat demand. Although this method provides relatively quick estimates, it lacks specific process information. It is not possible to derive the capacity of a heat pump for a specific application this way. The bottom-up approach analyses individual processes and aggregates this to a higher level. This usually results in limited market coverage but can provide information on capacity of heat pumps and specific temperature conditions. The nature of industrial heat pump operation, whereby a waste heat source is upgraded in temperature to produce process heat requires that heat pump integration potential should be determined from information obtained on an individual process level, rather than generalised data from a sectoral or total industrial level. For this reason, the remainder of this paper utilises a bottom-up approach to determine the industrial heat pump market potential.

3.1. Industrial sectors

Energy intensive sectors which have a large heat demand in the temperature interval <200°C are most relevant for heat pump technology. Utilising recent literature results, an indication of the most relevant sectors for heat pump integration can be given. Numerous top-down

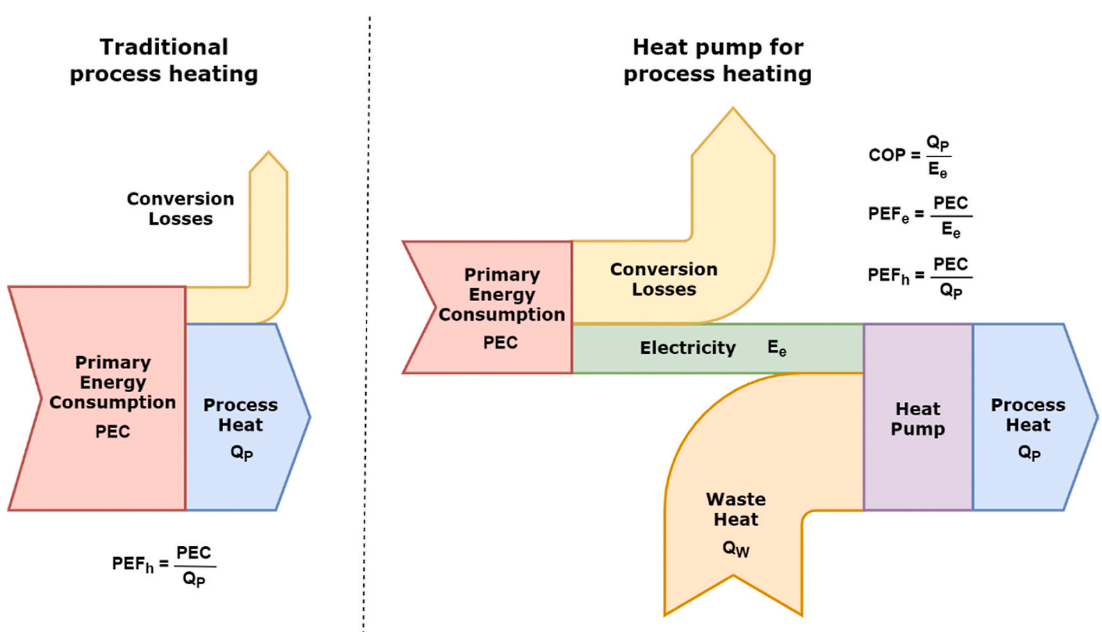

Fig. 3. Simplified energy flow diagram illustrating the transition from primary energy to process heat for a process without (left) and with a heat pump (right).

[25–27] and bottom-up [28] studies were found which attempt to determine process heat requirements in various industrial sectors and subdivide this process heat use into differing temperature levels. Of these, only a single study presented results which explicitly indicate the heat demand in the temperature level <200°C. In the study, Rehfeldt et al. [28] utilised a bottom-up approach to determine the heating and cooling demand in industries in EU28 + 3 for 2012. This study indicates that the largest heat demand <200°C can be found in the paper, (842 PJ), other industries (634 PJ), food (450 PJ) and the chemical sectors (436 PJ). Relatively low amounts of heat demand <200°C were found in other energy intensive industries, such as non-metallic minerals sector (154 PJ), machinery and transport sector (148 PJ), iron and steel sector (56 PJ) and the non-ferrous metals sector (32 PJ). Despite the differing methodologies employed in the differing studies investigated (i.e. top-down, bottom-up), as well as results differing in temperature intervals, the results of the Rehfeldt et al. [28] study regarding the relative heat demand at various temperature intervals of industrial sectors are broadly in agreement with other studies found in the literature. On the basis of these results, there is sufficient evidence to suggest that the paper, chemical and food sectors are the most suitable for heat pump integration and will therefore be the focus of this study.

It is noted that whilst Rehfeldt et al. [28] uses a bottom-up methodology to calculate process heat demand in industry by temperature level, the data is not sufficient to calculate the heat pump market potential. This is due to Rehfeldt et al. [28] omitting data on characteristics of individual processes as well as not considering waste heat in the analysis. The bottom-up approach used in this study adds to the work of Rehfeldt et al. [28] by outlining the characteristics of heat use in industry whilst also overcoming the limitations preventing the estimation of the heat pump market potential.

Notably absent from the literature investigated was the availability of data regarding heat demand and temperature levels in the refinery sector. The energy intensive nature of processes within the refinery sector and the similar nature to those in the chemical sector (cracking, separating, reacting) suggest it may be interesting for integration of heat pump technology and therefore its suitability is also investigated in this study.

3.2. Bottom-up methodology

The bottom-up approach utilised in this study entails the following main steps:

1. Gather process data, specifically heating and cooling profiles of individual processes, containing temperature levels and energy use per unit of product
2. Determine the applicability of a heat pump for a given process
3. Determine the thermodynamic performance of a heat pump applied to a given process
4. Upscale the information obtained on an individual process level to a sector, and EU-level using data on typical plant capacities and relevant production statistics for each sector

Each of these steps is elaborated in more detail in sections 3.2.1 through 3.2.4 which follow.

3.2.1. Process data

Products which are either highly energy intensive to manufacture, or consume high amounts of energy, have been the focus of this study. Process information has been sought for manufacture of these products from multiple sources. Where feasible, process flowsheet data from operating manufacturing facilities has been utilised.

For each process, the attention has been on utilising the residual streams from the process to integrate heat pump technology. For the process heat requirement, this represents the hot utility. Similarly, for the excess waste heat, streams are considered which are discarded to either ambient or a cold utility. The analysis was simplified by characterising heat streams as being either constant heat capacity or constant temperature, whilst for moist air waste streams, in most cases the temperature was taken at the dew point. Whilst both technical and economic potential of waste heat recovery should be considered [12], these details are not evaluated within this study.

In total, 57 products or processes have been considered in the four industrial sectors. Each process is characterised by the temperature and the heat quantity per produced product amount (GJ/t) of each residual heat stream. Where available, the pinch temperature of the process is also noted. Where multiple process datasets are available for the manufacture of a particular product, the specific energy consumption of the processes has been averaged, and the relative temperature levels in the process adjusted accordingly. In this way, a single set of process data has been generated for the manufacture of each product identified, which is considered to be indicative of the manufacturing process of that product within EU28. In this way, it is evident that the resulting process and waste heat characteristics are generic in nature and not always representative of the best available technology (BAT) for manufacturing of that product.

