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ABBREVIATIONS AND ACRONYMS

BAT: Best Available Techniques

BAU: Business As Usual

CAGR: Compound Annual Growth Rate

COP: Coefficient of Performance

ESG: Environmental, Social and Governance

FEC: Final Energy Consumption

FF: Fossil Fuels

GDP: Gross Domestic Product

GWP: Global Warming Potential

HP: Heat Pumps

HTHP: High Temperature Heat Pumps

PESTLE: Political, Economic, Sociological, Technological, Legal, Environmental

SME: Small and Medium Enterprise

SPF: Seasonal Performance Factor

SPIRIT: Implementation of sustainable heat upgrade technologies for industry

WH: Waste Heat

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1. INTRODUCTION

This deliverable presents an analysis of the industrial heat pump market evolution and its potential impact on energy transition towards 2050.

The research methodology is structured in three complementary approaches:

- a top-down analysis examining broad market trends and industrial heat demand patterns
- a bottom-up analysis investigating specific industrial processes and their technical requirements for heat pump integration
- PESTLE analysis for market evolution based on political, economic, social, technological, legal, and environmental factors.

The result of these three combined approaches is the development of adoption scenarios for the High Temperature Heat Pump (HTHP) technology.

The analysis encompasses market size projections in terms of installed capacity and unit deployment, with particular attention to technical specifications such as sink temperatures, temperature lifts, and system dimensions.

This research contributes to milestone M5.1, quantifying potential energy savings and CO_2 emission reductions achievable through industrial heat pump deployment, while providing insights for global market extrapolation.

2. TOP-DOWN ANALYSIS OF INDUSTRIAL SECTORS IN THE EU

2.1 Introduction

The top-down analysis was designed to identify and evaluate the most promising industrial sectors for high-temperature heat pump implementation. This systematic approach focused on sectors with significant potential for heat pump integration, particularly where process temperatures below 200°C are prevalent.

The assessment methodology was structured around specific characteristics that determine the feasibility of HTHPs integration. For each industrial sector, we analyzed four fundamental parameters:

1. Final Energy Consumption (FEC)
    a. Quantifying the total energy demand of each sector
    b. Identifying the proportion of thermal energy needs
2. Process Heat Temperature Profiles
    a. Mapping temperature requirements below 200°C
    b. Analyzing temperature distribution across different processes
3. Waste Heat Availability
    a. Assessing quantity and quality of available waste heat
    b. Identifying potential heat sources for heat pump integration
4. Heat Pump Operational Requirements
    a. Evaluating suitable temperature lifts
    b. Determining optimal operating conditions

This data collection and analysis framework enables the identification of sectors with the highest potential for successful heat pump implementation, considering both technical feasibility and energy saving potential.

The preliminary qualitative analysis examines the HTHPs potential across the following industrial sectors:

- Chemical and petrochemical industry
- Non-metallic minerals
- Paper pulp and printing
- Food and beverage
- Machinery

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- Transport equipment
- Textile and leather
- Non-ferrous metals

These sectors represent 76% of the total industrial energy consumption in the EU.

For each of these sectors, our comprehensive analysis evaluates multiple critical parameters to determine HTHP implementation potential. This assessment examines process heat utilization patterns, including both the temperature requirements and their distribution across different processes. We analyze the energy consumption profile of each sector, breaking down usage into categories such as electricity consumption, space heating and cooling requirements, process heat demands, and electricity specifically used for industrial processes. Additionally, we assess the availability and characteristics of waste heat streams, as these present significant opportunities for heat recovery and efficiency improvements through HTHP technology.

This detailed technical and energy analysis provides crucial insights into the feasibility and potential impact of HTHP implementation across these key industrial sectors, which collectively represent more than three-quarters of the EU's industrial energy consumption.

2.2 Final energy consumption

According to Eurostat data from 2022 (Figure 1 and Figure 2), the total energy consumption of industry is 2,790 TWh/yr.

The chemical and petrochemical industry stands as the largest energy consumer, accounting for 21% of total consumption with 598 TWh per year. This is followed by the non-metallic minerals sector at 14% (395 TWh/year), and the paper, pulp, and printing industry, also at 14% (378 TWh/year). The food, beverages, and tobacco sector ranks fourth, consuming 12% of the total industrial energy (324 TWh/year).

Beyond these dominant sectors, the iron and steel industry represents a substantial portion at 10% (285 TWh/year), while the machinery sector accounts for 7% (186 TWh/year).

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Industrial sector	Energy consumption (TWh/year, 2022)	Share on total
Chemical & petrochemical	**598**	**21%**
Non-metallic minerals	**395**	**14%**
Paper, pulp & printing	**378**	**14%**
Food, beverages & tobacco	**324**	**12%**
Iron & steel	285	10%
Machinery	186	7%
Not elsewhere specified (industry)	125	4%
Construction	119	4%
Non-ferrous metals	108	4%
Wood & wood products	108	4%
Transport equipment	84	3%
Mining & quarrying	43	2%
Textile & leather	36	1%

Figure 1 industrial sectors energy consumption in the EU (TWh/yr), 2022 [1]

Several sectors demonstrate moderate energy consumption patterns, each representing 4% of the total: construction (119 TWh/year), non-ferrous metals (108 TWh/year), and wood and wood products (108 TWh/year). The transport equipment sector shows slightly lower consumption at 3% (84 TWh/year). At the lower end of the spectrum, mining and quarrying accounts for 2% (43 TWh/year), while the textile and leather industry represents the smallest share at 1% (36 TWh/year).

The category "Not elsewhere specified" accounts for 4% of total consumption (125 TWh/year), encompassing various industrial activities not classified under the main categories.

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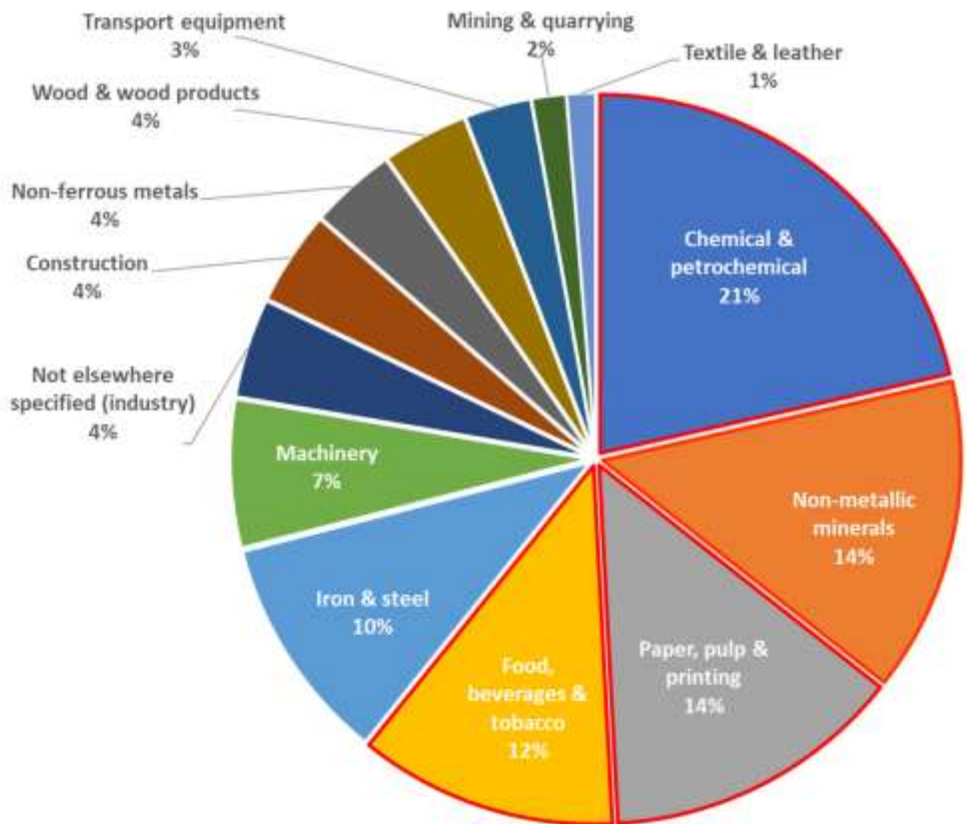

Figure 2 industrial sectors energy consumption in the EU (shares), 2022

European Union's industrial energy consumption shows a significant concentration in four major sectors, which together represent 61% of total industrial energy usage:

This distribution pattern is particularly significant for understanding industrial energy use in the EU, highlighting where energy efficiency improvements could have the most substantial impact. The concentration of consumption in just four sectors suggests these areas should be primary targets for energy optimization strategies and technological innovations.

2.3 Industrial sectors analysis

The preliminary qualitative analysis across EU industrial sectors evaluates the potential implementation of HTHP technology, with particular focus on process heat requirements and decarbonization opportunities.

Through our assessment of the iron and steel sector, we determined that current process heat temperatures are not compatible with HTHP technology. However, this sector remains significant for broader decarbonization initiatives and potential district heating network integration.

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In examining the construction sector, we found that manufacturing components represent only 15% of the sector's total energy consumption, suggesting limited scope for comprehensive heat pump implementation. This finding helps prioritize where technological interventions might be most effective within the construction value chain.

Our analysis of the mining and quarrying sector revealed minimal process heat utilization, indicating limited potential for industrial heat pump applications. This insight helps redirect focus to sectors with more substantial opportunity for impact.

The wood products industry presents a distinctive case where process heat is predominantly derived from biomass generated through their production processes.

Additionally, we identified that 4% of industrial energy consumption falls under "not elsewhere specified" industries: this generic sector cannot be addressed since there is a lack of information about the heat used in industrial processes.

Based on our preliminary qualitative assessment, we have identified the key sectors that warrant focused attention (Figure 3):

- Chemical and Petrochemical industry
- Non-metallic minerals
- Paper pulp and printing
- Food and beverage
- Machinery
- Non-ferrous metals
- Transport equipment
- Textile and leather

Industrial sector	Energy consumption (TWh/year, 2022)	Share on total
Chemical & petrochemical	598	21%
Non-metallic minerals	395	14%
Paper, pulp & printing	378	14%
Food, beverages & tobacco	324	12%
Iron & steel	285	10%
Machinery	186	7%
Not elsewhere specified (industry)	125	4%
Construction	119	4%
Non-ferrous metals	108	4%
Wood & wood products	108	4%
Transport equipment	84	3%
Mining & quarrying	43	2%
Textile & leather	36	1%

Figure 3 Highlighted sectors suitable for our analysis

2.4 Energy use in the industrial sectors

Understanding energy use patterns in industry requires examination of three main categories:

- Space heating and cooling demands
- Process heat requirements
- Electricity consumption for industrial processes

Figure 4 chart illustrates energy consumption patterns across various industrial sectors in the EU; energy use is broken down into four categories, represented by different colors:

- Blue: Space heating and cooling
- Orange: Process heat
- Gray: Electricity for industrial processes
- Yellow: Process heat + electricity (aggregated, shown in sectors where we could not determine process heat and electricity separately)

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The chemical and petrochemical industry dominates energy consumption, reaching around 570 TWh/yr.

Following this are the non-metallic minerals and paper, pulp and printing sectors, consuming 338 and 272 TWh/yr of energy for process heat. The food, beverages and tobacco sector, along with iron and steel, show significant process heat consumption levels of about 170-260 TWh respectively.

Sectors like non-ferrous metals and textile and leather show considerably lower energy consumption, but a high share of process heat (with 49 and 20 TWh/yr).

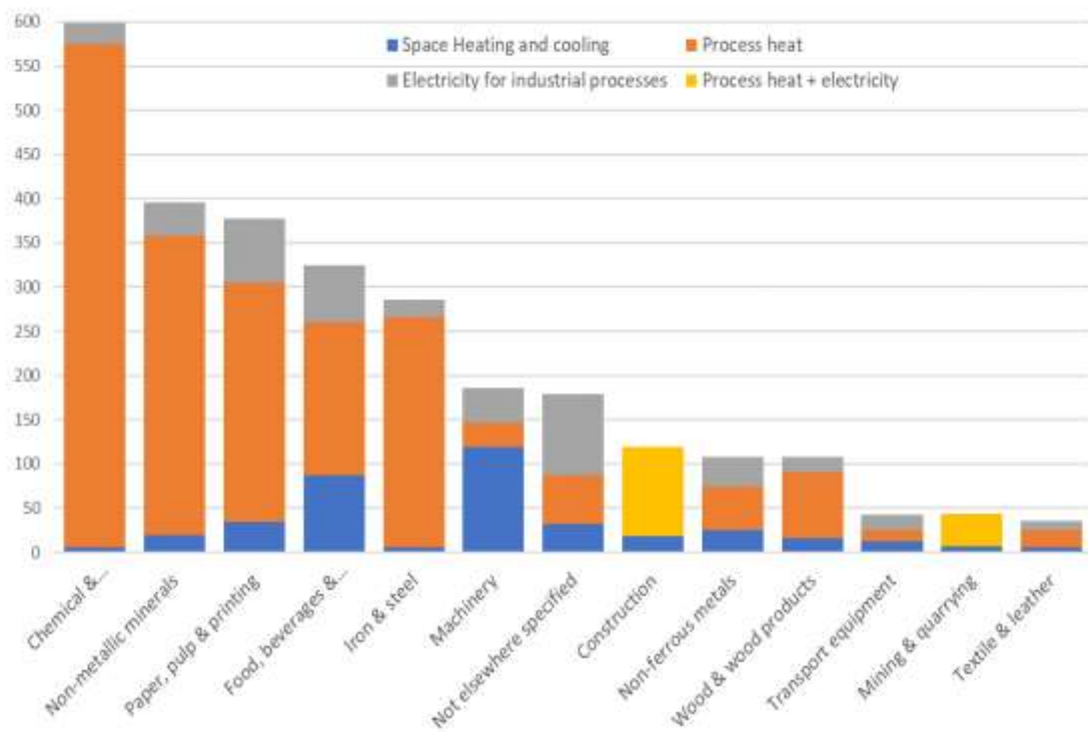

Figure 4 Energy consumption by use in the EU industrial sector (TWh/yr), 2022 (data from [1] calculated using [2] methodology)

Process heat represents the largest share of energy consumption across most sectors, particularly in energy-intensive industries like chemicals and non-metallic minerals. Space heating and cooling requirements vary significantly across sectors, with some industries like food and beverages and machinery showing higher proportional demands for this type of energy use.

