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Bridging Data Gaps for Industrial Heat Pump Deployment: A Sector-Based Approach Using NACE Classification

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Abstract

Heat demand below 200 °C in buildings and industry remains a major contributor to natural gas use and associated greenhouse-gas emissions in Germany. High-temperature heat pumps (HTHPs) offer a technically mature option to decarbonize this demand, but deployment is slowed by limited availability of plant-level information, including load profiles, process temperatures and waste-heat characteristics. This paper presents an outside-in screening method that identifies HTHP opportunities using only public statistics and sector classifications.

Industrial activities are referenced through the NACE Rev. 2 classification (the EU's Statistical Classification of Economic Activities). Sectoral energy balances and process-level energy distributions are taken from JRC-IDEES (the Joint Research Centre's Integrated Database of the European Energy System), which reports harmonized energy-carrier splits for EU industry. The method links Eurostat employment statistics with IDEES energy data to scale sectoral final energy to representative site sizes. Temperature levels, operating hours and typical waste-heat streams are compiled from technical literature. A best-practice database provides source and sink temperatures, temperature lifts and capacities from realized HTHP projects; where no case exists, standard integration schemes are applied and the COP is estimated for the corresponding source and sink temperatures using an empirical correlation.

The approach is demonstrated for the pulp and paper sector. The scaled energy intensities per employee, thermal loads and waste-heat characteristics are consistent with values reported by industry associations, sustainability reports and documented HTHP demonstrators. The screening also identifies process-specific waste-heat streams, supporting the early assessment of suitable heat sources and integration points.

Overall, the results show that even with limited public data, an outside-in approach can indicate dominant energy-intensive processes, characteristic temperature levels, associated waste-heat potentials and plausible HTHP integration schemes. The workflow provides a transparent and reproducible basis for identifying promising industrial sites and supporting early-stage design and energy-system analysis.

Keywords: High-temperature heat pump; industrial process heat; NACE sectors; waste-heat assessment

1. Introduction

Heat below 200 °C in buildings and industry still drives most of Germany's natural gas demand and a large share of national greenhouse-gas emissions. Decarbonizing this temperature band is therefore pivotal. High-temperature heat pumps (HTHPs) can supply process-relevant temperatures efficiently while coupling heat production to an increasingly renewable power system. Yet market uptake remains slow, because beyond the persistent gas-to-power price spread, adoption is hindered by heterogeneous processes, diverse temperature requirements, and limited experience with system integration.

Existing studies already quantify the HTHP opportunity. For Germany, Wolf's [1] top-down analysis concludes that existing heat-pump technology could technically supply around 23 % of industrial process-heat demand. When economic boundary conditions are taken into account, the economically realizable potential amounts to approximately 3.4 %. At the EU-28 level, Marina [2] estimates an industrial heat-pump market of roughly 23 GW that could supply up to 641 PJ per year of process heat at temperatures at or below 200 °C, with most applications below 10 MW. TIMES-based modeling by Obrist [3] shows profitable deployment in Switzerland's food and beverage as well as pulp and paper sectors. Technology mapping narrows the addressable share: Kosmadakis [4] reports an EU industrial HTHP potential of 102.1 PJ per year, corresponding to about 15 % of heat consumption in the 100 to 200 °C range and roughly 1.5 % of total industrial heat. Arpagaus [5] identifies about 113 PJ in the 100 to 150 °C range as particularly accessible for industrial HTHPs.

On the supply side, unavoidable process heat generates waste-heat streams that represent an ideal source for heat pumps. Studies consistently distinguish theoretical, technical, and economic waste-heat potentials. Cross-country syntheses highlight proportionality between industrial energy use and waste heat, but also substantial methodological variation and a need for standardized reporting [6]. Method reviews place total industrial waste-heat potentials in Germany broadly in the range of 12 to 40 % of final industrial energy consumption [7]. Sector-spanning surveys classify waste-heat resources by temperature grade and technology route, with high-grade waste heat accounting for roughly half of the total resource [8]. Regional and national studies provide additional detail. For Baden-Württemberg, combined top-down and bottom-up assessments estimate an industrial HTHP potential of 5.4 to 9.3 TWh per year, corresponding to around 9 to 15 % of the state's industrial process-heat demand. The potential is concentrated in a relatively small number of large waste-heat sources that are predominantly suitable for on-site integration [9]. New mandatory reporting on waste-heat sources above 2.5 GWh per year shows strong spatial overlap between industrial emitters and urban demand zones [10]. At the same time, surveys reveal that although many enterprises already recover some waste heat, most cannot quantify annual volumes, which underscores the need for standardized data collection and transparent reporting [11].