The process and waste heat quantities and temperature levels for the 57 processes are made available in an external data repository [29]. It is noted that the 57 processes do not cover all possible industrial heat pump applications in the four industrial sectors. An effort is made by the authors to continually add relevant processes to the database and therefore increase the obtainable process heat coverage of the differing sectors.

3.2.1.1. Paper and pulp sector. The paper and pulp sector can be characterised as being heterogeneous in nature, responsible for a multitude of product outputs [30]. Despite the diverse range of product outputs and differing feedstock inputs, there is minimal variation in the underlying processes [31]. The energy requirements for the sector are dominated primarily by heat demand for drying of the paper, and mechanical energy used for pumps, compressors, fans and machine drives. Despite a similar underlying process, a distinction is still made between differing paper grades and the slight variations in specific energy use, temperature requirements and distribution of plant sizing for each. In total, 11 paper grades were identified and implemented within this study. In general, mills which are well integrated, having a relatively low specific energy consumption have been utilised to generate the data for determining the heat pump potential. Excluded from the present analysis is the manufacture of paper and pulp utilising the Kraft or Sulfite processes. Production of black or brown liquor respectively in these processes can be burned in recovery boilers to produce steam in excess of that which is required for drying of the pulp or paper. This ensures that application of heat pump technology within these processes would be unsuitable.

3.2.1.2. Chemical and refining sectors. The chemical and refinery industries are responsible for the transformation of numerous raw products and feedstocks into thousands of end use products. Whilst there is a wide diversity in manufactured products, both sectors are characterised by similar unit operations.

Distillation is the main separation technology and most common unit operation utilised in the chemical and refinery industry. It is also recognised as the most energy intensive operation in the chemical industry [32]. The large heat demand for distillation operations is often at temperature levels that are below 200°C. From this perspective, a focus on distillation processes within this work seems logical. This is further exacerbated by the fact that integrating heat pumps within distillation columns has been identified by numerous authors [32–35] as a means of reducing the specific energy consumption of distillation processes. Through integration of a heat pump with a distillation process, low temperature heat rejected in the condenser section can be upgraded in temperature to be input to the reboiler section. Both the waste heat and process heat streams from the condenser and reboiler sections respectively are located in close vicinity to each other, further outlining the benefit of integrating a heat pump with such a process.

For the chemical sector, generalised data was sourced for distillation columns utilised in the manufacture of 26 chemical products. For the refinery sector, generalised distillation column data has been sourced for 9 of the main processing steps in transformation from crude oil to end products.

3.2.1.3. Food sector. The food sector has by far the largest variation in production processes of all the sectors considered. A priority was given to products and processes which employed large scale drying and dewatering (i.e. starches, milk powder, whey powder and white sugar) as these are usually associated with large energy requirements. Overall, process data was sourced for the manufacture of 11 food products. This limited number of applications is not sufficient for gaining an understanding of the entirety of heat pump processes in the sector, specifically the large number of processes in the smaller heating capacity range. However, it is hoped that the inclusion of these applications will shed some light on the larger heat pump applications within the sector which would likely be most economically attractive for heat pump integration.

The need for simultaneous heating and cooling in the food sector provides an opportunity for heat pump applications whereby the heat output of the cooling system can be used as a heat source, which can lead to overall COP improvements for the total system. Examples of such applications were found during process data collection, with the condenser duty from the refrigeration plant taken as a waste heat source. It is noted however, as process cooling needs in industry are reported to be a small fraction (4.3% [28]) of the process heating requirements, heat pump applications providing simultaneous process heating and cooling are expected to be niche applications of the technology.

3.2.2. Heat pump integration

The focus in this study has been on utilising the residual heat streams in the process for heat pump integration. No attempt was made to modify the processes through passive heat recovery or other energy efficiency methods. Whilst this method may not result in the most thermodynamically optimised process network, it does ensure the heat pump applications are practically achievable without fundamental changes to existing processes.

The following rules were applied to determine whether a heat pump can be applied to a specific process:

- The heat pump sink temperature is limited to <200°C. Although the technology to do this is not currently available, it is hoped that further development of industrial heat pumps will result in commercially available products up to this temperature.
- The temperature lift of the heat pump is limited to <100°C between inlet source and outlet sink or outlet source and inlet sink. Although theoretically possible, higher temperature lifts are excluded since the COP will be too low to achieve any economic benefits.
- The heat pump must cross the process pinch. For all processes, heat pumps are only applied if source and sink temperatures are below and above the pinch temperature respectively. Although this is thermodynamically correct, it will exclude feasible applications. As passive heat recovery across the pinch temperature should be avoided, it implies that this aspect can be omitted before heat pump application.
- All waste heat input to the heat pumps originates from the process itself. Whist other heat sources external to the processes investigated may be feasible to use in the absence of a waste heat supply (i.e. ambient air, district heating) this was not considered in the current study.
- Heat pumps could cover part of the process heat demand in cases where sink temperatures or temperature lifts became too high (>200°C and >100°C respectively) or waste heat availability was insufficiently low.

3.2.3. Heat pump performance

A simplified modelling approach was utilised for estimating the performance (COP) of each heat pump application. The approach is based on the use of the Lorenz COP, defined in section 2 (Equation (2)). An efficiency factor (η_{Lorenz}, Equation (4)) of 50% relative to the Lorenz COP is utilised to give an indicative performance which could be achieved in practice.

3.2.4. Upscaling process data

The individual process data for the manufacture of a given product has to be upscaled to an EU28 level. For this, typical plant capacities (kT/a) for each of the individual production processes are identified. Where possible, a distribution of plant capacities is sought. Additionally, the typically yearly operating hours for facilities manufacturing each product is determined. Such a distribution of plant capacities, combined with yearly operational hours allows the individual production process information to be extrapolated such that for each plant size, typical heating capacities can be deduced.

The final step involves translating the resulting data from individual plant level of differing capacities to the EU28 level. For this step, production quantities (kT/a) within EU28 for the manufacture of each individual product for which process information existed was sourced. Production statistics from the year 2016 have been utilised from a number of sources, most commonly from the Eurostat Prodcom database [36], as well as numerous industry bodies [37–40]. Production quantity data allows the number of production facilities to be estimated including the capacity of each. This in turn, allows the industrial heat pump market potential to be fully characterised in terms of heating capacities, temperature levels and number of units.

3.3. Quantifying savings (energy, CO_2) and required investments of the industrial heat pump market

As a supplementary result in this study, an attempt has been made to quantify the energy and CO_2 saving potential of the calculated industrial heat pump market as well as the investment needed to realise this market potential. The investment needed to realise the market potential gives an indication of the revenues that can be achieved from heat pump sales, which is expected to be particularly relevant for manufacturers looking to develop products for this market.

3.3.1. Energy and CO_2 saving potential

Two scenarios are considered for calculating the yearly energy and CO_2 saving potential of industrial heat pump technology in EU28. The two scenarios are calculated in comparison to a reference scenario in which no heat pumps are implemented. Of the two scenarios considered, the first one is closely representative of implementation of heat pumps within the current energy system (Scenario 1). The second scenario represents a case whereby there is a higher penetration of renewables in the energy system such that the electricity system is fully decarbonised (Scenario 2). For the second scenario, no indication is given as to if or when this would be achievable, however this represents the best case scenario and therefore the maximum energy and CO_2 emission saving from the application of industrial heat pumps.