In Figure 5 is represented the percentage breakdown of energy consumption across the sectors, helping us in visualizing which are the most process heat dependent sectors in industry.

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The chemical and petrochemical sector confirms the highest concentration of process heat usage at 95%, with minimal space heating (1%) and electricity consumption (4%). This indicates a sector heavily dependent on thermal processes.

Non-metallic minerals and paper and pulp industries also demonstrate high process heat requirements at 86% and 72% respectively, though with increasing proportions of electricity use for industrial processes (10% and 19%).

The food and beverages sector presents a more balanced distribution, with 53% process heat and a significant 27% dedicated to space heating and cooling, reflecting the sector's diverse energy needs including refrigeration requirements.

The textile and leather industry presents a balanced distribution with 56% process heat, 29% electricity for industrial processes, and 15% space heating, reflecting the diverse energy requirements of textile manufacturing processes.

Notably, the machinery and transport equipment sectors show the highest proportion of space heating and cooling at 64%, suggesting these industries operate in more controlled environmental conditions with less intensive process heat requirements.

This distribution pattern is relevant for evaluating the potential implementation of HTHPs, as sectors with higher proportions of process heat may present more immediate opportunities for heat pump applications.

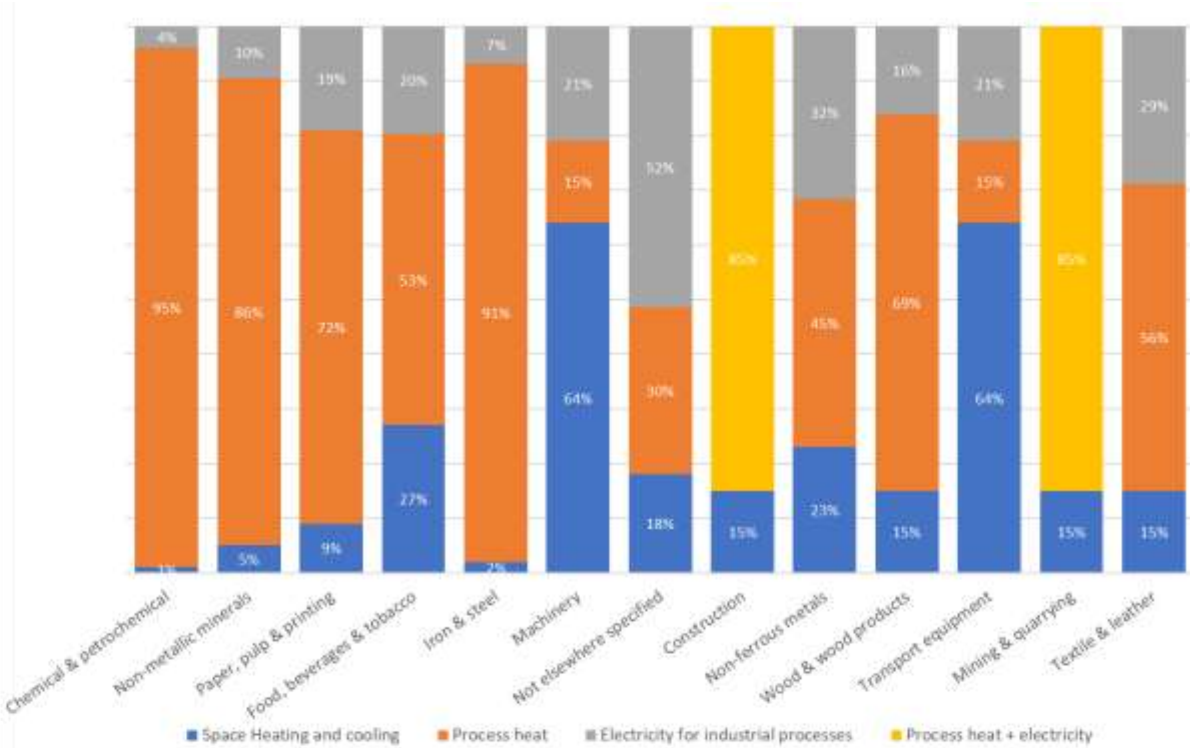

Figure 5 Energy consumption shares by use in the EU industrial sector, 2022 [1]

2.5 Industrial sectors process heat temperature distribution

The categorization made in the previous paragraphs has to be improved by the temperature of the process heat used in the industrial sectors analysed: it is essential to note that temperatures above 200°C are currently beyond the technological capabilities of HTHPs, which significantly influences the potential implementation across different sectors.

For this reason it is important to understand the average temperatures in which the sectors are operating (Figure 6); this chart illustrates the temperature distribution of process heat requirements across industrial sectors.

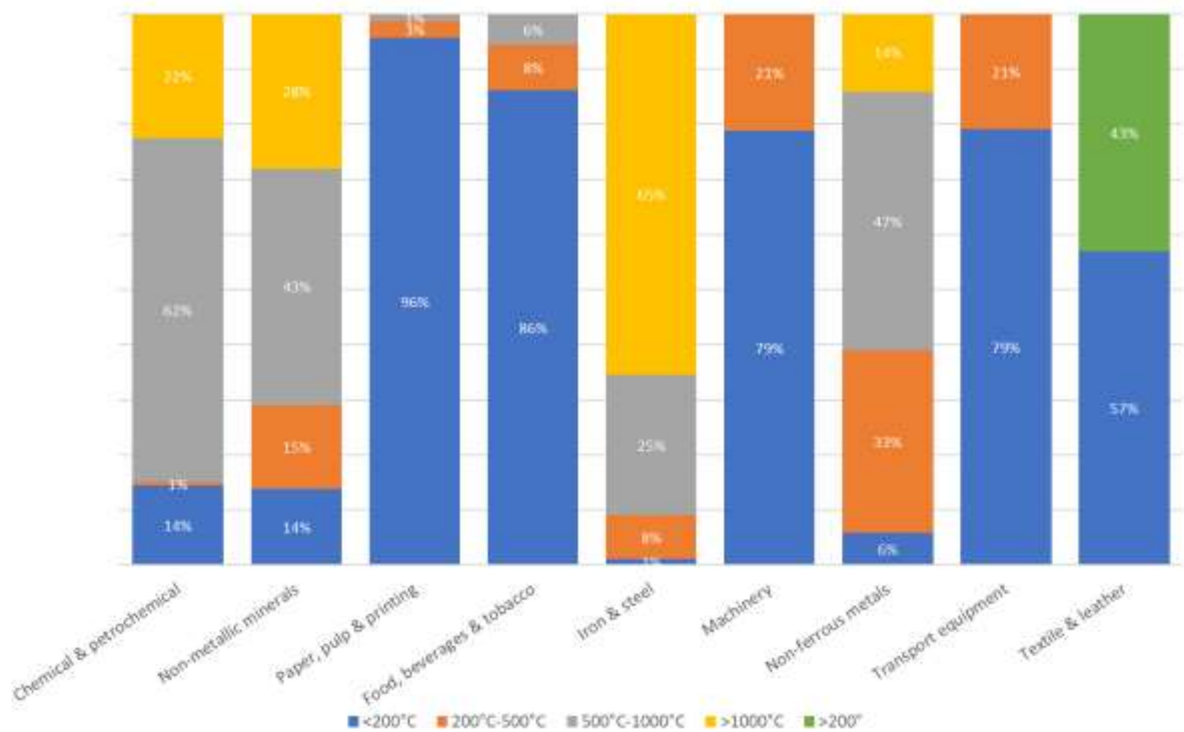

Figure 6 Temperature distribution of process heat in EU industry, 2022 (data from [1] calculated using [2] methodology)

The chemical and petrochemical industry shows that 85% of its process heat requirements operate above 200°C (62% between 500°C-1000°C and 22% above 1000°C), leaving only 14% of processes within the suitable temperature range for HTHP applications.

The non-metallic minerals sector similarly presents challenges for HTHP adoption, with 86% of processes requiring temperatures above 200°C.

In contrast, the paper, pulp, and printing sector emerges as highly promising for HTHP implementation, with 96% of processes operating below 200°C.

The food and beverages industry also presents significant opportunities for HTHP adoption, with 86% of processes operating below 200°C.

Iron and steel (as preliminary qualitative analysis suggested) presents substantial challenges for HTHP implementation, with 98% of processes requiring temperatures above 200°C (65% above 1000°C and 25% between 500°C-1000°C). Only 1% of processes operate within HTHP-suitable temperatures, indicating that alternative decarbonization strategies may be necessary.

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The machinery and transport equipment sectors show that 79% of their processes operating below 200°C, while textile and leather industry presents a divided profile with 57% of processes below this temperature.

2.6 Industrial sectors process heat temperature below 200°

This temperature range is particularly significant as it represents the operational threshold where HTHPs can be effectively implemented. The bar chart and pie chart in Figure 7 and Figure 8 present the process heat energy consumption below 200°C across industrial sectors in the EU.

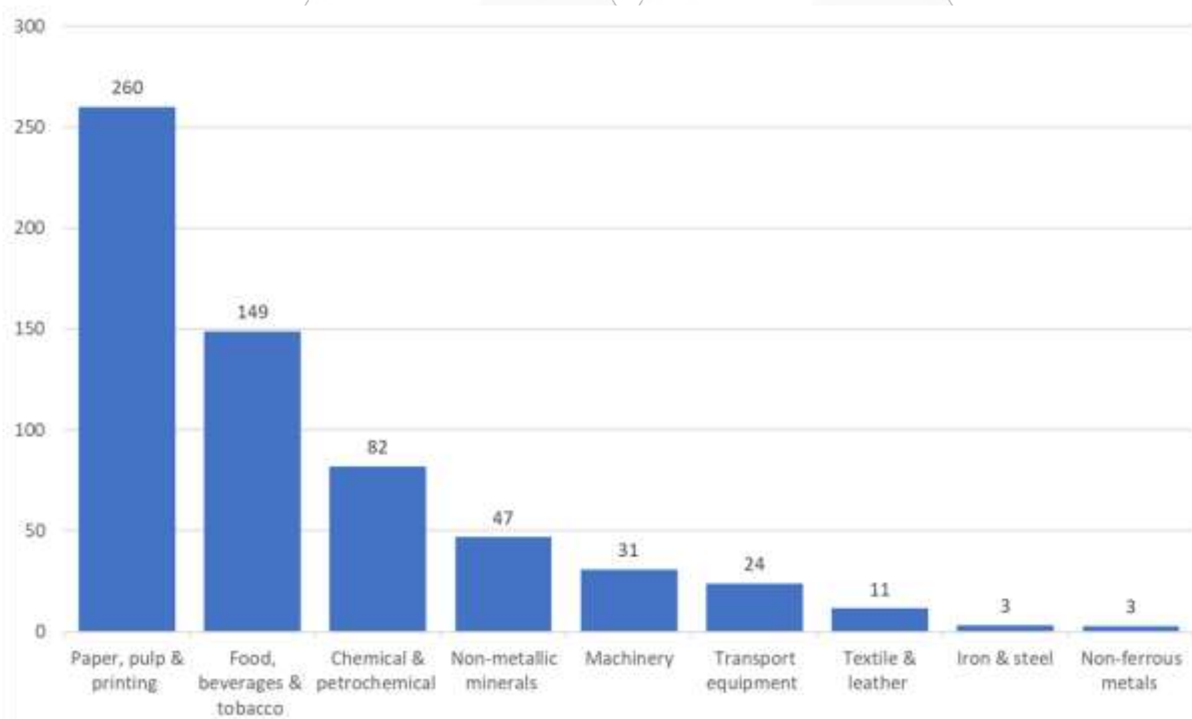

Figure 7 Industrial process heat <200°C energy consumption in the EU (TWh/year),2022

The paper, pulp, and printing sector emerges as the largest consumer of low-temperature process heat, with 260 TWh/yr of energy consumption below 200°C.

The food and beverages industry follows as the second-largest consumer, utilizing 149 TWh/yr of process heat below 200°C.

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The chemical and petrochemical sector, despite having a smaller proportion of low-temperature processes, still consumes 82 TWh/yr of energy below 200°C, representing a notable opportunity for HTHP integration in specific processes.

Non-metallic minerals (47 TWh/yr), machinery (31 TWh/yr), and transport equipment (24 TWh/yr) sectors show moderate consumption levels within the HTHP-suitable range. While their absolute consumption is lower, the high percentage of processes below 200°C in machinery and transport equipment sectors suggests good potential for HTHP adoption.

The textile and leather (11 TWh), iron and steel (3 TWh), and non-ferrous metals (3 TWh) sectors demonstrate relatively low consumption of process heat below 200°C. However, for sectors like textile and leather, where a significant portion of processes operate below 200°C, even this smaller energy demand represents an opportunity for HTHP implementation.