Translating potential into projects relies on proven integration schemes and reference plants. Standardized layouts [12] and a growing set of best-practice cases, including steam-generating heat pumps (IntSGHP), multi-energy system integration [13], and projects such as eeethos, SPIRIT, and Push2Heat, provide actionable design archetypes.

Two cross-cutting gaps remain. First, there is no widely available set of industrial load profiles that would allow robust matching of heat-source availability, temperature levels, and HTHP operation. Only isolated datasets exist for industrial load profiles, and their limited coverage does not yet allow broad or systematic application. Early open-data efforts (e.g., fFf Open Data Portal) and synthetic-profile methods [14] are promising approaches. Second, many assessments depend on plant-internal information that external analysts rarely possess at the scoping stage.

This paper focuses on the following question: How much decision-grade information about HTHP potential can be obtained from an outside-in assessment before detailed site audits? We propose a fast, transparent workflow that combines sector statistics, process classifications and reported waste-heat data to produce first-order, process-specific opportunity maps. The method links end energy by carrier to process classes, assigns representative temperatures, and scales from NACE sector totals to typical site sizes where energy-intensive processes are flagged. We retrieve process-level temperatures and loads and match them to integration archetypes and best-practice cases. We then validate the screening outputs against public company reports.

2. Methods / Approach

The goal is a rapid, outside-in screening that identifies where high-temperature heat pumps (HTHPs) are most promising before any site visit. The workflow links official statistics with process classifications, temperature archetypes, and reported waste-heat data. Industrial sectors are referenced using the NACE Rev. 2 classification (Statistical Classification of Economic Activities in the European Union). Sectoral energy balances and process breakdowns are taken from the JRC-IDEES database (Joint Research Centre – Integrated Database of the European Energy System), which reports final energy consumption and process-level energy distributions for EU industry. The analysis relies on the following publicly available data sources:

- Eurostat energy statistics (final energy by NACE sector and carrier) [15]
- Eurostat structural business statistics (enterprises and employment by size class) [16]
- JRC-IDEES (energy carrier splits and process-level energy shares) [17]
- BREF documents (typical operating hours and process characteristics) [18]
- Sectoral and technical literature (temperature ranges, waste-heat streams)
- Demonstrator and sustainability reports (measured process data and realized HTHP performance)

Figure 1 illustrates which data are aggregated at the process level and how these can be linked, through the NACE mapping, to best-practice examples and integration schemes. Figure 2 shows the datasets used to derive company-level information and how they are combined within the data pipeline.

The sectoral energy dataset draws on Eurostat's annual energy statistics and the JRC-IDEES database, both of which report final energy consumption by sector and by carrier. To ensure consistency with the most recent IDEES release, 2021 is adopted as the reference year and all values are harmonized across carriers. While Eurostat provides final energy at the NACE Rev. 2 Level-2 resolution, JRC-IDEES consolidates several of these NACE classes into broader industry categories. The corresponding aggregations are listed in Table 1 and form the basis for transferring the IDEES process breakdown to the underlying NACE structure used in this work.