The equations used to calculate the energy and CO_2 saving potential of industrial heat pump technology for the two scenarios are presented in Equation 5 through 12, seen in Table 1. These equations are applied to each sector individually and the results later collated. Fig. 4 has been provided to assist the reader in understanding the transformation of primary energy to process heat demand in the new scenarios.

In both scenarios, calculation of primary energy consumption of heat

Table 1
Equations used for calculating energy and CO_2 saving potential.

Equation	Notes	Equation No.
Intermediate equations:		
$FEC_{com(ref)} = \sum_{i=1}^{n_{fuels}} FEC_{fuel,i}$		(5)
$Q_{P,com(ref)} = \sum_{i=1}^{n_{fuels}} \eta_{conv,i} FEC_{fuel,i}$		(6)
$Q_{P,com(1,2)} = Q_{P,com(ref)} - Q_{P,HPmarket}$	$Q_{P,HPmarket}$ given in Table 4	(7)
$FEC_{com(1,2)} = FEC_{com(ref)} \frac{Q_{P,com(1,2)}}{Q_{P,com(ref)}}$		(8)
Final energy consumption (FEC) reductions:		
$FEC_{red(1,2)} = FEC_{com(ref)} - FEC_{com(1,2)} - E_{e,HPmarket}$	$E_{e,HPmarket}$ given in Table 4	(9)
Avoided fossil fuel (AFF) usage		
$AFF_{(j)} = FEC_{com(ref)} - FEC_{com(1,2)} - E_{e,HPmarket}(PEF_{e(j)} - \beta_{(j)})$	$\beta_{(1)} = 29.6\%$, $\beta_{(2)} = 100\%$ $PEF_{e(1)} = 2.1$, $PEF_{e(2)} = 1.0$	(10)
Primary energy consumption (PEC) reductions		
$PEC_{red(j)} = FEC_{com(ref)} - FEC_{com(1,2)} - (E_{e,HPmarket} PEF_{e(j)})$		(11)
CO_2 emission (CDE) reductions		
$CDE_{red(j)} = \left(\sum_{i=1}^{n_{fuels}} EF_{fuel,i} FEC_{fuel,i} \left(\frac{Q_{P,HPmarket}}{Q_{P,com(ref)}}\right)\right) - (E_{e,HPmarket} EF_{e(j)})$	$EF_{e(1)} = 76.6$ t/TJ, $EF_{e(2)} = 0$ t/TJ	(12)

pump technology is determined based on calculated heat pump heat coverage and electricity usage, as well EU28 averaged PEF_e values. For the first scenario, a PEF_e value of 2.1 value is taken, in line with that referenced by the European Commission Energy Efficiency Directive [24]. We assume a PEF_e of non-combustible renewables to be equal to 1.0 (physical energy content method), and therefore this value is utilised for the second scenario.

Calculation of the avoided energy usage and CO_2 emissions from the implementation of heat pumps in both scenarios is based on the main assumption that heat pumps will replace the three fossil fuels forms (solid, liquid, gaseous) in proportions based on their relative use within each sector. The amounts of solid, liquid and gaseous fossil fuels, subcategorised into specific fuels, is taken from the Eurostat database [6].

The primary energy usage for the scenarios is determined from the process heat requirements, heat pump coverage and coupled with energy conversion efficiencies (COP, PEF_h ($1/\eta_{conv}$) and PEF_e) values. Values for the conversion of primary energy to final energy for combustible fuels are taken from Ref. [27] and presented in Table 2 with the assumption that all fuel sources in a given category have the same conversion efficiency. The primary energy calculated in this step is used in the calculation of the avoided fossil fuel use. Calculation of this value in the first scenario is non-trivial. It is determined on the basis that 29.6% of gross electricity consumption in EU28 is generated from renewable sources [41]. Under this assumption, and the additional assumption that the PEF_e of renewable electricity has a value of 1 in the first scenario, the avoided fossil fuel use can be calculated by Equation

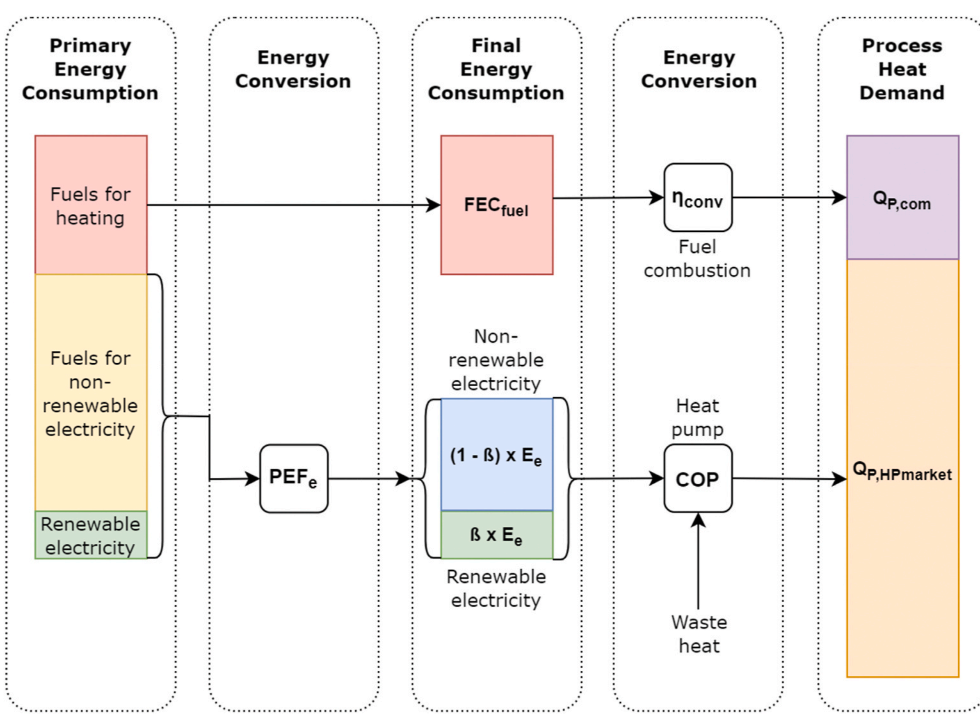

Fig. 4. Transformation from primary energy consumption to process heat demand for the new scenarios.

Table 2
CO_2 emission factors and conversion efficiency values used for various fuels [27, 42].

Product	Emission Factor, EF (t/TJ)	Energy Conversion Efficiency η_{conv} (−)
Solid fuels		
Anthracite	102.8	85%
Coking coal	99.7	
Other bituminous coal	99.4	
Sub-bituminous coal	100.8	
Lignite/Brown coal	104.2	
Coke oven coke	112.2	
Coal tar	85.8	
BKB	102.8	
Peat	108.3	
Peat products	108.3	
Oil		
Natural gas liquids	75.6	85%
Refinery gas	68.9	
LPG	78.1	
Motor gasoline (w/o bio)	87.2	
Other kerosene	83.3	
Naphtha	84.7	
Gas/Diesel oil (w/o bio)	85.0	
Fuel oil	88.9	
White spirit and SBP	84.7	
Petroleum coke	108.9	
Other products	84.7	
Gas		
Natural gas	66.7	90%
Coke oven gas	49.2	
Gasworks gas	49.2	
Other recovered gas	49.2	

(10) of Table 1.