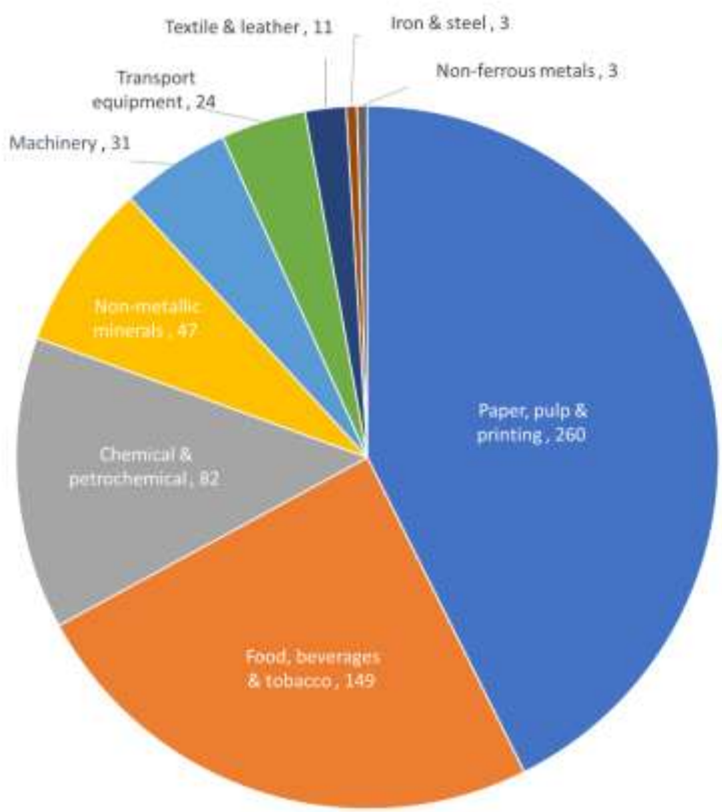

Figure 8 Industrial process heat <200°C energy consumption in the EU (TWh/year), 2022

2.7 Industrial sectors waste heat

The availability and effective utilization of waste heat sources represent critical factors in the successful implementation and expansion of HTHP technology across industrial sectors.

Waste heat, which is currently discharged from various industrial processes, offers a valuable opportunity to enhance the efficiency and economic viability of HTHPs. The presence of accessible waste heat streams can significantly improve the coefficient of performance (COP) of heat pumps, making them more attractive from both environmental and financial perspectives: the widespread adoption of HTHP technology is intrinsically linked to the identification and exploitation of suitable waste heat sources within industrial processes.

HTHP technology implementation must carefully evaluate waste heat availability, temperature levels, and recovery potential to ensure optimal system design and performance. Furthermore, the strategic integration of waste heat recovery systems in HTHPs can create synergistic effects, maximizing energy efficiency and reducing operational costs, making process integration studies crucial for the success of the HTHP technology.

Table 1 presents the share of waste heat potential across major industrial sectors in the European Union for 2022. The data of Table 1 takes into account the technical potential of waste heat [3], [4].

The iron and steel sector, along with non-metallic minerals, shows the highest waste heat potential at 11.4%. This significant percentage indicates substantial opportunities for heat recovery and reuse, despite these sectors' typically high-temperature processes. The chemical and petrochemical industry follows closely with 11.0% waste heat potential, while the textile and leather sector demonstrates a similarly high potential at 11.0%.

The paper, pulp, and print industry exhibits a considerable waste heat potential of 10.6%, which is particularly noteworthy given this sector's predominantly low-temperature processes that align well with heat pump technology. The "Other" category shows a substantial 10.38% potential, suggesting significant opportunities across various smaller industrial segments.

Non-ferrous metals present a moderate waste heat potential of 9.6%, while the food and beverage sector shows 8.6%. Although these percentages are lower compared to other sectors, they still represent significant opportunities for heat recovery,

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especially considering the food industry's substantial low-temperature process requirements.

The wood and wood products sector demonstrates the lowest waste heat potential at 6.0%, possibly due to its existing use of biomass and efficient heat integration systems.

Table 1 Waste heat potential of industrial sectors in EU, 2022 (own calculation based on [5])

Sector	Waste Heat Potential
Iron and Steel	11.4%
Chemical and Petrochemical	11.0%
Non-Ferrous Metals	9.6%
Non-Metallic Minerals	11.4%
Food and Tobacco	8.6%
Paper, Pulp and Print	10.6%
Wood and Wood Products	6.0%
Textile and Leather	11.0%
Other	10.4%

Figure 9 presents the calculation of non-recoverable process heat and waste heat potential across major industrial sectors, based on the shares of Table 1.

The chemical and petrochemical sector demonstrates the highest overall heat consumption, with 506 TWh/yr of non-recoverable process heat and 63 TWh/yr of waste heat potential.

Non-metallic minerals follows as the second-largest consumer, showing 300 TWh/yr of non-recoverable process heat and 39 TWh/yr of waste heat potential. The paper, pulp, and printing industry exhibits 243 TWh/yr of non-recoverable process heat with 29 TWh/yr of waste heat potential, while the iron and steel sector shows 230 TWh/yr and 30 TWh/yr respectively.

The food and beverages industry presents more moderate figures, with 158 TWh/yr of non-recoverable process heat and 15 TWh/yr of waste heat potential.

Smaller industrial sectors such as wood products, non-ferrous metals, machinery, textile and leather, and transport equipment show considerably lower heat consumption patterns, ranging from 70 TWh/yr down to 11 TWh/yr of non-recoverable process heat, with corresponding waste heat potentials between 1-5 TWh annually.

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This distribution of waste heat potential is particularly relevant for high-temperature heat pump implementation strategies, as it identifies not only the quantity but also the scale of potential applications across different sectors. The data suggests that while larger sectors offer greater absolute potential for heat recovery, even smaller sectors present meaningful opportunities for energy efficiency improvements through heat pump technology.

These results will be compared, in the bottom-up analysis, with the estimates reported by Marina et al. [6].

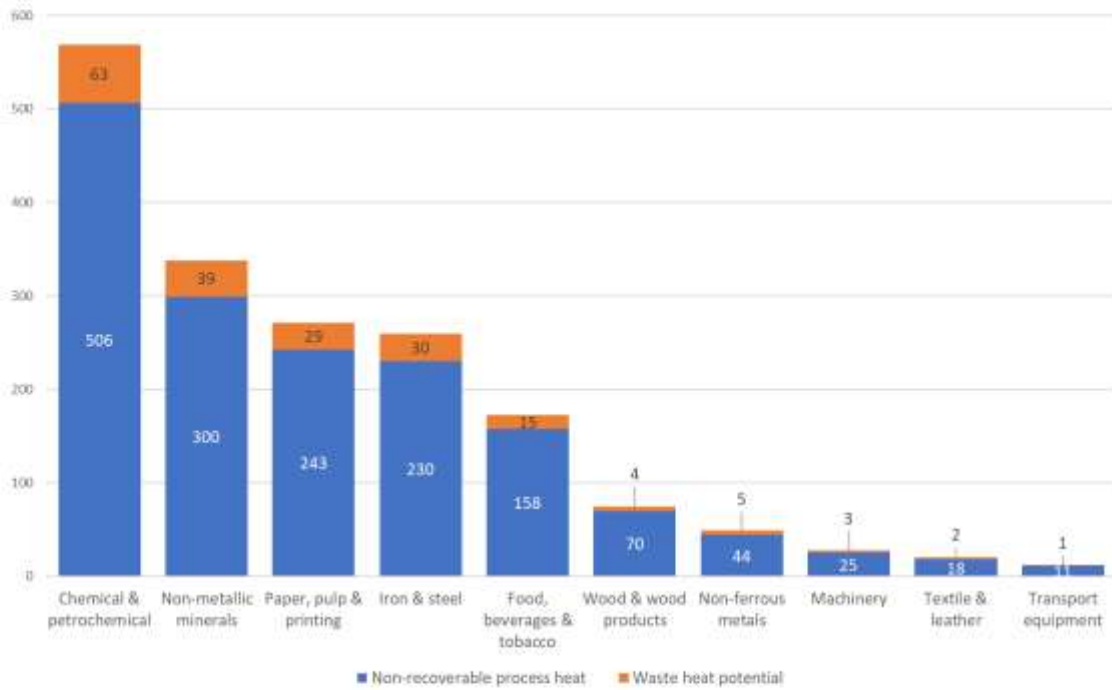

Figure 9 Non-recoverable process heat and waste heat potential in industrial sectors in EU (TWh/yr), 2022 (Own calculation, based on [3], [7], [8]

2.8 Top-down analysis results

Based on our top-down analysis of industrial sectors in the European Union, we have identified significant potential for HTHPs implementation, particularly in sectors with substantial low-temperature process heat requirements. However, this macro-level analysis presents limitations that need to be addressed through more detailed sector-specific investigations.

The analysis reveals that the paper and pulp industry, along with the food and beverage sector, demonstrate the most promising immediate potential for HTHP adoption, with 260 TWh and 149 TWh of process heat consumption below 200°C, respectively. However, to accurately assess market potential and implementation feasibility, a more granular analysis of specific processes and sub-processes within these sectors is essential.

A critical limitation of the current analysis is its inability to precisely identify where fossil fuel boilers could be effectively replaced with HTHPs, particularly in steam generation applications. This represents a significant gap in our understanding, as steam systems are central to many industrial processes and offer substantial decarbonization opportunities.

The role of waste heat recovery emerges as a crucial factor in HTHP implementation. Our analysis shows varying waste heat potentials across sectors, ranging from 6% to 11.4%. However, these figures require deeper investigation at the process level to understand the practical recovery potential and its impact on heat pump COP.

For instance, drying processes, common in both target sectors, typically generate significant low-temperature waste heat that is challenging to recover through conventional methods but could be effectively utilized through HTHP systems.

Moving forward, a detailed examination of the paper and pulp and food and beverage industries and other sectors will be made in the following chapter, focusing on:

- Process-level temperature requirements and distributions
- Specific waste heat sources, their temperatures, and recovery potential
- Steam generation requirements and opportunities for HTHP integration
- Sub-process characteristics that might facilitate or hinder HTHP implementation

This deeper analysis will provide the necessary insights to accurately assess market potential and develop targeted implementation strategies for HTHP technology in industrial applications. Understanding these specifics will be crucial for identifying the most viable opportunities and ensuring successful technology deployment.

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3. BOTTOM-UP ANALYSIS OF THE INDUSTRIAL PROCESSES

3.1 Introduction

In order to develop a comprehensive understanding of the HTHP market potential in industrial applications, we will conduct a detailed bottom-up analysis to complement the top-down assessment presented in the previous chapter. This dual approach will provide a more accurate and nuanced evaluation of HTHP implementation opportunities across key industrial sectors.

Our bottom-up analysis will focus on five strategic industries:

- Papermaking
- Food and beverage
- Textile
- Automotive
- Chemical

For each industry, we will examine specific processes and sub-processes, analyzing their temperature requirements, waste heat availability, and potential for HTHP integration. This granular approach will allow us to identify precise intervention points where HTHPs can effectively replace conventional heating systems, particularly in steam generation applications.

By matching this bottom-up assessment with our previous top-down analysis, we aim to validate and refine our market potential estimates. This comprehensive approach will provide valuable insights into the practical constraints and opportunities for HTHP deployment, helping to identify the most promising applications and guide technology implementation strategies.

Through this detailed investigation, we expect to uncover specific opportunities that may have been overlooked in the broader analysis, while also identifying potential challenges that need to be addressed for successful HTHP implementation. This combined approach will provide the detailed understanding necessary for developing effective strategies to advance industrial heat pump adoption and contribute to industrial sector decarbonization.

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The starting point of our analysis are the analyses of processes and sectors suitable for heat pumps adoption in Figure 10.

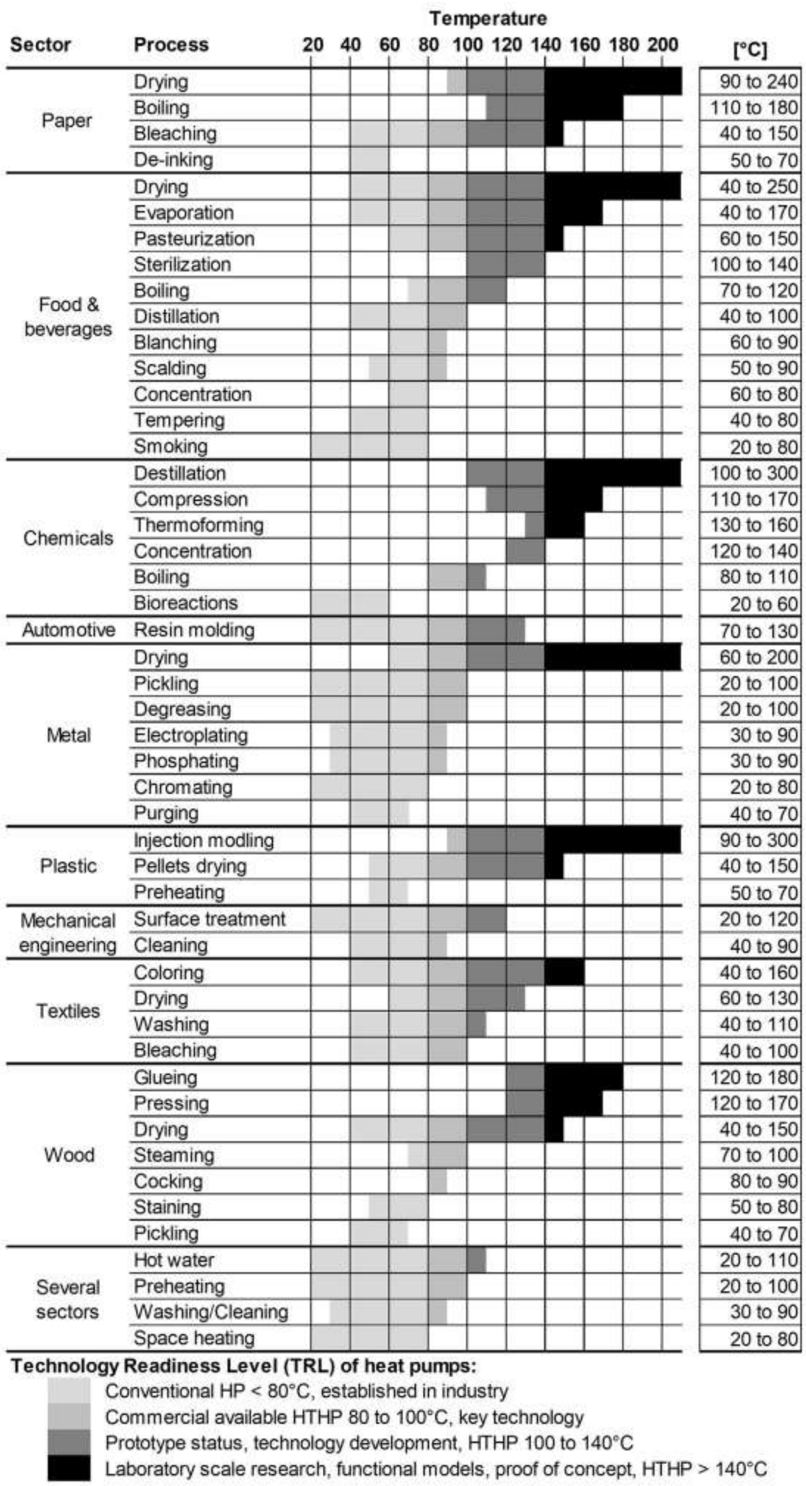

Figure 10 Industrial processes suitable for heat pumps in different industrial sectors [9]

The annual energy demand in MWh/yr (E) of each industrial process was calculated by multiplying the specific energy intensity of the process in MWh/t (i)by the total annual production of the corresponding good in T/yr (p), according to:

$$E = i \cdot p$$

The corresponding installed thermal capacity in MW (P) was then derived by dividing the annual energy demand by the assumed yearly operating hours of the process (t):

$$P = \frac{E}{t}$$

Table 2 summarizes the operating hour assumptions adopted for each industrial sector and process considered in the analysis.