Table 1. Aggregation of NACE Rev. 2 classes within JRC-IDEES industry sectors

JRC-IDEES Sector	NACE
Chemical industry (CHI)	C20, C21
Pulp, paper and printing (PPA)	C17, C18
Food, beverages and tobacco (FBT)	C10, C11, C12
Transport equipment (TRE)	C29, C30
Textiles and leather (TEL)	C13, C14, C15
Other industrial sectors (OIS)	B, F, C22, C31 C32

To scale sectoral final energy to representative facilities, Eurostat structural business statistics are used to obtain the number of enterprises and persons employed EMP_{sector}. The approach assumes that the indicative final energy consumption of a site is proportional to its share of sectoral employment and to the distribution of energy carriers and processes within the corresponding IDEES sector. The sectoral final energy of an IDEES category is denoted as E_{sector}, while EMP_{site} describes the number of employees of the facility under consideration.

The allocation of site-level energy by carrier follows Equation (1). Here, $E_{site,i}$ denotes the annual final energy associated with carrier i, and $s_{carrier,i}$ represents the carrier share within the IDEES sector. This share expresses the percentage contribution of each energy carrier to the sector's total final energy.

The process-specific load is obtained using Equation (2). In this expression, $\dot{Q}_{process,i,j}$ denotes the average load of process j attributable to carrier i, $s_{process,j}$ is the share of sectoral final energy consumed by process j, and n denotes the typical annual operating hours of that process. These operating hours are taken from BREF documents (Best Available Techniques Reference Documents) and sectoral publications, which provide representative values for the respective industrial activities. The process share therefore reflects the relative distribution of energy across the IDEES process categories.

For completeness, Equation (3) defines the sectoral energy intensity E_{EMP}, which expresses final energy per employee within the corresponding IDEES sector.

The parameters $s_{carrier,i}$ and $s_{process,j}$ are derived from the energy balances and process breakdowns reported in JRC-IDEES.

$$E_{site,i} = E_{sector} * \frac{EMP_{site}}{EMP_{sector}} * s_{carrier,i} \quad (1)$$

$$\dot{Q}_{process,i,j} = \frac{E_{site,i} * s_{process,j}}{n} \quad (2)$$

$$E_{EMP} = \frac{E_{sector}}{EMP_{sector}} \quad (3)$$

In several industrial sectors, a substantial share of enterprises falls into the smallest Eurostat size class (0–19 employees). When company-level data are unavailable and average values per enterprise are used as proxies, these micro-enterprises can strongly distort the implied distribution of plant sizes and lead to unrealistically small representative facilities. To mitigate this effect, the enterprise statistics can be analyzed by size class and restricted to categories that better reflect energy-relevant production sites. Industry associations and sectoral reports often apply similar thresholds, commonly considering only enterprises with twenty or more employees. Applying such a size filter yields more representative average enterprise sizes for the purpose of estimating site-level energy use.

The top-down accounting is complemented by a process library compiled from the technical literature. For each industrial process, temperature ranges rather than single values are retained in order to capture the variability caused by different products, operating conditions and technologies. The library is aligned with the IDEES process labels and the corresponding NACE codes, which allows each segment of the top-down energy balance to be associated with a realistic temperature band and a representative process unit.

For each candidate process, representative source and sink temperatures are specified. Sink temperatures are derived from published process data and sectoral studies. Consolidated overviews of typical temperature ranges can be found in [5], [19] and [20].

The best-practice library contains documented high-temperature heat pump applications and established integration schemes. Published case studies typically report the coefficient of performance (COP), heating capacity and the corresponding source and sink temperatures. These data are linked to the relevant integration concept and assigned to the associated NACE categories and process types. If a COP is not reported, it is estimated using the empirical correlation presented in [20] in Equation (4), which is based on analyzed high-temperature heat pump data.

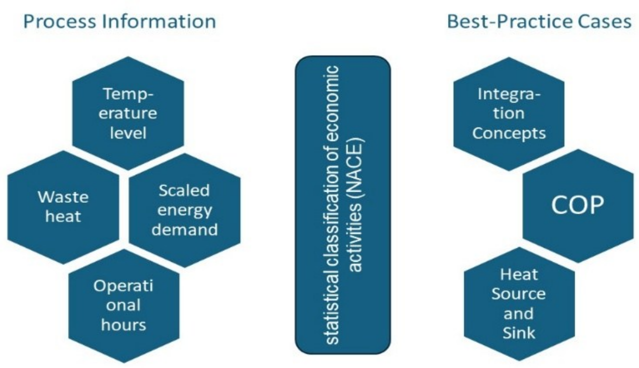

Figure 1. Information blocks used for outside-in screening: process information (temperature level, scaled energy demand, operational hours, waste heat) and best-practice cases (integration concepts, heat source/sink, COP), linked through NACE classification.