Following the calculation of the energy saving potential, the CO_2 emission saving potential has been calculated for the two scenarios described. Based on the primary energy usage from each of the fossil sources in each sector, CO_2 emission factors are utilised to determine the emissions for the reference scenario. The CO_2 emission factors for fuels used are values specific to the Europe and are based on a life cycle assessment approach, which therefore accounts for emissions from the entire supply chain [42]. These CO_2 emission factors are also presented in Table 2.

For the two scenarios in which heat pumps are implemented, calculation of the CO_2 emissions in the various sectors is based on the calculated heat pump electrical energy use and the subsequent EU averaged CO_2 emission intensity for electricity generation. For the first scenario a value of 76.6 t/TJ (275.9 gCO_2/kWh) is utilised, taken from the European Environment Agency (EEA) for the year 2014 [43]. For the second scenario, the assumption is made that the electricity system is fully decarbonised, hence a value of 0 t/TJ is used. This, combined with the reduced fuel use in the various sectors and subsequent emission factors related to these fuels, allows an estimation of the reduction in CO_2 emissions for the two scenarios described.

3.3.2. *Investment needed to realise the market potential*

Investment costs for heat pump systems are usually derived by a representative cost per process heat output value (€/$\dot{Q}_P$, unit €/kW_P), also known as the heat pump specific investment costs. In addition to the cost of the heat pump itself, the investment cost also accounts for ancillary equipment, labour associated with the design and installation, as well as all costs associated with process integration. The vast difference in process applications and temperature levels as well as differing degrees of process integration means that there is no simple rule of thumb that can be utilised to accurately estimate the heat pump and integration costs. For the industrial case, the issue of integration will have a large influence on the achievable specific investment cost. This is particularly evident when comparing a greenfield application to the case of retrofitting an existing plant whereby large modifications to the process may be required, leading to significantly higher costs. Up until now, there are no studies which have attempted to quantify industrial heat pump costs based on a limited number of parameters using available market data (because it is such a small installed base). Such a statistical method is needed to accurately quantify the valuation based on the data generated.

Rather than use a detailed and complex statistical method, in this study, a simple approach is proposed to determine the valuation of the heat pump market based on range of specific investment costs for heat pumps taken from data in the literature. The simple approach presented is sufficient for this study to give indicative estimate to manufacturers looking to produce products for the market.

In a recent study by Meyers et al. [44], data was collated from various studies regarding the specific investment cost of heat pumps with heating capacities larger than 100 kW. It was noted that the cost varies greatly, however values were typically between €300/kW_P and €1000/kW_P with a reported industry average of €400/kW_P. Lower investment costs in the range of €200/kW_P to €250/kW_P were reported to be achieved for the case of China.

Rapid increases in technology development from manufacturers, suppliers and research facilities, combined with increase in installation and end-user experience will be drivers for the reduction in the price of industrial heat pumps over the coming years. For these reasons, within this study, valuation of the heat pump market is based on a heat pump and integration specific investment cost in the range of €200/kW_P and €500/kW_P.

This paper presents an estimation of the investment needed to realise the calculated market potential, however avoids business case calculations for individual heat pump applications and comparisons with alternative heating technologies due to the complexity of the subject. For information on this topic, the reader is referred to the work of Zühlsdorf et al. [45], where the business case analysis for two heat pump applications is presented including comparison with alternatives such as natural gas, biomass and biogas boilers.

4. Results and discussion

The calculated heating characteristics and heat pump market potential are presented and discussed in this section, based on the methodology of section 3. Firstly, the cumulative process and waste heat quantities are presented. Following this, the characteristics of the industrial heat pump market are given. Finally, the energy and CO_2 saving potential of the calculated industrial heat pump market and the investment needed to realise this market potential are quantified. It is noted that in this section, the results are not compared to other industrial heat pump market studies (as outlined in section 1), mainly due to the structural differences in methodology and results presented between studies, which prevent meaningful comparisons from being made.

4.1. *Process heat and waste heat availability and coverage*

The process heat demand as well as the waste heat availability have been characterised for the four industrial sectors in the temperature interval 15°C – 200°C (<200°C). Firstly, the data has been filtered to remove any process and waste heat outside the aforementioned temperature range. Following this, the numerous processes have been cumulated on both a sectoral and total industry level.

4.1.1. *Characterising process heat demand and waste heat availability*

The calculated process and waste heat quantities in EU28 are presented in Table 3 for the four sectors in the temperature interval

Table 3
Summary of cumulative process and waste heat in the temperature intervals <150°C and <200°C in EU28, identified in processes which make up the heat pump market study.

Sector	<150°C		<200°C	
	Process Heat Q_P (PJ/a)	Waste Heat Q_W (PJ/a)	Process Heat Q_P (PJ/a)	Waste Heat Q_W (PJ/a)
Paper	228	231	356	231
Chemical	295	320	355	337
Food	130	96	193	97
Refinery	92	393	219	465
Total (Σ)	**745**	**1039**	**1123**	**1130**

<200°C. For the interested reader, the process and waste heat quantities are also presented in the temperature interval <150°C within Table 3. The results in the temperature interval <150°C are relevant for the calculation of the industrial heat pump market up to this temperature (see section 4.2), however specific analysis of these numbers is omitted in this section.

In total, 1123 PJ/a of process heat and 1130 PJ/a of waste heat was calculated for the evaluated processes. The highest amount of process heat was calculated for the paper sector (356 PJ/a) and the chemical sector (355 PJ/a). Lower, but still substantial amounts were calculated for the food (193 PJ/a) and refinery sectors (219 PJ/a). In terms of waste heat quantities, the highest calculated values were found in the refinery (465 PJ/a) and the chemical (337 PJ/a) sectors, both of which are made up exclusively of the condenser utility in distillation processes. Significant waste heat sources were also identified in the paper (231 PJ/a) and the food sectors (97 PJ/a).

Regarding the process heat and waste heat values for each sector presented in Table 3, intuition may lead to the assumption that the presented values for each sector should be comparable, however this is not the case. For industrial processes, factors such as endothermic or exothermic reactions, electrical or mechanical energy input as well as conversion losses will lead to differences in waste heat and process heat quantities. In the current data set, this is further exacerbated by considering process and waste heat in a given temperature interval as opposed to the entire heat at all temperatures within the sector. This is evident for the case of the refinery sector, whereby the waste heat greatly exceeds the process heat amounts. This is a characteristic of the sector whereby there is large process heat demand at temperatures greater than 200°C, which is rejected from the process at temperatures lower than 200°C. For other sectors, such as the paper as well as the food sectors, whereby virtually all process heat in these sectors was found to be below 200°C, the balance is far from complete leading to the process and waste heat values once again not being comparable.