Table 2 Operating hours for selected industries

Sector/Process	Operating hours (h/yr)	Justification
Sugar production	4,000	Seasonal beet campaign
Papermaking	7,000	Continuous operation
Food & beverage (non-sugar)	7,000	Multi-shift
Animal feed	7,000	Industrial pelleting lines
Brewing	7,000	Industrial average (heterogeneous sector)
Oilseed processing	7,000	Extended seasonal / near-continuous
Dairy (pasteurisation, drying)	7,000	Base-load thermal processes
Canned fruit & vegetables	7,000	Industrial processing lines
Textile	7,000	Harmonised assumption
Automotive painting	7,000	Continuous multi-shift

Ethanol distillation	7,000	Continuous operation
Chemical	7,000	Continuous operation

3.2 Papermaking industry

The paper and pulp industry presents substantial opportunities for the electrification of its processes and the deployment of high-temperature heat pumps. A comprehensive analysis indicates that energy consumption at temperatures below 200ºC is notably significant.

The papermaking process (Figure 11) begins with wood as the primary raw material: this fundamental stage involves carefully selected timber that will be transformed through a complex series of industrial processes into paper.

The initial wood processing involves debarking and chipping, where trees are stripped of their bark and cut into small, uniform pieces. These wood chips then undergo two critical pulping stages: mechanical and chemical pulping. Mechanical pulping breaks down wood fibers using mechanical force, while chemical pulping uses chemical solutions to separate wood fibers more thoroughly, ensuring a cleaner and more refined pulp.

Following pulping, the material goes through a de-barking and cleaning process to remove impurities and prepare the pulp for further refinement. The headbox becomes a crucial component, where the pulp mixture is carefully distributed onto a moving wire section. Here, water begins to drain away, and the initial paper sheet formation takes place.

The wire section is where the liquid pulp starts to transform into a cohesive sheet. As water drains, the fibers begin to interlock, creating the foundational structure of the paper. This is followed by pressing, where the wet paper sheet passes through multiple rollers that squeeze out additional moisture and begin to compress the fibers.

The drying section is critical, with the paper passing through heated rollers that remove the remaining moisture. This process not only completes the water removal but also helps establish the paper's final physical properties. Some papers may undergo additional coating processes to enhance their surface characteristics or specific performance attributes.

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Finishing stages involve calendering, where the paper is further smoothed and compressed to achieve the desired surface texture and thickness. For recycled paper, an additional de-inking process removes print and contaminants, allowing previously used paper to be transformed into new paper products.

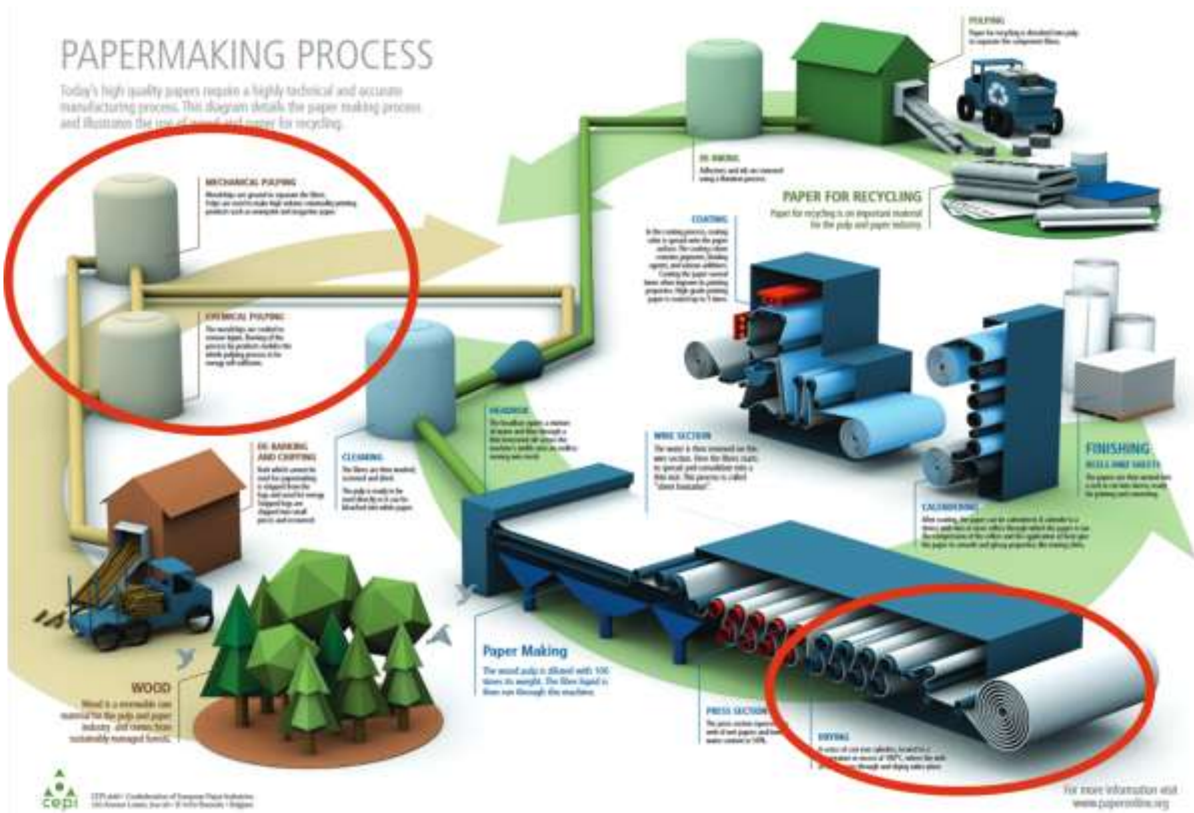

Figure 11 The papermaking process[10]

a) Suitable industrial processes for HTHP

The industrial processes in the production of pulp and paper have been analysed in many papers in the literature.

According to Arpagus [11], at least 4 processes are suitable for heat pumps (see Figure 10):

- Drying (90 to 240°C)
- Boiling (110 to 180°C)
- Bleaching (40 to 150°C)
- Steaming (70 to 200°C)

According to experts, interviews performed and the consortium of SPIRIT the most promising process for HTHPs is Drying for papermaking.

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Drying

The drying process in papermaking can be performed with different techniques:

- **Conventional Cylinder Dryer** (Figure 12). This consists of a series of steam-heated cylinders arranged in rows. The paper web passes over and under these cylinders, with wet sheets contacting the heated surface. The system includes air supply, fans, exhaust, wet sheets entering from one side, and dry sheets exiting from the other. This traditional design uses multiple contact points to gradually dry the paper.

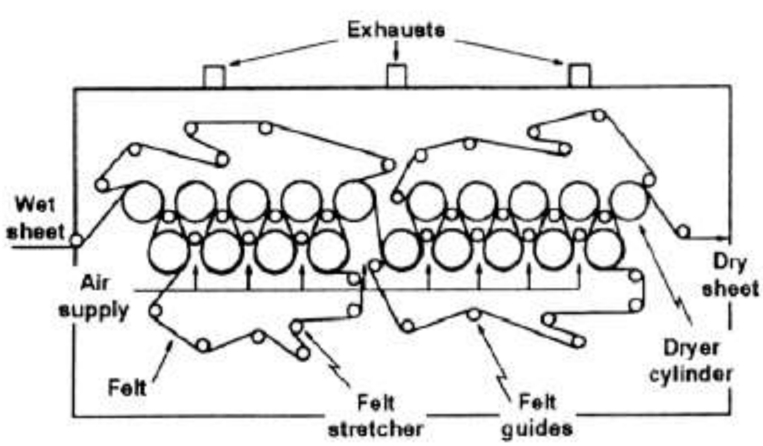

Figure 12 Conventional cylinder dryer

- **Single-Tier Dryers** (Figure 13). These are newer dryers designed for high-speed machines to improve runnability. The paper web is threaded around a single row of dryers with a bottom row of cylinders that serve as turning rolls. The paper is continuously supported by fabric, eliminating free draws. Only one side of the paper is heated, and a section with dryers on the bottom row can be inserted in the dryer configuration.

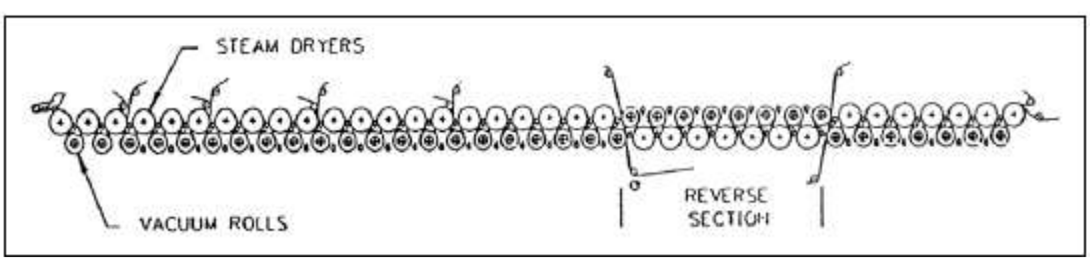

Figure 13 Single-Tier Dryer

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- **Yankee Dryers**. These are large diameter (8 m) steam-heated cylinders with high-velocity hoods having jets of hot air blowing on the paper surface. They're primarily used for tissue machines. The design allows tissue to be easily dried while being continuously supported. Their light weight makes them particularly suitable for tissue production.

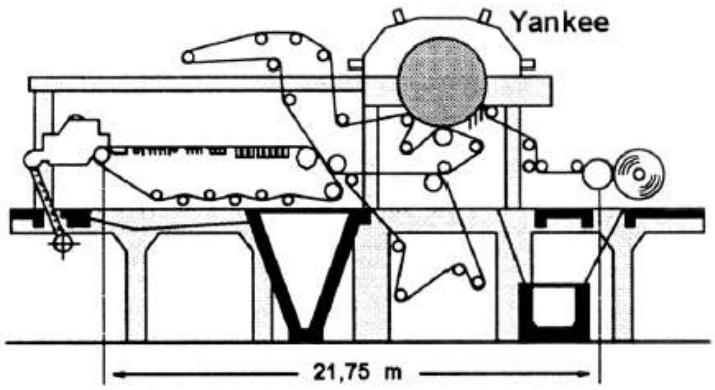


Figure 14 Yankee Dryers

- **Flakt (Air Flotation) Dryer** (Figure 15). This dryer is commonly used on pulp machines. The web passes through multiple tiers where hot air is blown on the web. This system provides lower temperature drying than used for paper, which helps prevent darkening, embrittlement, and bonding issues. These factors are important when the pulp is later repurposed by papermakers.

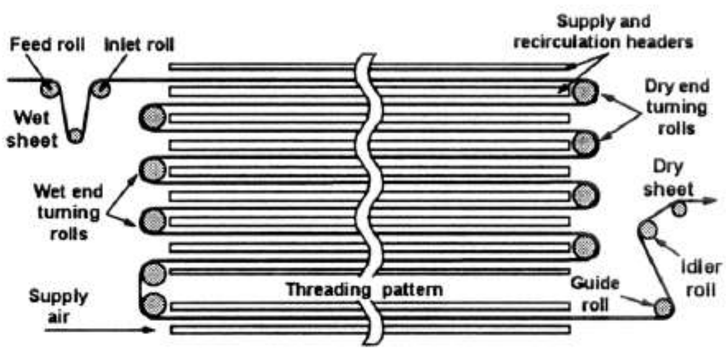
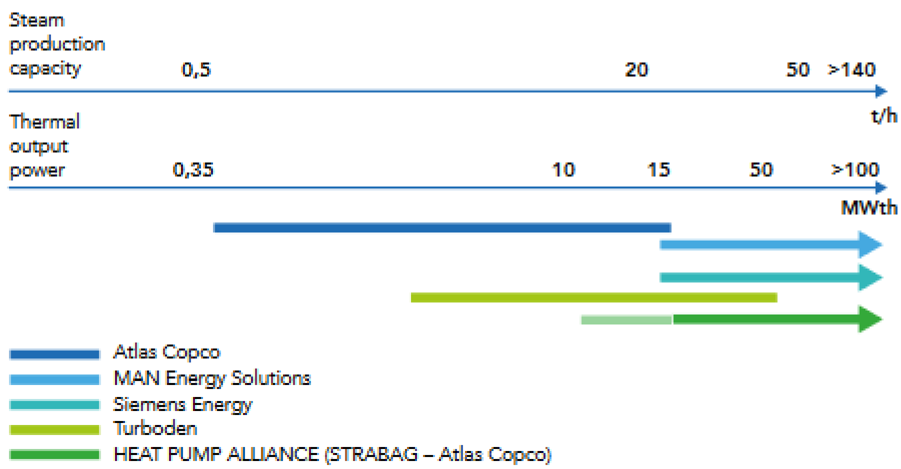


Figure 15 Flakt (Air Flotation) Dryer

The waste heat temperature of drying is between 50-55°C ([5]), while the process heat is applied through steam-heated cylinders to evaporate water from the wet paper web.