$$COP_H = 68.455 * \Delta T_{Lift}^{-0.76} \tag{4}$$

The outside-in estimates are validated against public sustainability reports and realized high-temperature heat pump demonstration projects. The energy use per employee is compared with sectoral averages and published case studies in order to verify that the implied site-level energy intensities fall within realistic ranges. In addition, the downscaled process loads are checked for plausibility by benchmarking them against reported capacities of existing demonstrators. The purpose of this validation is not to reproduce the performance of any individual plant but to ensure that the screening framework yields results of the correct order of magnitude.

Three sources of uncertainty propagate through the workflow. First, the sector-to-site scaling introduces uncertainty because the distribution of plant sizes is not fully captured by employment or enterprise statistics. Second, process temperatures and required steam levels vary within and across sites, which affects both the feasible integration schemes and the required temperature lift. Third, the carrier and process shares derived from IDEES represent sectoral averages and may not reflect the specific energy mix or process configuration of individual facilities.

The data used in this workflow are grounded in practice-oriented values rather than purely theoretical estimates. Reported energy and waste-heat figures from companies reflect measured consumption and are therefore directly comparable to operational conditions. Real-world installations are included as best-practice examples, which ensures that the derived parameters represent technologies and integration schemes already demonstrated in industry. Whenever new evaluations or documented demonstration results become available, they are incorporated to refine the database and to maintain its relevance for current industrial practice.

At present, the available waste-heat information is predominantly reported at the sectoral level rather than for individual processes. Ongoing efforts to expand national and regional waste-heat inventories, such as the

German “Plattform für Abwärme (PfA)”, will gradually improve the level of detail in reported waste-heat characteristics. As these datasets become more comprehensive, they can be used to enhance the quality of process-specific assumptions and strengthen the empirical basis of the screening framework.

3. Results and Discussion

To assess the validity of the scaled energy estimates, the results were benchmarked against publicly available sustainability reports in which companies disclose their total energy consumption and its distribution by energy carrier. These reports are used to verify whether the scaling from Eurostat sectoral data to the