The distribution of process heat over the differing temperature levels is shown in Fig. 5. This figure illustrates the cumulative process heating requirements below a given temperature level for the four sectors. The refinery sector is characterised by process heating above 100°C. Despite the similar nature of the processes in the chemical industry, there is significant process heat demand (126 PJ/a, 35.6% of calculated heat demand <200°C) at temperatures lower than 100°C. Similar to the refinery sector, the paper sector has no process heating demand below 125°C. The heat demand in this sector is characterised by the requirement for steam at differing temperatures. For the food sector, limited process heating requirements less than 100°C (33 PJ/a, 17.1% of calculated heat demand <200°C) were identified for the products which were the focus of this study. A number of processes in this sector demand steam greater than 100°C as represented by step changes in the cumulative curve. The remainder of the heat demand in the food sector was primarily made up of sensible heat streams, leading to a distribution of the heating requirements up to 200°C.

As was the case with the process heating requirements, the distribution of waste heat over the differing temperature levels is shown in Fig. 6. This figure illustrates the cumulative waste heating available above a given temperature level for the four sectors. Only a minimal amount of waste heat, 220 PJ/a or 19.5% of the total waste heat <200°C is available above 100°C. Of the 220 PJ/a of waste heat available above 100°C, the majority (162 PJ/a, 73.8%) is from processes within the refinery sector, with limited amounts available in the chemical (53 PJ/a, 23.9%) and food sectors (5 PJ/a, 2.3%). For all sectors, the majority of the waste heat (764 PJ/a, 67.6% of calculated waste heat <200°C) falls in the interval of 40°C – 100°C. This result could be expected as the focus is mainly on processes which have process heating requirements in the interval of 100°C – 200°C. The waste heat sources in the 40°C – 100°C range are almost exclusively made up of (moist) air and condensate streams, which indicate the recovery of these streams should be the focus of heat pump integration. The heat is distributed relatively evenly amongst this temperature interval with the exception of the paper sector. Latent heat in the form of moist process air (with the heat taken at the dew point) primarily characterise the waste heat in these processes, leading to step like changes in the cumulative curve for this sector.

4.1.2. Process heat coverage of the bottom-up data

An effort is made to gain an indication of the process heat coverage that has been achieved in this study. As the focus was on processes in the temperature interval <200°C, comparison with Eurostat data reporting on all energy usage in the sector would be of limited insight. However, comparison with the study of Rehfeldt et al. [28] in the temperature interval considered in this study is possible with the exception of the

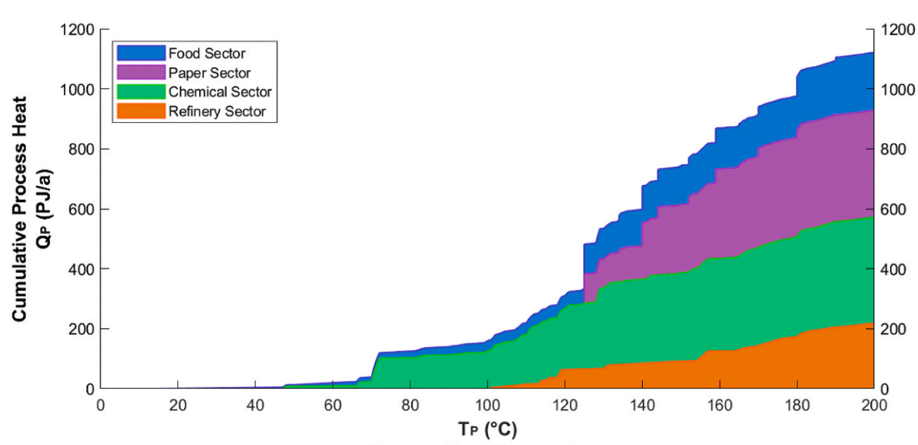

Fig. 5. Cumulative process heat <200°C in EU28 identified in processes which make up the heat pump market study.

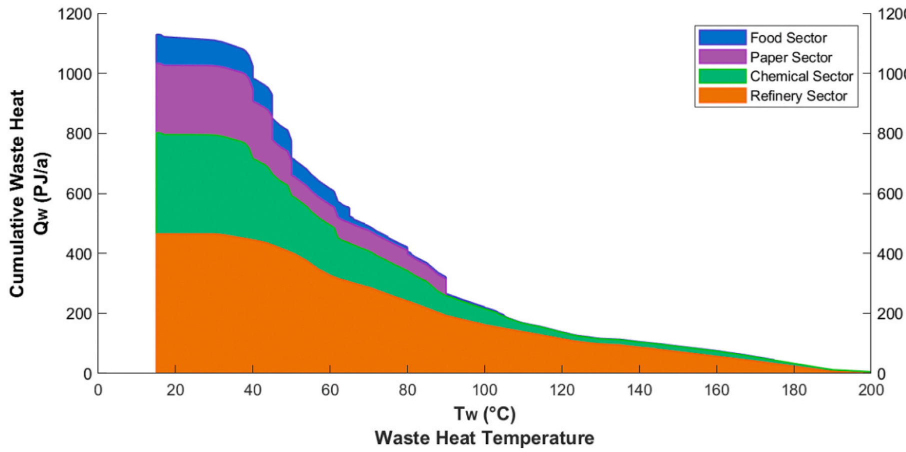

Fig. 6. Cumulative waste heat <200°C in EU28 identified in processes which make up the heat pump market study.

refinery sector. The bottom-up study of Rehfeldt et al. [28] considered processes of all temperatures and reported good coverage (≈106% – 111%) of the Eurostat energy balance in the sectors considered in this study, with the exception of the chemical sector which showed lower coverage (≈73%) attributed to large number of small processes not covered.

Fig. 7 presents the process heat demand as obtained by this study compared with the results of Rehfeldt et al. [28]. The results for the chemical sector compare well with only minimal deviation. For the paper sector, the difference is largely attributed to the large energy requirements in the Kraft and Sulfite processes, which are not accounted for in this study. Eurostat energy use statistics indicates the use of solid biomass in the sector, primarily used in these processes as being 534 PJ/a [6]. Accounting for this energy usage would bring the results of this study more in line with the Rehfeldt et al. [28] results. For the food sector, the low percentage of process heat accounted for relative to the Rehfeldt et al. [28] study indicates insufficient process coverage.

The results of this comparison gives an indication that the heat pump market potential calculated in this study for the paper and chemical sectors will be representative of the true potential. For the food sector, it is evident that further processes are needed to properly characterise the heat pump market potential. Conclusions are more difficult to make for the refinery sector for which data is not available. However, high coverage (79%) relative to the Rehfeldt et al. [28] study in the chemical sector in the given temperature interval, and the similar nature of the refinery sector, give an indication that the process heat coverage in the refinery sector should also be high, therefore leading to a representative estimation of the heat pump market potential.

4.2. *The industrial heat pump market potential*

Utilising the bottom-up methodology presented in section 3.2 applied to the 57 products or processes for which data has been collated, the market potential for industrial heat pumps has been calculated. The sections which follow quantify the calculated industrial heat pump market potential. Insights are given into the relevant heating capacities and temperature levels of heat pumps, giving targets for future technology development.