This process is currently electrified trough heat pumps. The current technology commercial available is with heat pumps that reach temperatures between 80-100°C.

Temperatures above 100° are currently reached by different compressors and heat pumps producers and research projects [12], [13], [14], [15], [16], [17], [18]. Producers like Atllas CopCo, MAN, Siemens Energy and Turboden can provide these machines up to 25-30-70 MWt, producing steam at T up to 150°C at 3.7 barg.



	Standardized / Industrialized	Engineered / Standardized	Engineered
LP Steam Mass Flow [t/h]	0,5 - 4	6 - 10	15 - 140
Heat input (max) [MWth]	0,35 - 2,7	4 - 7	10 - 100

Available (single unit) heat pump capacities

Figure 16 Available current industrial heat pumps

Conventional System Process			Process steps	Process Using Electric Dryer		
Equipment	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)		Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)	Equipment
Liqure Evaporator	996	46	Liqure Evaporation	996	46	Liqure Evaporator
Pulp machine	567	40	Pulping Chemical Preparation	567	40	Pulp machine
Cooking machine	656	95	Wood Cooking	656	95	Cooking machine
Conventional bleaching plant	312	75	Bleaching	312	75	Conventional bleaching plant
Steam/fuel-based dryer	1,245	128	Paper Drying	0.0	1,236	**Infrared dryer**
Paper making machine	310	296	Paper Machine Wet End	310	296	Paper making machine
	4,088	682	Subtotal	2,842	1,791	
	4,771		Total Energy		**4,633**	

Figure 17 Energy intensities of conventional and electric pulp and paper production processes [19]

This technology is the one that is more promising for the decarbonization of the sector.

Based on the findings of a joint working group comprising EHPA and CEPI members, heat pump systems integrated with steam compression and optimized paper production processes can achieve a Coefficient of Performance (COP) of 3 or higher. This performance level translates to energy savings of at least 67% and is attainable using both standardized and custom-engineered heat pump solutions [20].

According to CEPI [20], integrating of HTHPs into paper drying process is possible following these steps:

- Optimization
- Heat recovery
- Steam generation

Optimization. Enhancing paper production efficiency involves strategic temperature management throughout the process. By reducing the temperature differential required for heat pump operation, significant improvements in energy efficiency can be achieved. This can be accomplished through two primary approaches: first, by identifying and utilizing higher-temperature waste heat sources (such as drying hood vapors with temperatures of 60°C or greater[21]), and second, by implementing modifications to decrease the required process temperatures or steam pressure levels. These optimization strategies contribute to improved heat pump performance and overall energy conservation in the paper manufacturing operation.

Heat recovery systems can be implemented to capture both latent and sensible heat from wet air discharged by drying hoods, converting this thermal energy into usable warm water streams. While heat recovery implementation specifics must be tailored to each production facility's unique characteristics, standardization of heat exchanger components is recommended to ensure consistency and reliability. Given the presence of contaminants in the vapor stream, integration of Cleaning in Place (CIP) systems should be considered as a preventive maintenance measure.

Regarding steam generation, compression technology selection, screw compressors offer a particularly reliable solution for small to medium-sized operations. These units provide exceptional operational flexibility and maintain efficient performance across various pressure levels, making them well-suited for facilities with varying steam demands or those requiring adaptable production capabilities.

b) Estimation of the HTHP market potential

Paper industry is an important economic sector in the EU and also very energy consuming.

The European paper industry operates with 716 paper and board mills containing 1,173 paper machines, resulting in 1.64 machines per mill. The industry produces 74 Mtonnes per year of paper and board materials, operating at 77% of its total production capacity of 96.4 Mtonnes per year.

The graphic paper segment accounts for 16.7 Mtonnes annually, while Packaging paper and board accounts 49.6 Mtonnes and 7.6 Mtonnes for sanitary and household.

Papermaking is represented in this analysis by the drying stage of paper, board and graphic paper production only. The assessment uses as reference the stock of active paper machines, focusing on the final drying process where recoverable waste heat is available. Although integrated and recycled fibre mills differ at site level (notably due to upstream pulping and energy system configuration), this distinction is not material for the scope considered here, which isolates the dryer section of the paper machine. In addition, only a limited share of European mills are integrated (around 18% [22]). Therefore no further split between integrated and recycled mills was applied for the purpose of sizing the drying related HTHP market.

Energy Demand

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The pulp and paper industry consumes 310.3 TWh of fuels and 86.5 TWh of electric energy annually, with 96% generated through Combined Heat and Power (CHP) systems.

The drying process in the paper industry requires 1.37 MWh per tonne of paper/board products produced [21]. This translates to a total drying energy demand of 124.4 TWh annually, representing one-third of the total energy usage of the whole pulp and paper sector, and 70% of the energy consumed in a single papermaking mill[23].

If we assume an utilization of 7,000 h/yr of a paper machine, we calculate that the installed power in EU for drying processes is 21 GW. Since there are 716 paper and board mills, we can calculate an average installed power for every factory is around 30 MW.

We assume that the maximum sizes of a HTHP is 5 MW of installed power.

Therefore, the market potential is 4,208 units with an average installed power of 5 MW per unit.

Marina et al. [22] provide a bottom-up estimate of the EU28 industrial heat pump market potential, reporting the number of units, cumulative heating capacity, process-heat coverage, and electricity requirement for two maximum sink-temperature limits (150 °C and 200 °C). In Marina analysis the process heat demand in the 15–200 °C range is estimated at 99 TWh/yr, while waste heat in the same temperature range amounts to 64.1 TWh/yr, corresponding to 65% of process heat demand. The average duty across papermaking processes is 9 MW, whereas the weighted average duty (computed by weighting individual process duties by their corresponding energy demands) reaches 12 MW. Building on the Marina et al. dataset, we extrapolated the potential number of heat pump units using the same approach adopted in this deliverable, where the number of units U is calculated by dividing the annual process heat below 200 °C, expressed in MWh/yr (E), by the product of the unit duty $(P)$and annual operating hours (O_t= 7,000 hours/yr):

$$U = \frac{E}{P \cdot O_t}.$$

This yields a market potential of 2,063 units for the paper sector, associated with a weighted average unit size of 12 MW.

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3.3 Food and beverage industry

3.3.1 Sugar industry

The production of sugar from sugar beet follows a systematic sequence of operations designed to extract and purify sucrose (Figure 18)[24].

- **Juice Production (Extraction)**

The process begins with the preparation of sugar beets. Beets are stored in large piles before entering the production facility. Initially, the beets undergo thorough washing to remove soil and adhering plant matter. After cleaning, the beets are mechanically sliced into thin strips called "cossettes," which maximize the surface area for efficient sugar extraction. These cossettes are then fed into a diffusion apparatus where hot water is circulated in a counter-current flow to extract the sugar. This diffusion process dissolves the sucrose from the plant cells, resulting in raw juice containing sugar along with various dissolved impurities from the plant. The remaining solid material, known as beet pulp, is mechanically pressed to recover additional juice before typically being dried for use as animal feed.

- **Juice Purification**

The raw juice undergoes a calco-carbonic purification process to remove non-sugar impurities. In this stage, quicklime (CaO) is added to the raw juice, followed by the introduction of carbon dioxide (CO_2). This causes a chemical reaction that forms calcium carbonate precipitates, which bind with impurities in the juice. This process, known as carbonation, creates particles that can be removed from the solution. The juice then undergoes filtration through filter thickeners to separate the precipitated impurities from the clarified juice. The result is a clear juice with significantly reduced non-sugar content. The removed material, carbonate precipitate or "carbolime," can be repurposed as an agricultural amendment, providing additional value from the process.

- **Juice Evaporation**

The clear juice contains approximately 15% solids and must be concentrated through evaporation. This occurs in a multi-stage evaporation system, typically consisting of five to six effects arranged in series. Each evaporation stage operates at progressively lower pressures and temperatures, creating an efficient thermal cascade. This configuration allows the vapor generated from one effect to serve as the heating medium for the next effect, thus maximizing energy efficiency. The evaporation process removes most of the water content, resulting in a thick syrup containing 65-70% solids. This multi-effect approach is highly energy efficient as it enables the same unit of steam to be used multiple times throughout the evaporation sequence.

- **Crystallization**

The final stage involves crystallization and separation of the sugar crystals. The thick syrup enters vacuum pans where it is further concentrated under reduced pressure, which allows boiling at lower temperatures to prevent caramelization. Under controlled conditions, sugar crystals begin to form in this supersaturated solution. The resulting mixture of crystals and mother liquor, called massecuite, is then sent to centrifuges which separate the sugar crystals from the remaining liquid (molasses). The separated crystals are dried, cooled, and may undergo further processing depending on the desired end product, which could be white sugar or refined sugar. The separated molasses undergoes subsequent crystallization steps to extract additional sugar until it reaches a point where no more sugar can be economically recovered. This final molasses may be used for animal feed, fermentation processes, or other applications.

Throughout this process, cogeneration of heat and electricity is typically employed, with multiple effect evaporation allowing the same unit of energy to be used repeatedly. The process produces various co-products including dried pulp for animal feed, molasses, biogas in some facilities, and carbonate lime, which contribute to the overall economics and sustainability of beet sugar production.

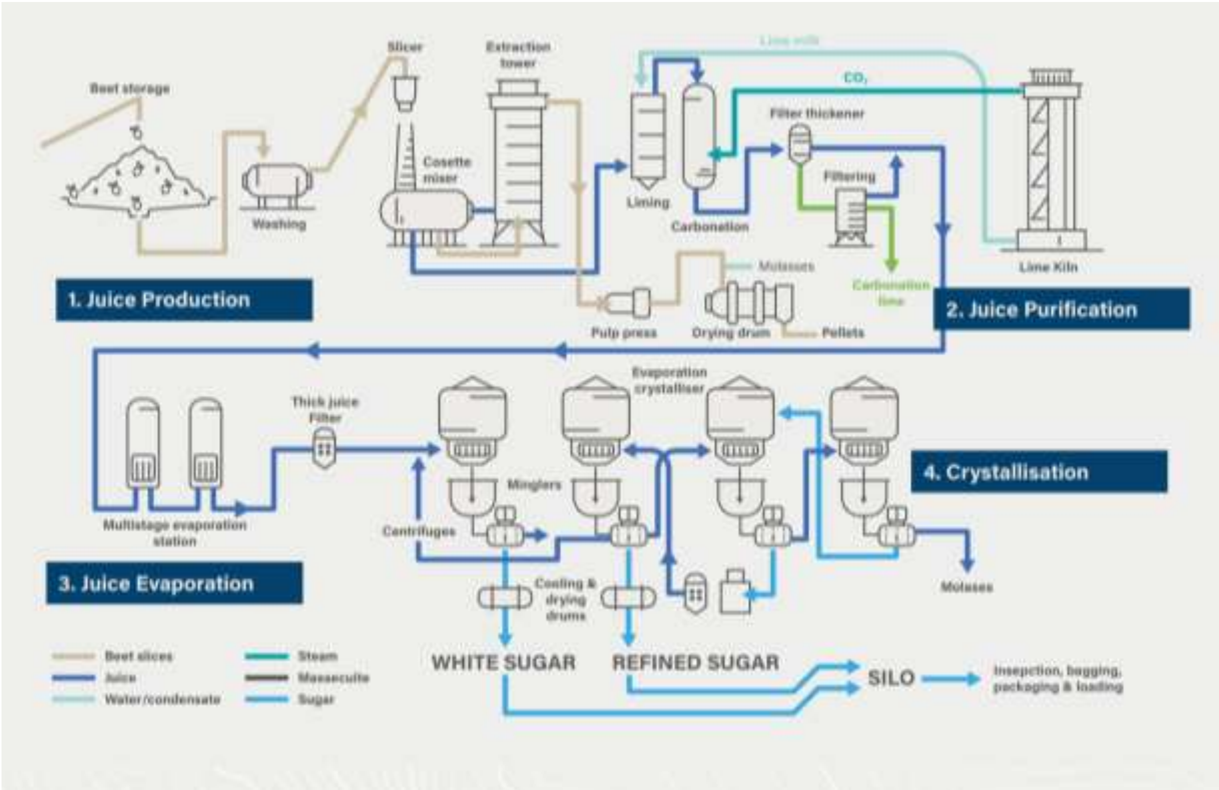

Figure 18 The beet sugar production process [24]

a) Suitable processes for HTHP

Several strategic intervention points emerge from analysis of the thermal system:

- Evaporation Stage Enhancement: HTHPs could upgrade waste heat from later evaporation effects (operating at approximately 89-103°C) to serve earlier effects requiring temperatures up to 130°C, reducing primary steam demand (Figure 19).
- Condensate Heat Recovery: The diagram indicates substantial condensate flows that could serve as heat sources for heat pump systems, particularly in the crystallization and diffusion processes.
- Process Electrification: Strategic electrification via heat pumps could decouple heat and power production, potentially enabling more flexible operation and integration with variable renewable electricity.
- Waste Heat Valorization: Low-temperature waste heat streams could be upgraded for district heating applications, creating synergistic relationships with surrounding communities while improving overall system efficiency.

The process that has been selected as the most promising for HTHPs is sugar evaporation.