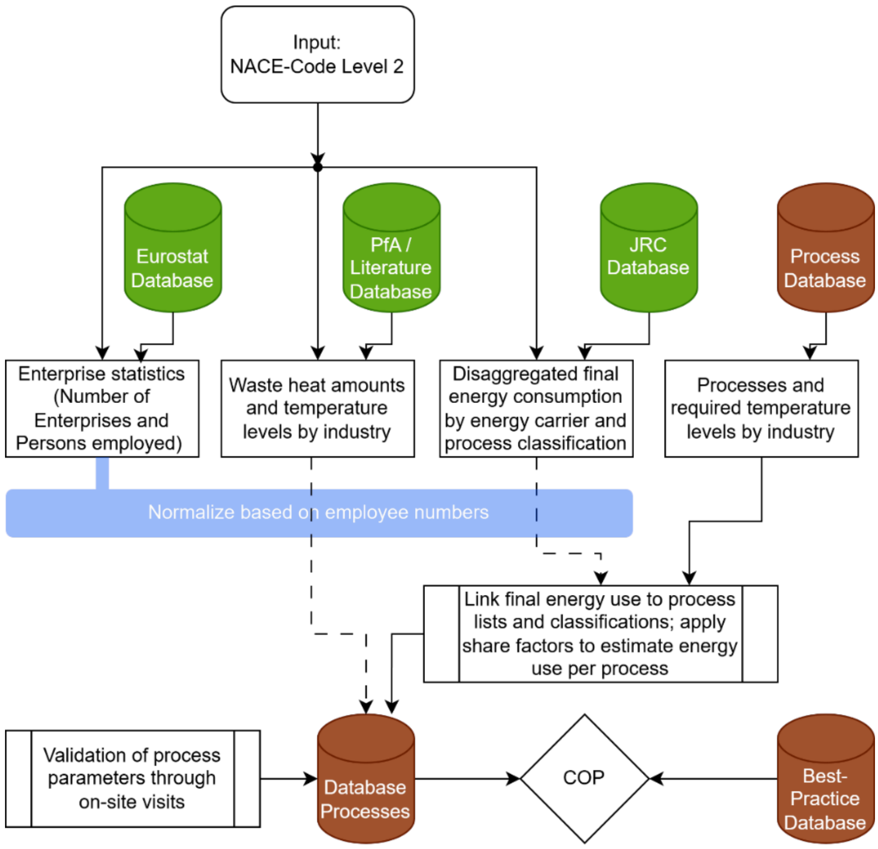

Figure 2. Data pipeline. Inputs: Eurostat (energy by carrier, enterprise statistics), JRC-IDEES (process shares), and a process library. Steps: normalize by employees, link carriers to process classes, apply share factors, assign temperatures, and match to integration archetypes and COP. Outputs: process-level energy, power, temperature bands, waste-heat, and candidate integration schemes. Validation is performed against company reports and on-site data where available.

company level yields realistic orders of magnitude. Eurostat and JRC-IDEES provide harmonised datasets that can be filtered by country and year across Europe. In this study, Eurostat data were selected specifically for Germany. The workflow is demonstrated using the pulp and paper sector as a detailed example from screening to design, with bottom-up cross-checks performed for Germany.

Because the JRC updates the IDEES database on a decadal cycle, the most recent reference year currently available is 2021. In Eurostat, the paper industry is separated into two subsectors, namely C17.1 (Manufacture of pulp, paper and paperboard) and C17.2 (Manufacture of articles of paper and paperboard). To verify the representativeness of the underlying energy data, the sector’s total energy consumption was normalized by the number of employees, which results in an annual energy use of approximately 1,545 MWh per employee. A comparison with figures reported by the German industry association [21] shows close agreement, with an average of around 1,530 MWh per employee and year. This correspondence indicates that the underlying energy and employment statistics provide a consistent basis for the scaling procedure.

The JRC-IDEES database provides a detailed breakdown of energy use within the NACE category, including the distribution across processes and the mix of energy carriers. Figure 3 illustrates the annual thermal energy input by carrier at the sector level. Pulp and paper production is further divided into stock preparation, the paper machine, product finishing and pulping. General consumption for lighting, air compressors, motors, pumps and low-enthalpy heating, as well as processes that are not disaggregated by energy carrier, such as wood preparation, grinding and cleaning, are not included in the chart.

The paper machine accounts for 58.1 % of the sector's fuel and heat use, or 67.9 % when electricity is included. The Sankey diagram displays only the fuel and heat input by carrier that is associated with steam generation. This representation aligns well with the approximately 70 % share of total energy demand attributed to drying processes, as reported by EHPA and CEPI [24].