4.2.1. *Characterisation of the industrial heat pump market*

The calculated heat pump market potential is primarily characterised by the total number of heat pump units and the cumulation of their individual heating capacities. An overview of the industrial heat pump market potential for EU28 is presented in Table 4 for both sink temperatures up to 150°C and up to 200°C. For the market potential up to 150°C, the cumulative heating capacity was calculated to be 20.0 GW which can be installed over a total of 3229 heat pump units. For the market potential to 200°C, the cumulative heating capacity increases by 15% to 23.0 GW, however this can be installed over 4174 heat pump units, a relatively large increase of 29% in the number of units. As indicated previously, the market potential up to 150°C can be covered in the relative short term by pioneering developments from manufacturers, whilst research efforts to develop products to 200°C will take longer to be applied in the market. It is clear the added market potential for applications up to 200°C is not insignificant, and as such the authors would like to stimulate the creation of products up to this temperature. Therefore, the remainder of the analysis of the heat pump market potential is focused on applications up to 200°C. For this market, the largest potential in terms of cumulative heating capacity was found for the chemical sector (9.1 GW), followed by the paper sector (7.9 GW) and the food sector (5.5 GW). The refinery sector showed very low potential of only 0.5 GW.

A common assumption in the literature is that heat pumps are able to produce the entirety of the process heat up to their maximum supply temperature [13]. Whilst technically this may be possible, the heat coverage that could be achieved with heat pumps is less than the process heat identified <200°C. This can be attributed to a number of factors depending on the process. For the refinery sector, many of the process pinch points fell either above the reboiler temperature or below the

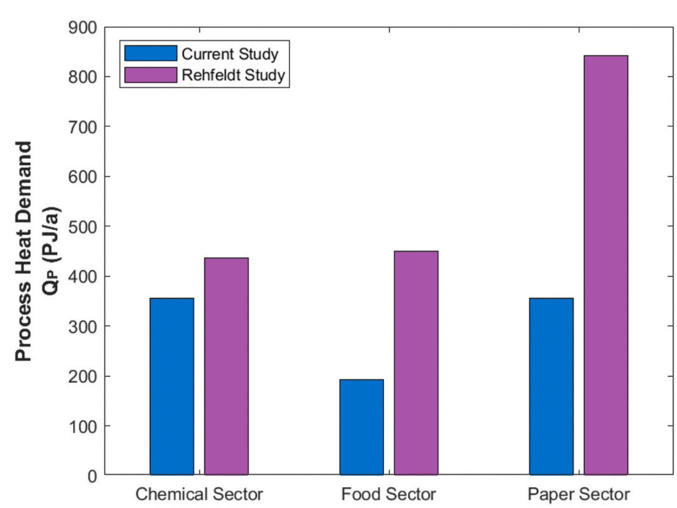

Fig. 7. The process heat demand calculated in this study in comparison with the Rehfeldt et al. study [28].

Table 4
Summary of the EU28 industrial heat pump market potential.

Heat pump market to 150°C					
Sector	**Cumulative Heating Capacity, $\dot{Q}_{P,HPmarket}$ (GW)**	**EU28 Heat Pump Units, $N_{HPmarket}$ (#)**	**Heat Pump Process Heat Coverage, $Q_{P,HPmarket}$ (PJ/a)**	**Electricity Requirement, $E_{e,HPmarket}$ (PJ/a)**	**Heat Pump Relative Process Heat Coverage, $Q_{P,HPmarket}/Q_P$ (%)**
Paper	6.6	938	203	78	89%
Chemical	8.1	1164	252	59	85%
Food	5.0	1107	83	25	64%
Refinery	0.3	20	9	4	10%
Total (Σ)	**20.0**	**3229**	**547**	**166**	**73%**
Heat pump market to 200°C					
Sector	**Cumulative Heating Capacity, $\dot{Q}_{P,HPmarket}$ (GW)**	**EU28 Heat Pump Units, $N_{HPmarket}$ (#)**	**Heat Pump Process Heat Coverage, $Q_{P,HPmarket}$ (PJ/a)**	**Electricity Requirement, $E_{e,HPmarket}$ (PJ/a)**	**Heat Pump Relative Process Heat Coverage, $Q_{P,HPmarket}/Q_P$ (%)**
Paper	7.9	1351	245	94	69%
Chemical	9.1	1291	283	65	80%
Food	5.5	1463	98	31	51%
Refinery	0.5	69	14	6	6%
Total (Σ)	**23.0**	**4174**	**641**	**195**	**57%**

condenser temperature or alternatively the temperature lift exceeded 100°C. In these cases, the process was excluded as a potential heat pump application. Despite the focus on distillation processes in both the chemical and refinery sectors, temperature lifts >100°C or out-of-bound pinch were not so prevalent for the case of the chemical sector, and as such significantly greater amounts (80%) of process heat in the interval <200°C could be covered with heat pump technology.

The heat pump coverage in the paper sector was also reduced to 69% due to numerous potential heat pump applications with prohibitively high (>100°C) temperature lifts. In these cases, modification of the process to either reduce the utility temperature or increase the dew point of the waste heat stream should be considered.

The relatively low coverage (51%) in the food sector, is partially attributed to the low calculation of technically retrievable waste heat, which was roughly 50% of the process heat requirements. In addition to this, in some cases temperature lifts which would exceed 100°C and thereby exclude a feasible heat pump application. Further applications were excluded for heat pump applications due to process temperatures which exceeded 200°C.

An overview of the characteristics of the individual heat pump units which make up the total industrial heat pump market potential is given in Fig. 8. Each data point indicates an individual heat pump unit applied to a given process or manufacture of a product, with the colour showing the relative sizing of each individual unit. As a process for the manufacture of a given product may have multiple heat pumps applied with different characteristics (temperature levels, heating capacity), the number of data points in Fig. 8 exceeds the number of processes for which data was collected. In many cases, there are overlapping data points due to a distribution of plant capacities implemented. The total heat pump market potential of 4174 heat pump units is made up of multiple instances of each of the individual heat pump units, depicted by the data points in Fig. 8.

The distribution of heat pump COP for the entirety of the 4174 heat pump units which make up the calculated heat pump market potential is presented with more clarity in Fig. 9. This figure shows the distribution of COP for each of the industrial sectors. It is evident that COPs in the range of 2 – 5 are typical, with 76.5% of applications occurring in this range. The overall COP of the industrial heat pump market

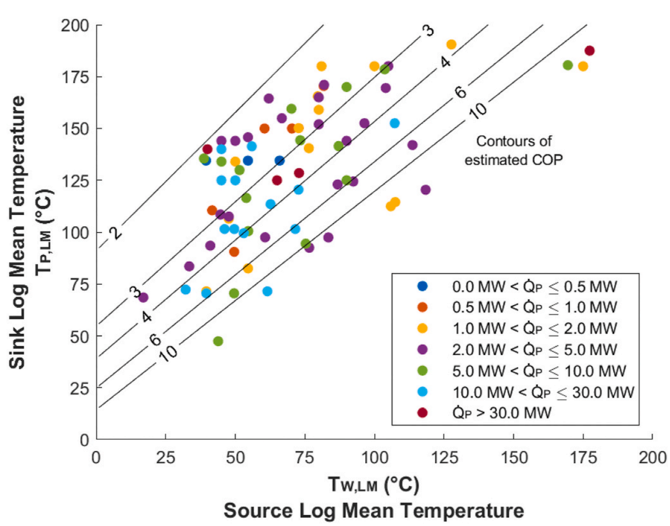

Fig. 8. Summary of the characteristics of the individual heat pump units which make up the total EU28 industrial heat pump market.