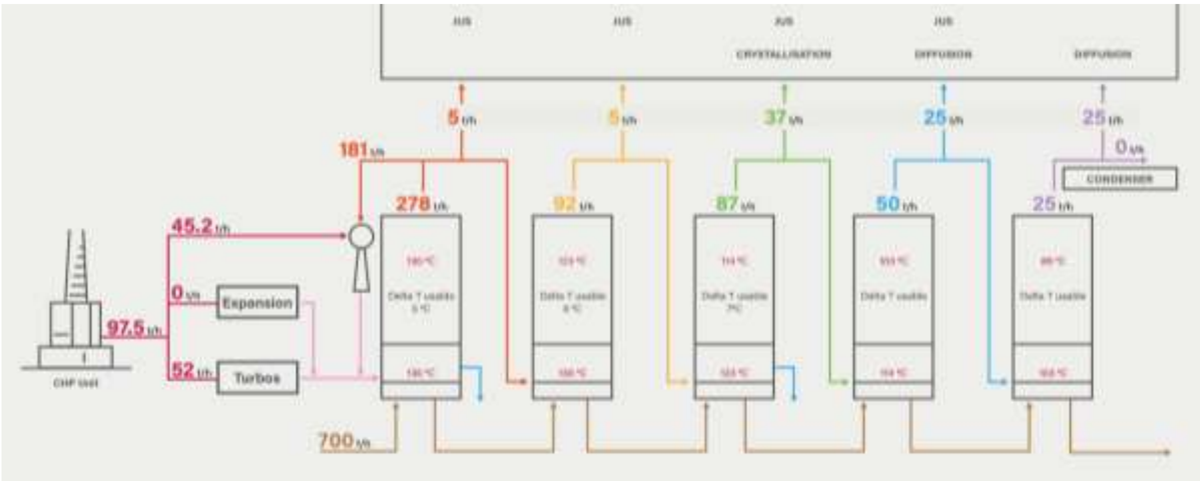

Figure 19 Example of a thermal diagram of a sugar factory (cogeneration and multiple effect evaporation)[24]

b) Estimation of HTHP market potential

The European sugar industry represents a significant industrial sector with substantial thermal energy requirements.

The production infrastructure is characterized by medium-to-large scale facilities, processing collectively around 16 million tonnes annually, produced in 88 factories across Europe [25].

The process of evaporation this sector has an installed capacity of approximately 1.3 GW across the subsector, with individual factories averaging 15 MW of installed thermal capacity, considering 4,000 operation hours per year.

Energy demand in the sugar production process is predominantly concentrated in the evaporation stage, which operates at temperatures between 115-120°C using steam as the primary thermal medium. This process demonstrates significant energy intensity at 60 kWh per tonne of processed material[22][21], resulting in a substantial annual thermal energy demand of 6.6 TWh across the sector. A notable characteristic of the process is the generation of waste heat from cooling processes, which represents an untapped energy resource. The multiple-effect evaporation systems already employed in modern sugar factories demonstrate the industry's experience with thermal cascades and heat recovery principles, suggesting receptiveness to further efficiency innovations. The seasonal operational profile of

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sugar processing facilities—typically running intensively during harvest periods—creates specific challenges and opportunities for energy system optimization.

The integration of high-temperature heat pumps in the sugar industry shows considerable technical potential based on the thermal requirements and existing infrastructure. With evaporation processes requiring temperatures of 115-120°C, modern HTHPs can effectively deliver heat at these temperatures with significant efficiency advantages over direct fossil heating. Waste heat from cooling processes provides an ideal low-temperature heat source for these systems.

The sector with 267 potential units of significant scale (5 MW each maximum installed power per unit in 88 factories across Europe) creates opportunities for standardized technological solutions and economy of scale benefits in deployment, potentially accelerating market penetration as technology costs decrease and carbon prices increase across Europe.

For white sugar, the process database compiled by Marina et al. [6] indicates a total EU-28 process heat demand of 15.1 TWh/yr, of which 14.2 TWh/yr falls within the 15–200 °C range. The associated waste heat amounts to 11.1 TWh/yr, entirely in the 15–200 °C range and reported as condensate streams at 50–65 °C. When considering only the process heat below 200 °C, the waste-heat stream linked to the 125 °C steam demand is 3.25 TWh/yr, corresponding to a waste heat to process heat ratio of 0.23 in the 15–200 °C domain. In contrast, when the full heat balance is considered (including a high-temperature steam demand at 250 °C, outside the 15–200 °C window), the overall waste heat-to-process heat ratio increases to 0.74, reflecting the large low-temperature condensate stream (7.88 TWh/yr) associated with the >200 °C heat demand. In terms of unit sizing, the arithmetic mean duty reported for the two steam levels is 64 MW, while the demand weighted average duty for the 15–200 °C process heat segment is 120 MW.

Applying the same unit estimation approach used in this deliverable, the potential number of HTHP units, calculated as $U = \frac{E}{P \cdot O_t}$, with sector specific operating hours O_t= 4,000 hours/yr, resulting in 30 units of market potential for white sugar in the EU-28 (within the 15–200 °C process heat boundary).

3.3.2 Animal feed industry

The production of compound animal feed (Figure 20 and Figure 21) [26] begins with a comprehensive intake system that handles various raw materials through multiple entry points. These materials arrive in different forms - as bulk raw materials, bagged goods, and liquid substances - and are initially processed through a carefully designed storage infrastructure of silos and bin storage systems.

The initial processing stage involves grinding, which transforms the raw materials into more manageable consistencies. Some materials pass through blending bins, allowing for initial mixing and preparation. A secondary grinding stage ensures that the materials achieve the desired particle size and uniformity, preparing them for the next critical phase of production.

At the heart of the process is the main mixer, where multiple ingredients converge. Molasses and dry products are combined with precision, creating a base mixture that will become the final animal feed. Steam conditioning follows, a crucial step that helps to modify the mixture's properties, improving digestibility and reducing potential pathogenic risks.

The conditioned mixture then moves through a pressing process, which shapes the feed into its final form. A cooling stage immediately follows, stabilizing the product and ensuring its structural integrity. Some production lines incorporate a fat coating process, which can enhance the feed's nutritional profile and palatability.

The final stage involves careful packaging and storage. Depending on the intended market and distribution requirements, the feed can be stored and packed in bulk quantities, placed in intermediate totes, or packaged in bags ready for direct sale to farmers and agricultural businesses.

This methodical process ensures that each batch of animal feed meets stringent quality standards, providing optimal nutrition for livestock while maintaining efficiency in industrial production.

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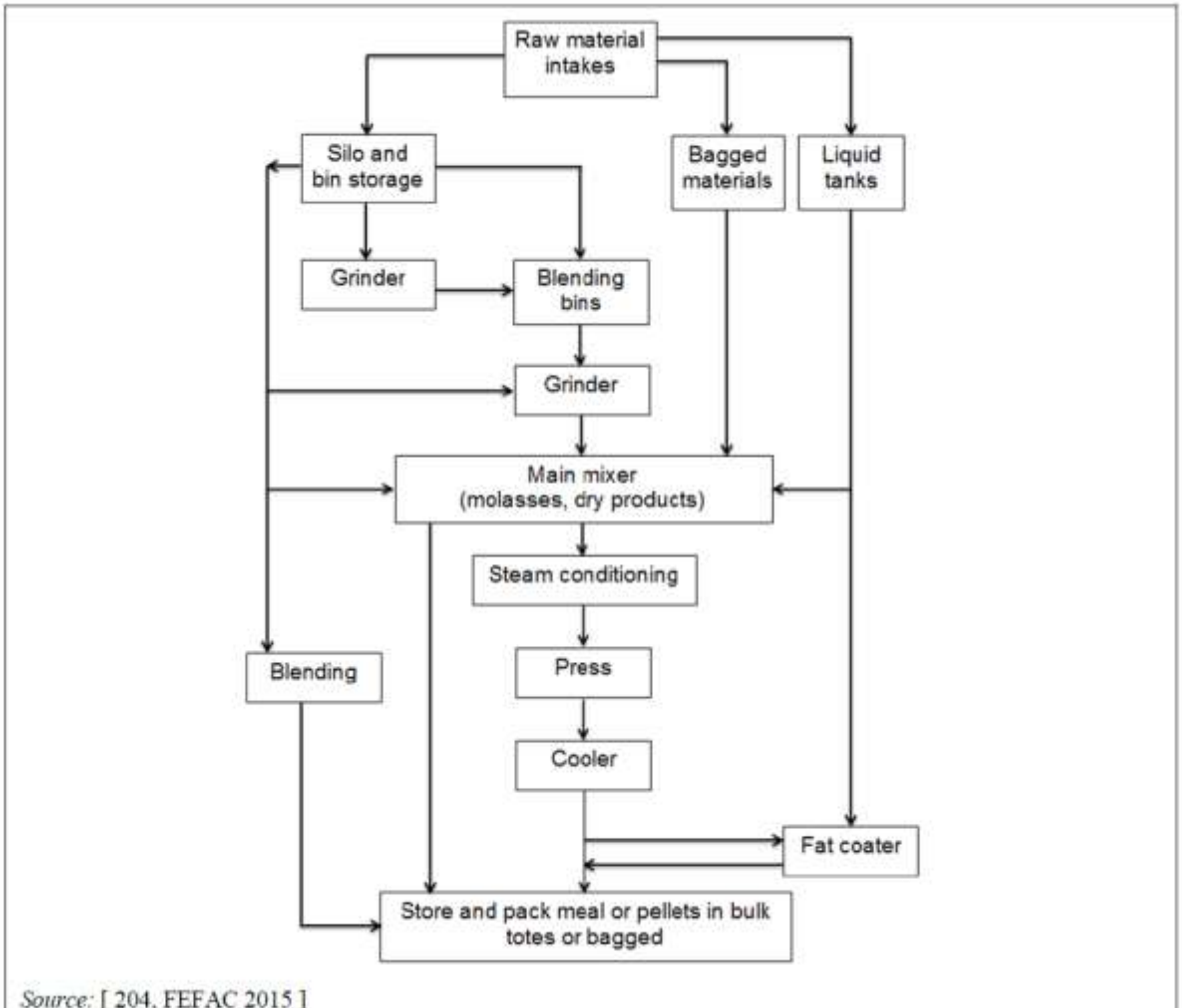

Figure 20 Diagram of process of animal feed industrial production[26]

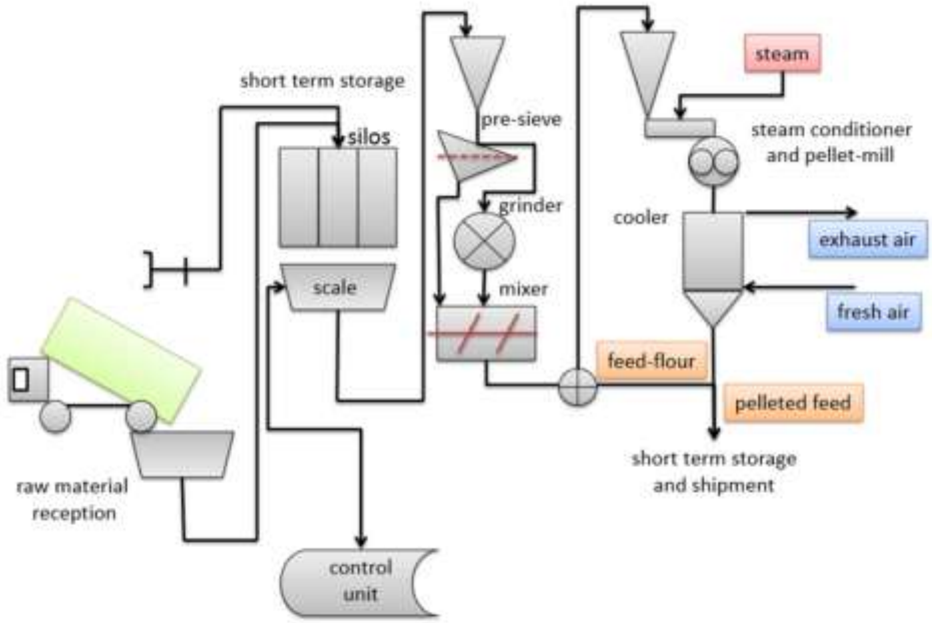

Fig. 1: Flow sheet of a single-line compound feed production plant

Figure 21 Flow sheet of a single lie compound feed production plant [27]

a) Suitable industrial processes for HTHP

Steam conditioning of feed pellet is a very promising process for HTHPs.

There are already examples of existing installations of conventional heat pumps for producing steam at 120ºC in pet feed production (Figure 22, Figure 23 and Figure 24), like the 1.6 MWth installed in Norway in the Company Felleskiøpet [28].

Waste heat is recovered from the cooling of the pellets.

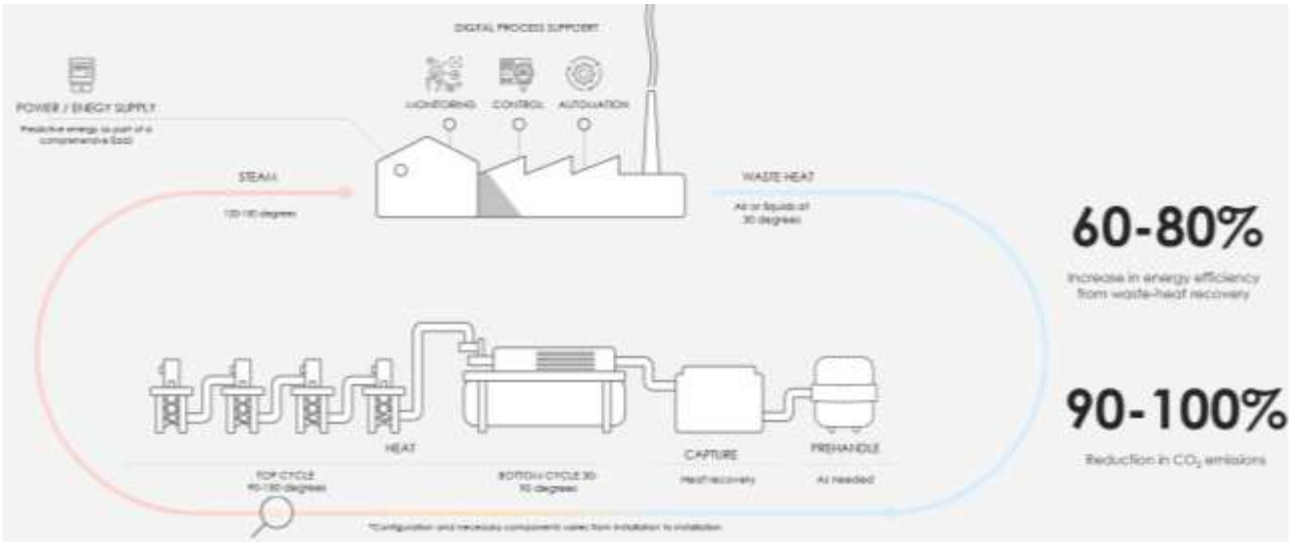

Figure 22 Example of electrification of pet food production [28]

Figure 23 describes the process that has been electrified with heat pumps.