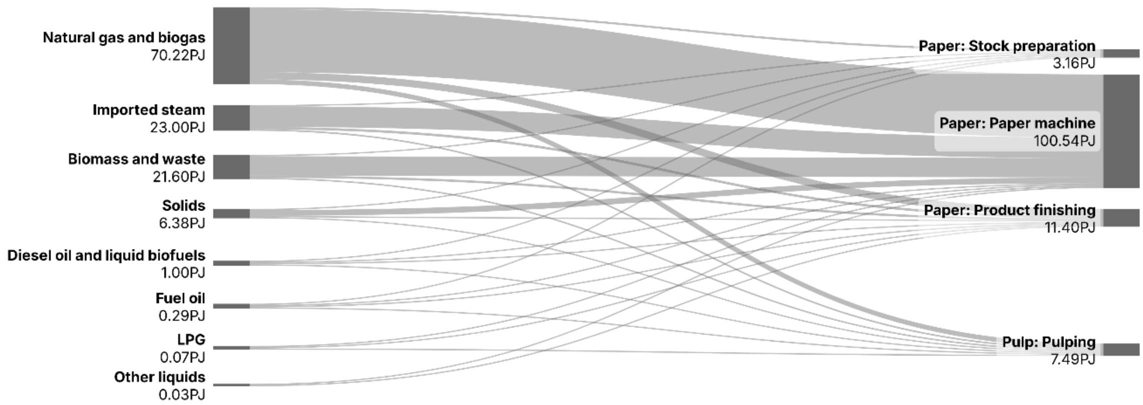

Figure 3. Energy flow diagram of thermal energy input by energy carrier in the pulp and paper industry (NACE C17.1), based on JRC-IDEES data.

3.1. Paper manufacturing

To convert the annual energy consumption of the paper machine into an average thermal and electrical load, the total energy use is divided by the annual operating hours. According to TAPPI [23], modern paper machines achieve an uptime of approximately 94 %, which corresponds to about 8,234 operating hours per year. Dividing the sectoral thermal energy attributed to paper machines by the number of operating paper machines in Germany (248) [21] yields an average thermal load of 16.6 MW per unit. This estimate is consistent with the values reported by DIE PAPIERINDUSTRIE e. V. [21] and the Confederation of European Paper Industries (CEPI) [22]. Based on average paper output per tonne and the associated specific energy consumption, the resulting average paper machine load falls within a range of 15.9 MW [21] to 20.2 MW [22]. A second plausibility check uses company-level data from six paper mills. The final energy consumption and the number of operating paper machines were taken from the sustainability reports of the companies listed in Table 2, and the corresponding thermal loads were calculated using the method described above. Across these six mills, the resulting average thermal load of the paper machines is 25.8 MW, and the average final energy use per employee is 1,752 MWh per employee and year.

These values are consistent with the previously established sectoral benchmarks. The somewhat higher loads observed in the company sample are plausible because the mills in Table 2 are substantially larger than the average facilities represented in Eurostat statistics, which include many small enterprises operating smaller machines. Deviations between company-level and sector-average indicators are therefore expected and remain within a realistic and meaningful range.

Table 2. Company level data from paper mill sustainability reports

Paper mill and reporting year	Employees	Average thermal load of paper machine (MW)	Average energy use per employee (MWh per employee)
PKV – Varel (2023)	600	29.4	2,353
Steinbeis – Glückstadt (2023)	362	24.2	1,605
Model – Eilenburg (2023)	240	21.8	1,091
Sappi – Ehingen (2024)	520	19.3	2,232
Hamburger Containerboard Dunaújváros (2024)	440	41.8	2,284
Essity – Ortmann (2024)	469	18.5	947

The exact energy demand depends strongly on product type and raw material input, since paper production based on virgin fibers is considerably more energy-intensive than production from recovered paper. The values presented here should therefore be interpreted as indicative magnitudes for energy-intensive units rather than as fixed design loads.

Based on JRC-IDEES, about 87 % of the paper machine's final energy is used for steam applications. The steam-use share is largely supplied by natural gas and biogas at roughly 50 %, followed by biomass and waste at 15 % and solid fuels at 5 %, while 16 % is delivered as purchased steam from outside the site. Due to this high dependence on steam, the paper machine accounts for around 86 % of total CO_2 emissions in paper production, making it the most significant lever for decarbonization in the sector.

Designing a high-temperature heat pump concept requires an understanding of the thermodynamic characteristics of the underlying process, particularly whether it exhibits a temperature glide or operates at a constant temperature as in systems based on phase-change processes. Standardized temperature ranges from the literature are therefore used to define the boundary conditions for each process. For the most common paper machine configuration, the multi-cylinder dryer, cylinder surface temperatures typically range between 50 °C and 140 °C [25]. Achieving high mechanical strength and energy efficiency requires individual temperature control of each roll, which leads to this broad distribution of operating temperatures. Typical supply steam pressures are in the range of 1 to 9 bar, corresponding to sink temperatures of approximately 180 °C.