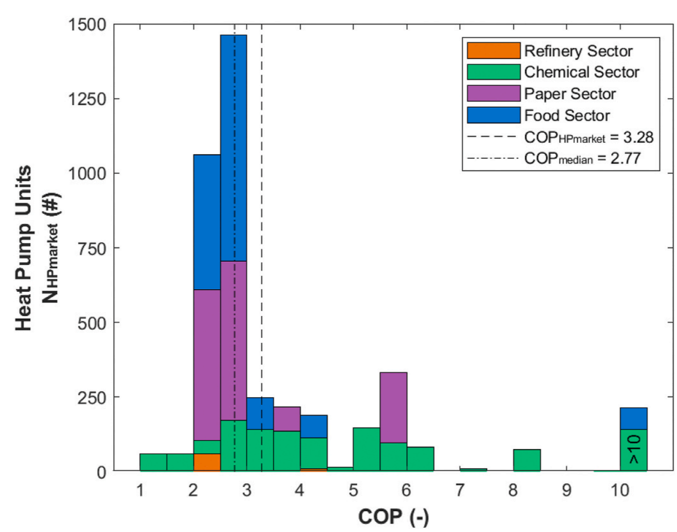

Fig. 9. Distribution of the COP for the heat pump units which make up the EU28 industrial heat pump market.

($COP_{HPmarket}$), calculated from the total heat pump process heat coverage and electricity requirement ($\Sigma Q_{HPmarket}/\Sigma E_{e,HPmarket}$, presented in Table 4), is well within the aforementioned range, with a value of 3.28. Similarly, the median COP of all 4174 heat pumps units was 2.77, meaning 50% of heat pump units will have a COP at or greater than this value. The lower median COP of the individual heat pump units relative to the overall COP of the heat pump market is attributed to small numbers of heat pump units with large heating capacities and high COPs that raise the overall COP.

The focus in this study on residual heat streams for heat pump integration leads to higher temperature lifts and lower COPs when compared with a situation whereby placement of the heat pump in the process network has been thermodynamically optimised. By considering process integrated heat pumps which operate closer to the required process temperatures, higher COPs would be expected. This aspect will improve the economics, however it does not change the thermal capacity of individual applications, nor market size.

4.2.2. Distribution of heat pump heating capacities

The distribution of the heating capacities of the heat pump units which make up the industrial heat pump market is expected to contain useful information for the manufacturers of industrial heat pumps. Fig. 10 presents a histogram with the number of heat pump units in a specific heating capacity range. Also shown is the percentage of total heat pump units which are at or larger than a given heating capacity (red descending line). Clearly, the largest number (3675, 88.0%) of heat pump units can be found for heating capacities <10 MW. The small number of heat pump units with high heating capacities (>10 MW) lead to a total market averaged heating capacity ($\Sigma\dot{Q}_{P,HPMarket}/\Sigma N_{HPMarket}$) of 5.5 MW, whilst the large number (1725, 41.3%) of heat pump units <2 MW in size means the median heating capacity of the 4174 heat pump units is significantly lower (3.0 MW).

Fig. 11 shows a histogram of the cumulative heating capacity from heat pump units in a specific heating capacity range. Similar to Fig. 10, the percentage of total cumulative heating capacity which is covered by heat pumps at or larger than a given heating capacity is shown (red descending line). It can be seen that the 3675 heat pump units <10 MW make up about 48% of the total cumulative heating capacity, with the remaining 52% made up of the small number (499) of larger (>10 MW) heat pump units. It is clear from Fig. 11 that heat pump units for both segments are needed in order to cover the total market potential. Units with a heating capacity <10 MW need to be produced in series to benefit from the economies of scale in their manufacturing. Units with a heating capacity >10 MW are relatively small in numbers, but can benefit from the economy of scale based on their large capacity.

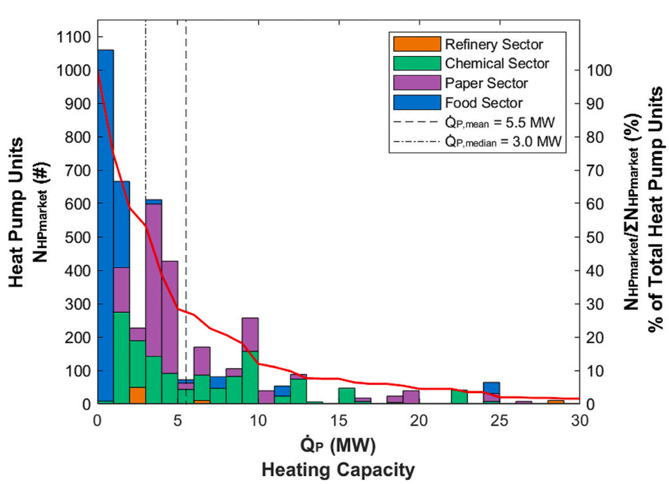

Fig. 10. Distribution of the heating capacity (<30 MW) for the heat pump units which make up the EU28 industrial heat pump market.

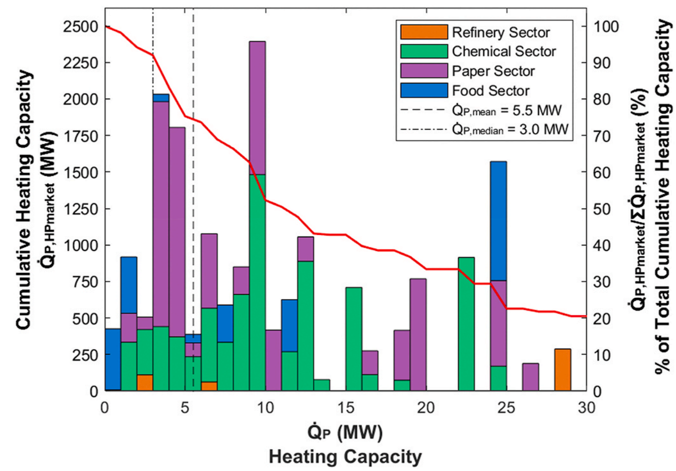

Fig. 11. Distribution of heating capacity (<30 MW) for the cumulative heating capacity of heat pump units which make up the EU28 industrial heat pump market.

The <10 MW heating capacity market segment should be characterised by cost effective standardised solutions that can easily be incorporated into the process. On the other side, the heating capacity market segment >10 MW should be characterised by bespoke solutions dedicated to the specific application.

4.3. Savings and required investments of the industrial heat pump market

This section quantifies the energy and CO_2 saving potential of the calculated industrial heat pump market as well as the investment needed to realise this market potential. This is calculated using the methodology presented in section 3.3, with the total estimated market potential to 200°C used for this quantification.

4.3.1. Energy and CO_2 saving potential

The energy and CO_2 emission savings potential for two scenarios are presented in Table 5. As indicated, scenario 1 is representative of implementing heat pumps in which the energy system is fundamentally unchanged compared to the current situation, whereas scenario 2 represents the best case for heat pumps, that is, a scenario whereby the energy system is fully decarbonised.