Raw product enters the system and undergoes mixing and heat treatment. This initial stage utilizes steam at specific parameters (2 bar pressure and 140°C temperature).

Pellet shaping section is where the mixed product is formed into pellets, then newly formed pellets enter the cooling phase, where their temperature is reduced.

The process concludes with pellets packaging as final production stage.

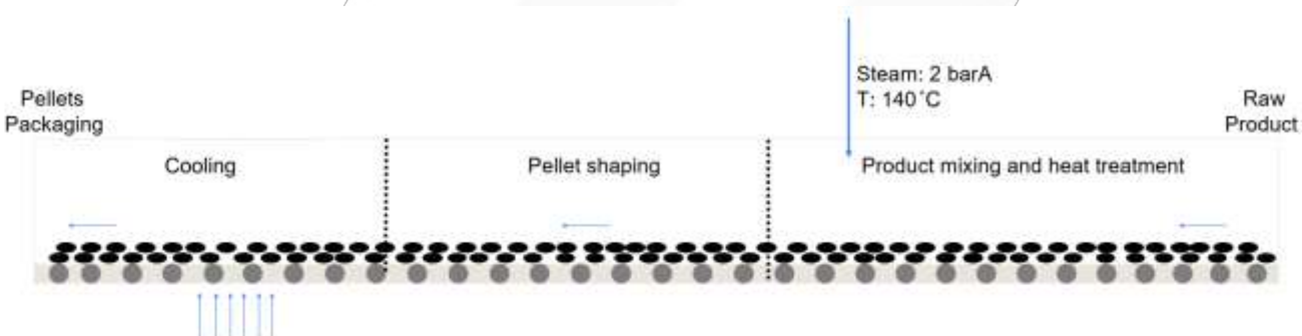

Figure 23 Pet feed pellets process with heat recycling [28]

In Figure 24 we understand that the steam production is performed through a cascade system with two heat pumps. The system operates with steam output at 120°C with a capacity of 2000 kg/h.

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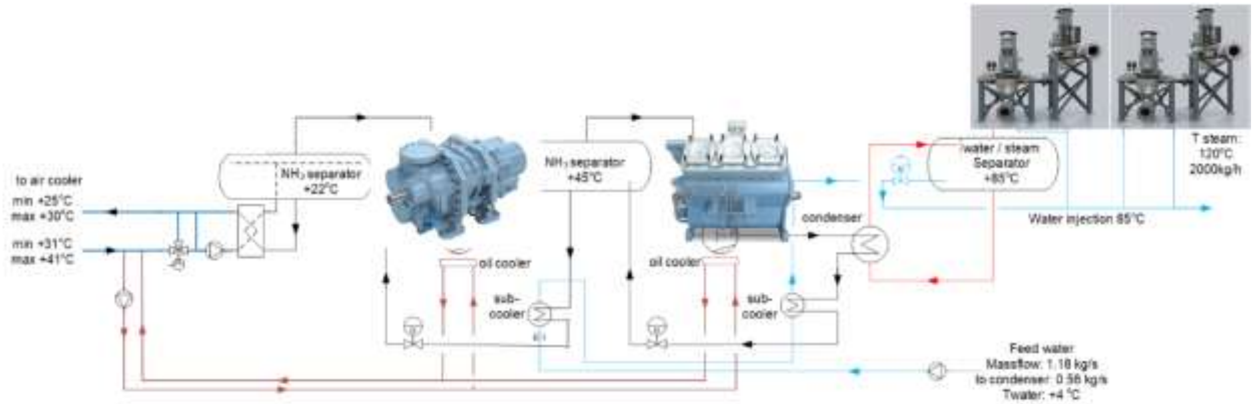

Figure 24 Simplified system design of installed system at Frigg[28]

b) Estimation of the HTHP market potential

The European feed industry operates with approximately 3,200 compound feed mills producing around 150 Mtonnes of feed annually [29].

The production is distributed across three primary segments: poultry feed accounting for 33% (48 Mtonnes), pig feed representing 34% (50 Mtonnes), and cattle feed comprising 28% (42 Mtonnes). The remaining 5% (12 Mtonnes) serves other animal categories including rabbits, fish, and pets.

The feed manufacturing industry consumes approximately 10 TWh of total energy annually, with 7 TWh in thermal energy and 3 TWh in electrical energy [30]. The distribution of energy demand varies significantly across process sequences.

The data presented in Table 3 provides a comprehensive breakdown of energy demand across various process sequences in animal feed production for three categories: rabbits, poultry, and large animals [31].

The total energy demand for the production process amounts to 0.068 MWh/tonne for rabbits feed, 0.060 MWh/tonne for poultry feed, and 0.025 MWh/tonne for large animals feed. Pelletization (Process 13) stands out as the most energy-intensive stage in the production chain, accounting for 72% to 83% (0.018-0.055 MWh/tonne) of total energy demand in feed production.

After pelletization, the next most energy-intensive processes include:

- Grinding (Process 3): Consuming approximately 5.2-5.8% of total energy demand
- Mixing (Process 10): Using 1.8-6.6% of total energy demand
- Handling stage 2 (Process 4): Requiring 2.4-2.6% of total energy deamnd

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The disproportionate energy demand during pelletization suggests that this particular process should be the primary focus for implementing energy recovery systems or heat pump technologies to improve overall energy efficiency in animal feed production facilities.

Moreover, the cooling process can be the waste heat source for the HTHP.

Table 3 Specific energy demand in manufacturing rabbits, poultry and large animals feed pellets [31]

Process Sequences	Process	Total Energy Consumed (MWh/t) - Rabbits feed	Total Energy Consumed (MWh/t) - Poultry feed	Total Energy Consumed (MWh/t) - Large animals feed	% of Total Energy Consumed - Rabbits feed	% of Total Energy Consumed - Poultry feed	% of Total Energy Consumed - Large animals feed
1	Raw materials receiving	0.000	0.000	0.000	0.02%	0.02%	0.1%
2	Handling stage1 (corn from storage tank to the mill, H1)	0.001	0.001	0.000	1.4%	1.6%	1.7%
3	Grinding	0.003	0.003	0.001	5.2%	5.8%	5.7%
4	Handling stage 2 (crushed corn to the corn tank, H2)	0.002	0.002	0.001	2.4%	2.6%	2.6%
5	Handling stage 3 (crushed corn to the weighing unit tank, H3)	0.000	0.000	0.000	0.2%	0.2%	0.2%
6	Handling stage 4 (soybean to the soybean tank, H4)	0.000	0.000	0.000	0.4%	0.4%	0.4%
7	Handling stage 5 (soybean to the weighing unit tank, H5)	0.000	0.000	0.000	0.2%	0.3%	0.3%
8	Handling stage 6 (to the weighing unit tank, H6)	0.000	0.000	0.000	0.4%	0.3%	0.4%
9	Handling stage 7 (to the mixer, H7)	0.000	0.000	0.002	0.4%	0.3%	6.6%
10	Mixing	0.002	0.001	0.002	2.8%	1.8%	6.6%
11	Handling stage 8 (to the pellet mill tank, H8)	0.002	0.000	0.000	2.4%	0.4%	1.4%
12	The feeder (H9)	0.001	0.000	0.000	0.8%	0.6%	0.9%
13	**Pelletization**	**0.055**	**0.050**	**0.018**	**80.8%**	**83.3%**	**71.9%**
14	The cooler	0.000	0.000	0.000	0.2%	0.2%	0.2%
15	Belt conveyor (H10)	0.001	0.001	0.000	2.0%	1.9%	0.5%
16	Handling stage11 (packaging, H11)	0.000	0.000	0.000	0.2%	0.2%	0.1%
17	Weighing and sewing	0.000	0.000	0.000	0.1%	0.1%	0.3%
18	Loading	0.000	0.000	0.000	0.02%	0.02%	0.02%
	Tot.	0.068	0.060	0.025	100%	100%	100%

Pelletization stands as the dominant energy-demanding process, accounting for 71.9-83.3% of total energy demand depending on the feed type. This process requires 0.055 MWh/tonne for rabbits feed, 0.050 MWh/tonne for poultry feed, and 0.018 MWh/tonne for large animal feed, representing a significant opportunity for energy optimization.

Secondary energy-intensive processes include grinding (5.2-5.8%), mixing (1.8-6.6%), and material handling stages (collectively 7-10% across all stages).

The animal feed sector represents a significant opportunity for industrial heat pump integration. Pelleting conditioning, a critical process in animal feed production, requires steam at temperatures ranging from 70°C to 90°C, with thermal energy demand of 5 TWh per year dedicated to this process.

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The energy intensity of pelleting conditioning (34 kWh/tonne) combined with the availability of waste heat from existing cooling processes creates favorable conditions for heat pump implementation. Currently, the subsector operates with an installed thermal capacity of 718 MW across the EU, with the average factory utilizing approximately 224 kW of thermal capacity for this process [32].

Analysis of the infrastructure and energy requirements indicates a significant market potential of approximately 3,200 units with an installed capacity of 224 kW each. The sector's moderate temperature requirements (70-90°C) make it an ideal early adopter for industrial heat pump technology, serving as a stepping stone toward applications requiring the 160°C capabilities currently being developed.

3.3.3 Brewing industry

The brewing process comprises four main phases that transform raw materials into the final beer product. Each phase involves specific operations with varying energy requirements (Figure 25) [33].

Phase 1: Dry Phase

The brewing process begins with the dry phase, where malted barley arrives at the brewery and undergoes milling. This process crushes the malt to ensure high yield extraction in subsequent steps. The dry phase:

- Uses minimal electrical energy and no thermal energy
- Is often incorporated into the brewhouse phase in operational analyses

Phase 2: Brewhouse Phase

The brewhouse phase requires substantial amounts of steam for heating and boiling:

1. Mashing: The milled malt is mixed with water and heated to approximately 70°C. During this process, enzymes in the mash convert starch into sugars such as maltose, creating a sweet substance called wort.
2. Filtration: The wort and grains are separated using a mash filter, resulting in filtered wort and spent grains.
3. Wort Boiling: The filtered wort is boiled with steam for up to 90 minutes, with an evaporation rate between 4-12%. During boiling, hops are added for bitterness and flavor. This critical step serves multiple purposes:
    - Sterilization of the wort
    - Concentration of the wort
    - Stabilization of the wort

- Isomerization of hops
- Removal of volatile compounds

4. Clarification: The boiled wort is clarified using a whirlpool to ensure efficient fermentation.

Phase 3: Cold Phase

The cold phase begins with cooling the wort to fermentation temperature:

1. Cooling: In modern breweries, heat extracted during wort cooling is typically recovered to pre-heat other processes.
2. Fermentation: Yeast is added to convert sugars into alcohol and carbon dioxide. This process takes a few days for ales and up to 10 days for lagers. Fermentation generates significant heat that must be dissipated to avoid damaging the yeast.
3. Yeast Removal: A centrifuge removes the yeast after fermentation.
4. Maturation: The beer is transferred to maturation tanks and held at conditioning temperatures between -1ºC to 10ºC for several days to over a month.
5. Filtration: A filter removes any remaining proteins before the beer is sent to bright beer tanks.

This phase requires substantial electricity for cooling and typically takes two to three weeks to complete.

Phase 4: Packaging Phase

The final phase involves packaging the finished beer:

1. Pasteurization: Depending on the packaging type, beer is either pasteurized first then packed, or bottled first then pasteurized. This process requires thermal energy (steam or hot water) to heat the beer to approximately 60ºC, eliminating harmful bacteria and stopping yeast activity.
2. Packaging: The beer is packaged into various containers such as bottles, cans, kegs, or bulk tanks. Energy requirements vary significantly by packaging type, with bottling being the most energy-intensive.