On the source side, the hood-exhaust air provides a large and steady waste-heat stream with a dew point of around 60 °C, as reported by EHPA and CEPI [24]. Based on these temperature levels, a representative heat-pump capacity can be estimated. Together with the thermal load of the paper machine, this allows the selection of an appropriate best-practice configuration.

Integration schemes for this temperature range are currently being developed in several demonstration projects. SPIRIT-Heat [26] (demonstration site 3) investigates a 180 °C, 6.1 bar steam system, while EEETHOS [27] (demonstration site 3) employs a cascaded two-stage turbo-compressor configuration with a sink temperature of 180 °C and 10 bar. As detailed operational data from these projects are not yet available, an integration scheme with an estimated COP is used in this case.

Figure 4 illustrates a possible high-temperature heat-pump integration based on [24]. The concept corresponds to the "steam-generation heat pump" (Concept C: steam compression) described in Annex 58 Task 2 [12]. Typical capacity ranges for this concept span from 0.5 to 100 MW, with achievable temperature lifts of up to 40 K per stage when using piston compressors and up to 60 K when using screw compressors.

The required heat-sink temperature of 180 °C corresponds to a temperature lift of approximately 120 K. The empirical correlation presented by Arpagaus [20] corresponds to a Carnot efficiency factor of approximately 0.45, derived from analyzed operational high-temperature heat pumps. Applying Equation (4) yields an estimated COP of 1.8.

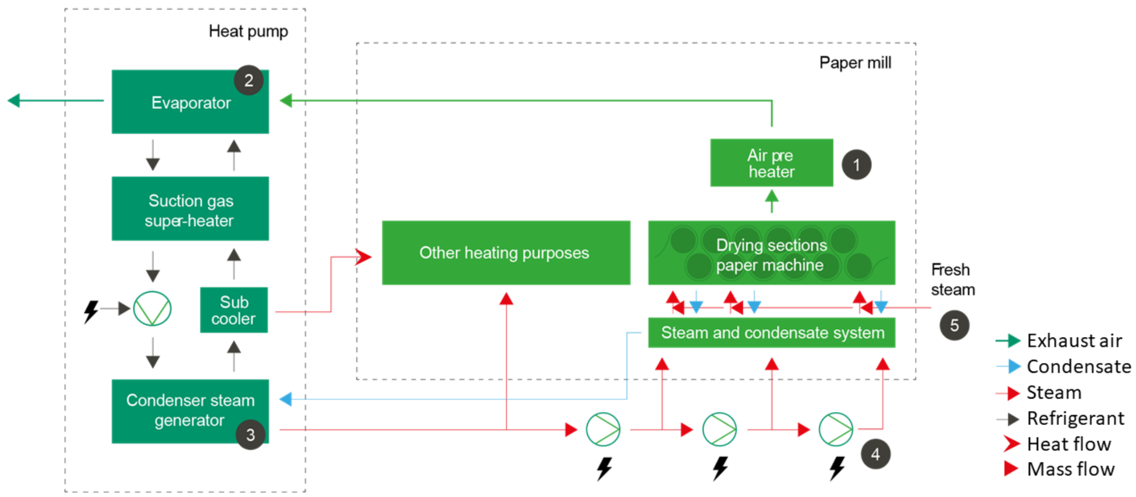

Figure 4. Integration of a high-temperature heat pump in a paper machine (reproduced from EHPA and CEPI [24]).

3.2. Pulp manufacturing

In pulp production, the pulping process accounts for approximately 5 % of the sector's thermal energy demand supplied by the energy carriers reported in JRC-IDEES. One high-temperature heat pump is already in industrial operation for drying de-inked pulp. A high-temperature heat pump is already in operation for drying de-inked pulp, namely the transcritical TransPAC (HFO R1234ze(E)) at WEPA Greenfield in Château-Thierry, France, with a heating capacity of 580 kW [28]. Reported COP values range from 3.6 to 4.2, with an average of 4.0. This performance exceeds the COP estimated from the empirical fit curve for a temperature lift of 70 K, which yields a value of 2.7. Table 3 summarizes the demonstrator parameters stored in the best-practice library, including the integration concept based on available hydraulic schematics and P&IDs.