It has been calculated that the final energy consumption in the four sectors which make up this study could be reduced by 528 PJ/a through application of heat pumps in the identified processes. The final energy reduction is highest in the chemical sector, with 256 PJ/a being achievable. Reductions in final energy consumption in the paper, food and refinery sectors were calculated to be 182 PJ/a, 80 PJ/a and 11 PJ/a respectively.

In addition to reduction in final energy consumption, both scenarios resulted in reductions in primary energy consumption, CO_2 emissions and fossil fuel energy use for all of the sectors investigated. In scenario 1, primary energy use can be reduced by 313 PJ/a, equivalent to approximately 371 PJ/a of avoided fossil fuel energy use. This results in a calculated reduction in 37.3 Mt/a of CO_2 emissions. In the second scenario, whereby the electricity system is fully decarbonised, primary energy consumption can be reduced by 528 PJ/a. This represents a reduction in the 724 PJ/a of fossil energy which could result in 52.6 Mt/a lower CO_2 emissions.

As expected, significant reductions in both the primary energy consumption (−215 PJ/a, −68.6%) and CO_2 emissions (−15.3 Mt, −41.0%) are seen when comparing scenario 1 to scenario 2. This reinforces the future proof credentials of heat pump technology which will further benefit from transition towards an electricity system made up of

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Table 5
Summary of the calculated industrial heat pump energy and CO_2 saving potential.

Sector	Scenario 1 & 2	Scenario 1			Scenario 2		
	FEC Reduction, $FEC_{red(1,2)}$ (PJ/a)	PEC Reduction, $PEC_{red(1)}$ (PJ/a)	CO_2 Reduction, $CDE_{red(1)}$ (Mt/a)	Avoided Fossil Fuel Use, $AFF_{(1)}$ (PJ/a)	PEC Reduction, $PEC_{red(2)}$ (PJ/a)	CO_2 Reduction, $CDE_{red(2)}$ (Mt/a)	Avoided Fossil Fuel Use, $AFF_{(2)}$ (PJ/a)
Paper	182	79	12.8	107	182	20.0	276
Chemical	256	184	18.4	203	256	23.4	321
Food	80	46	5.2	55	80	7.9	110
Refinery	11	5	0.8	6	11	1.2	17
Total (Σ)	**528**	**313**	**37.3**	**371**	**528**	**52.6**	**724**

Table 6
Investment required to realise the EU28 industrial heat pump market potential.

Sector	Cumulative Heating Capacity, $\dot{Q}_{P,HPmarket}$ (GW)	Lower Bound Investment (G€)	Upper Bound Investment (G€)
Paper	7.9	1.58	3.95
Chemical	9.1	1.82	4.55
Food	5.5	1.10	2.75
Refinery	0.5	0.10	0.25
Total (Σ)	**23.0**	**4.60**	**11.50**

primarily renewable sources.

4.3.2. Required investments for the industrial heat pump market

The investments required to realise the calculated industrial heat pump market potential in this study is presented in Table 6. Considering a cost for end-users in the range of €200-€500/kW_P, this requires an investment in the order of €4.60 billion – €11.50 billion to realise the industrial heat pump market for the processes identified. Based on this conservative value, it is evident that there exists significant opportunities for heat pump manufacturers to develop products specific to the industrial market. The requirement exists for new manufacturers to establish themselves in this market segment through development of cost effective heat pump products which have the capabilities to fulfil this market potential.

5. Conclusion

This study utilised a bottom-up approach to estimate the European (EU28) industrial heat pump market potential in terms of magnitude, sizing and number of units. The focus was on identifying potential heat pump applications considering a maximum sink temperature of 200°C. The market potential was calculated in the chemical, paper, food and refinery sectors, identified as being most suitable for heat pump integration due to large process heat demand <200°C.

To determine the industrial heat pump market, specific heat use and temperature data was sourced for a number of high energy consuming processes within the aforementioned sectors. Combining with other data such as plant size distribution and production statistics, the heat pump potential could be determined for the manufacture of various energy intensive products. For the four sectors combined, 1123 PJ/a of process heat and 1130 PJ/a of waste heat was accounted for in the temperature interval <200°C. It was determined that for the paper, chemical and refinery sectors, the data gathered was representative of the heat pump opportunities in those sectors. For the food sector, more processes are needed to increase the process heat coverage and give a representative overview of the actual heat pump market potential.

For the industrial heat pump market potential up to 150°C, the cumulative heating capacity was calculated to be 20.0 GW spread over 3229 heat pump units. Considering the market up to 200°C, which remained the focus of this study, a 15% increase in cumulative heating capacity to 23.0 GW was calculated, which resulted in a relatively large (29%) increase in the number of heat pump units to 4174. The median COP of the calculated heat pump market to 200°C was 2.77. Heat pumps up to 200°C were able to cover 641 PJ/a of process heat in the four sectors combined, with the largest opportunities in the chemical (283 PJ/a) and paper (245 PJ/a) industries. The market was divided into two segments: one with heating capacities smaller than 10 MW in which standardised units should be used, and one with heating capacities larger than 10 MW in which bespoke solutions can be implemented.

This study has also quantified the energy and CO_2 saving of the calculated industrial heat pump market as well as the investments needed to realise the market potential. In an ideal situation when the electricity system is fully decarbonised, the annual primary energy savings achievable were calculated to be 528 PJ/a, leading to CO_2 emission reductions of 52.6 Mt/a. The required investment needed to realise the calculated heat pump market potential was estimated to be in the range of €4.60 billion – €11.50 billion, clearly indicating the opportunities for heat pump manufacturers developing products for this market.

As this study utilised a bottom-up approach, taking into account a limited number of generic processes within a limited number of industrial sectors, with heat pumps integrated mainly on a utility level, the calculation of the heat pump market potential as well as the associated energy saving, CO_2 saving and required investment are all conservative in nature. Future work on this topic should be focused on achieving results which better reflect the true potential of the heat pump market. This should be primarily achieved by including more processes in the analysis, as well as additional sectors not considered in this study which have significant potential (non-metallic minerals, machinery and transport sector, iron and steel sectors). Furthermore, above and below pinch processes as well as heat pump applications with higher sink temperatures and temperature lifts should be considered for inclusion in the calculated heat pump market potential.

The aim of this research study was to provide technology suppliers and manufacturers of industrial heat pumps perspectives for the technology. It is expected that the main outcome of these results is a new focus from manufacturers on development of heat pumps with sink temperatures which approach 200°C, particularly standardised low cost designs for the market segment <10 MW. Furthermore, this study should stimulate research from end-users into the feasibility of integrating heat pumps into their process. These steps will indeed assist in accelerating the uptake of heat pump technology into the industrial sector in the coming years.

Credit author statements

Andrew Marina: Conceptualization, Methodology, Investigation, Formal Analysis, Data Curation, Visualization, Writing – Original Draft. **Simon Spoelstra:** Conceptualization, Methodology, Investigation, Writing – Original Draft, Funding Acquisition, Project Administration. **Herbert A. Zondag:** Conceptualization, Methodology, Investigation, Formal Analysis, Writing – Review and Editing. **Anton K. Wemmers:** Conceptualization, Methodology, Investigation, Formal Analysis, Writing – Review and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The dataset related to this article can be found at https://doi.org/10.17632/gyxjmvzbx8.1, an open-source online data repository hosted at Mendeley Data [29].

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