Table 3. Demonstrator data incorporated into the best-practice library

Parameter	Value	Range
Name	TransPAC	
Location	Château-Thierry, France	
Process	Drying	Spray drying, evaporation, distillation
Source temperature	65 °C (Refrigerant)	60 °C – 88 °C (Heat source)
Sink temperature	155 °C (Refrigerant)	120 °C – 140 °C (Heat sink)
Thermal power	580 kW	
Refrigerant	R1234ze(E)	
COP	4	3.6 – 4.2
Compressor type	Piston	
NACE code	C17.11	
Integration scheme	(concept C: steam compression)	

The site operating this heat pump employs 74 people. By scaling the average final energy use per employee to the enterprise and applying the JRC process share of 5 % for pulping operations, the corresponding thermal load is estimated. Using an uptime of 97 % [29], the annual energy is divided by the effective operating hours according to Equation (2), yielding an average thermal load of approximately 677 kW. This represents an average load over operating hours and does not include part-load modeling.

Taken together, the comparison between the scaled estimates, industry association data and company-level values confirms that the outside-in approach reproduces realistic magnitudes. This demonstrates that, even with limited publicly available data, a low-detail screening is capable of identifying credible load levels and supporting the prioritization of industrial sites and the conceptual design of high-temperature heat-pump integrations in energy-intensive sectors such as pulp and paper.

4. Conclusions

This paper presents an outside-in screening method that uses NACE-based sector statistics together with publicly available process and temperature information to identify high-temperature heat-pump opportunities across industrial sectors. The underlying Eurostat and JRC-IDEES datasets are harmonised across Europe and can be filtered by country and year. In this paper, Eurostat data are selected for Germany and the workflow is demonstrated for the pulp and paper sector, with bottom-up cross-checks limited to Germany. Applied to the pulp and paper sector, the approach reproduces realistic energy magnitudes and process distributions for the analyzed processes based on publicly available data. Scaling the sectoral final energy by employment yields values that align closely with industry association data.

Cross-checks using sustainability reports from several paper mills confirm that the indicative thermal loads derived from the scaling fall within the expected range. Although the number of publicly available reports remains limited, the consistency between scaled estimates, demonstrator data and sector averages shows that the approach generates reliable orders of magnitude for representative units. For the tested case, employment-based scaling appears suitable as a first-order estimator because it relies on widely available statistics and captures the order of magnitude of large industrial installations. Its applicability may be reduced for highly heterogeneous and strongly aggregated NACE classes such as machinery manufacturing, because a single category combines fundamentally different processes that are not meaningfully captured by one sector-average scaling. For these sectors, a more disaggregated NACE level should be used.

By integrating temperature ranges and process characteristics with a best-practice library of realized high-temperature heat-pump projects, the method directly supports early-stage conceptual design. For each NACE segment and process group, it provides representative temperature levels, temperature lifts and capacity ranges that can be mapped to suitable integration schemes. This creates a coherent workflow that links national energy balances to realistic site-level process conditions and demonstrated industrial heat-pump solutions.

In addition to estimating representative thermal loads, the screening framework captures the waste-heat streams associated with each process within a NACE sector. This allows the identification of potential heat sources at process level and enables a first quantification of sector-specific waste-heat potentials. By linking related processes and their corresponding temperature levels, the method also highlights technically feasible source options for high-temperature heat pumps. This structured overview of process-level heat sources provides practical guidance for selecting suitable waste-heat streams during early-stage integration studies.

Future work should extend the approach to additional NACE classes, expand the process and demonstrator library, and incorporate emerging waste-heat inventories to refine process-level assumptions. As more operational data from high-temperature heat pumps become available, empirical performance correlations can be updated to improve accuracy. Overall, the proposed NACE-based outside-in screening method provides a practical and scalable foundation for identifying and assessing high-temperature heat-pump opportunities and can support the acceleration of industrial process-heat decarbonization.

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