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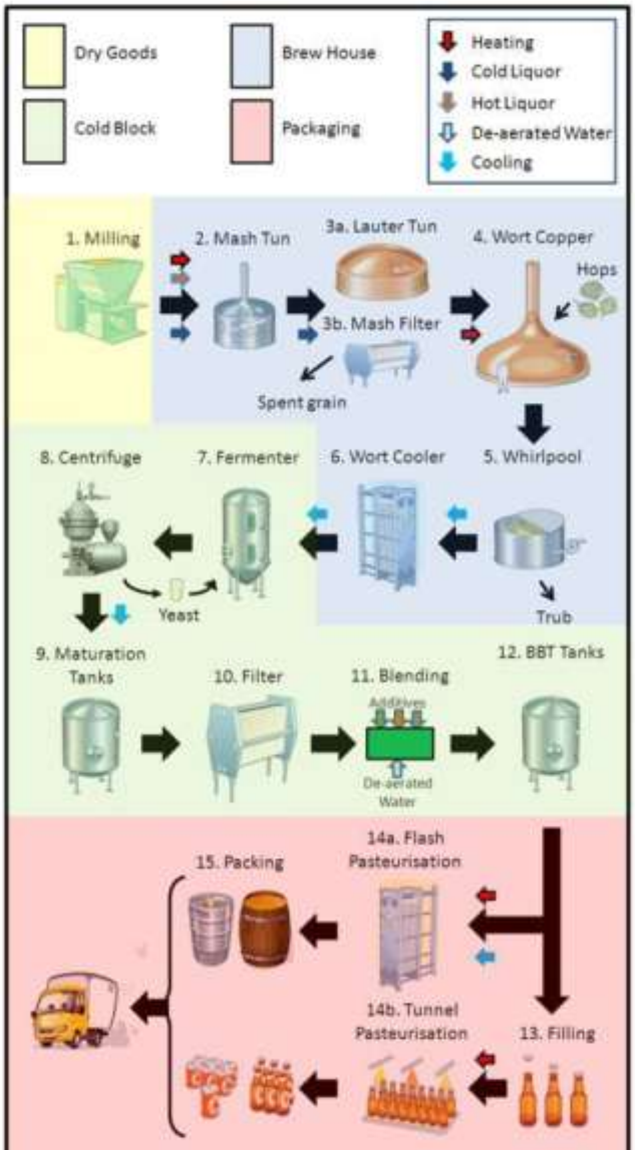

Figure 25 The brewing process diagram [33]

The brewing process requires both thermal and electrical energy:

- Thermal Energy: Generated in boiler houses or combined heat and power (CHP) plants using natural gas, and sometimes supplemented with biogas from wastewater treatment. Major consumers include wort boiling and mashing (approximately 50% of steam use), with wort boiling alone accounting for 20-40% of all thermal energy used in a brewery.
- Electrical Energy: Major consumers include refrigeration (44%), packaging (20%), and compressed air (10%), along with numerous smaller consumers like pumps, ventilators, drives, and lighting.

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Energy costs represent 3-8% of total production costs, making efficient energy use a significant factor in brewery profitability.

a) Suitable processes for HTHP

Wort boiling represents the single most energy-intensive process in brewing, accounting for 20-40% of total thermal energy demand. This process:

- Requires temperatures of 115-120°C
- Currently relies primarily on steam
- Serves multiple critical functions including sterilization, concentration, stabilization, hop isomerization, and volatile removal

The brewing process generates significant waste heat that can be harnessed to improve HTHP efficiency in wort boiling:

- Wort cooling: The transition from boiling to fermentation temperature (cooling from approximately 100°C to 20°C) generates substantial recoverable heat
- Vapor condensation**:** The 4-12% evaporation during wort boiling itself produces vapor that can be partially recovered
- Refrigeration systems**:** The cold phase of brewing requires extensive refrigeration that produces continuous waste heat streams

b) Estimation of HTHP market potential

The European brewing industry operates at significant scale and offers substantial market potential for HTHP deployment, with annual production of around 32 million tonnes of beer [34] and an estimated 15.1 TWh/yr of thermal energy demand for brewing processes. The subsector's total installed thermal capacity is approximately 2,159 MW, distributed across a highly fragmented infrastructure of roughly 10,000 breweries in the EU, where microbreweries account for about 60% of sites and industrial-scale breweries around 40%.

This structure results in a relatively low average installed capacity of about 220 kW per facility, largely driven by the high number of small plants, and implies that modular, standardized HTHP packages could be particularly suitable for widespread uptake. From a process-integration perspective, brewing relies predominantly on steam as the thermal medium, with key steps (most notably wort boiling) requiring temperatures in the 115–120 °C range, which are compatible with HTHP supply conditions. On this basis, and consistent with the cited infrastructure profile, the

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market potential is estimated at approximately 3,200 HTHP units with an indicative unit capacity of 675 kW [32].

For beer, the process database reported by Marina et al. indicates a total EU-28 process heat demand of 4.76 TWh/yr, entirely within the 15–200 °C range. The heat demand is supplied mainly by steam at 135 °C (4.14 TWh/yr) and, to a smaller extent, by hot water in the 15–70 °C (0.55 TWh/yr) and 12–75 °C (0.07 TWh/yr) ranges.

The associated waste heat amounts to 2.49 TWh/yr, with 2.32 TWh/yr in the 15–200 °C interval and primarily characterized as condensate streams (with representative temperature levels around 45–12 °C, 22–12 °C, and 75–12 °C), while additional waste streams are reported as spent grain (76–12 °C) and vapor (100–12 °C). Overall, the aggregated waste heat-to-process heat ratio is 0.29 (total basis) and 0.27 when restricting to 15–200 °C waste heat.

In terms of unit sizing, the dataset reports duties of 1.8 MW for the 135 °C steam demand and 0.2 MW for the hot water demand, resulting in a demand-weighted average duty of 1.6 MW for the beer subsector. Applying the same unit-estimation method used in this deliverable, the potential number of heat pump units is 328, considering only steam production.

3.3.4 Oilseed industry

Oilseed crushing process involves several sophisticated steps designed to extract and process oils efficiently while maximizing yield. The following description focuses primarily on rapeseed processing, but the fundamental principles apply to most oilseeds(Figure 26) [35].

Mechanical Extraction Phase

The process begins with seed preheating, where seeds are warmed to approximately 60°C without significant moisture change. This preheating improves seed plasticity for subsequent flaking.

Seeds then move to flaking equipment, which flattens them to increase surface area. This mechanical process does not significantly alter temperature, though some heat loss (approximately 5°C) occurs during conveying between processing stations.

Flakes enter cooking equipment where several critical changes occur:

- Reduction in oil viscosity, improving flow during pressing
- Coagulation of interfacial proteins, destabilizing cellular structures

- Controlled drying to reduce water content from approximately 7.9% to 5.0%

This moisture reduction is crucial as water acts as a plasticizer, which would otherwise reduce pressure effectiveness in subsequent pressing operations.

In the mechanical extraction step, prepared flakes are pressed in a screw press. The material is maintained in a cage designed to allow oil flow while withstanding high mechanical force from a rotating screw. The mechanical work generates heat, raising the temperature of both cake and oil. This process extracts approximately 70% of the available oil.

The remaining pressed cake, still containing about 21% oil, undergoes granulation in some facilities to create pellets with favorable characteristics for subsequent solvent extraction. This ensures consistent percolation of solvent through the material. The pellets are then cooled from 105-115°C to approximately 80°C before solvent extraction.

Solvent Extraction Phase

The cake or pellets enter a countercurrent extractor where hexane solvent percolates through the material. Key parameters include:

- Operating temperature: 45-60°C (typically 55°C)
- Solvent entry temperature: approximately 40°C
- Miscella (oil-solvent mixture) concentration: 25% oil
- Hexane retention: approximately 30% in the spent material
- Solvent usage: about 600 kg per tonne of processed seeds

After extraction, the solvent-laden material (marc) enters a desolventizer where:

- Indirect heating occurs through steam-heated trays
- Direct steam injection removes remaining solvent
- Temperature control is critical, with exhaust vapors maintained around 70°C
- Steam usage is approximately 0.12 kg per kg of hexane to be removed

This process results in meal with approximately 11.5% moisture content. Modern desolventizers are designed to minimize protein damage from excessive moisture and heat exposure.

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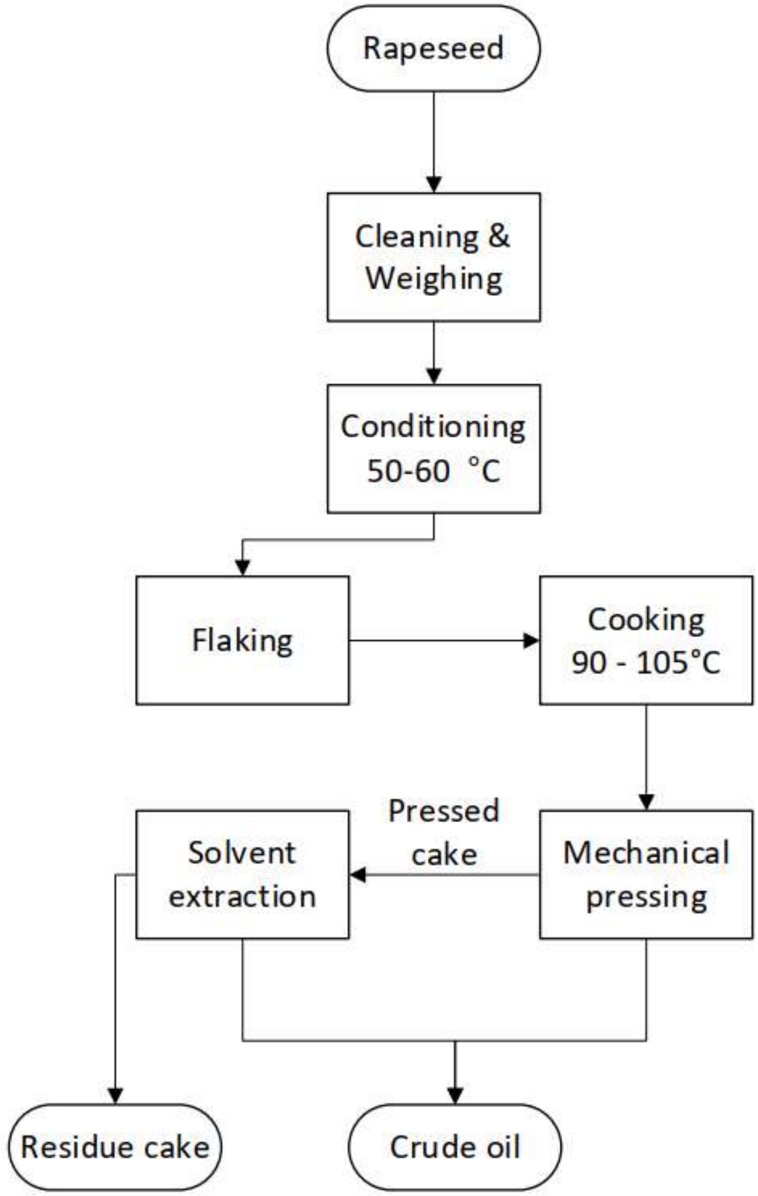

Figure 26 Crushing process flow of rapeseeds[36]

a) Suitable processes for HTHP

The flakes cooking process is a critical step in the rapeseed oil extraction workflow, positioned after flaking and before mechanical extraction. Flakes cooking serves three essential functions:

- Reducing oil viscosity to improve flow through the cake matrix
- Coagulating interfacial proteins to destabilize oil bodies and increase oil availability

- Performing controlled drying to reduce water content from approximately 7.9% to 5.0% in flakes

Water acts as a plasticizer in the cake. Excessive moisture reduces the cake's structural integrity during pressing, leading to lower pressure in the expeller and reduced oil extraction efficiency.

Table 4 Energy requirements per tonne of processed seeds[35]

Process	Heat Required (kWh)	Steam Demand (kWh)
Heating flakes (55°C to 105°C)	31	15
Vaporization of 30kg water	18	9
Heating drying air (20°C to 100°C)	2	1
Total	51	25

The data shows that approximately half of the total thermal energy requirement is delivered through steam demand, which constitutes a significant portion of the overall energy utilization in oil mill operations.

The cooking process represents approximately 70% of the total preparation energy (70 kWh/tonne) before extraction, making it a primary target for energy optimization efforts in oil mill operations.

b) Estimation of HTHP market potential

The European oilseed processing industry represents a significant industrial sector, with an annual production of 14.5 million tonnes of rapeseed and sunflower oil [37]. The 180 industry's production facilities are designed around core thermal processes: they are typically configured to optimize material flow between preparation, pressing, and extraction phases, with steam generation and distribution systems representing essential infrastructure components for maintaining consistent production parameters.

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Energy demand in the oilseed processing industry is dominated by thermal processes, with flakes cooking representing one of the most energy-intensive operations at 31 kWh per tonne of processed seeds[35]. The industry's total thermal energy demand for this process reaches approximately 1.1 TWh annually, primarily supplied through steam systems operating at temperatures above 100°C. This significant energy requirement stems from the need to heat flakes to optimal temperatures for protein coagulation and moisture reduction, while simultaneously overcoming the inherent challenges of heat transfer in materials with poor thermal conductivity. The cooking process alone represents approximately 70% of the preparation energy in oil extraction operations, highlighting it as a critical focus area for energy efficiency improvements within the industry's thermal profile.

The flakes cooking process is characterized by a network of processing facilities with an average installed thermal capacity of 800 kW per 180 factory, collectively contributing to the subsector's substantial installed capacity of 151 MW and a demand of 1.1 TWh/yr dedicated to this process.

Heat pump integration presents a compelling opportunity for energy optimization in the oilseed processing sector, with market potential for approximately 180 units at 800 kW installed capacity. The technical feasibility hinges on leveraging waste heat from cooling processes throughout the production chain, particularly from the cooling of press cake, meal, and extracted oils. High-temperature industrial heat pumps capable of delivering process temperatures up to 105°C would be required to serve the flakes cooking process effectively.

For sunflower and rapeseed oil processing, the process dataset reported by Marina et al. indicates a combined EU-28 process heat demand of 4.62 TWh/yr, fully within the 15–200 °C range and supplied as steam at 180 °C. Sunflower oil accounts for 1.1 TWh/yr, while rapeseed oil represents 3.5 TWh/yr.

The corresponding waste heat totals 1.93 TWh/yr, reported as condensate streams across several temperature levels (notably around 175 °C, 105 °C, 100 °C, and 66 °C). Focusing on the 15–200 °C domain, the dataset yields a relatively low aggregated waste heat-to-process heat ratio of 0.06, consistent across both products. In terms of unit sizing, the duty associated with the 180 °C steam demand is 8.9 MW for both sunflower and rapeseed oil. Applying the same unit-estimation approach used in this deliverable, the implied number of potential heat pump units is 74 units for oilseeds processing (17 for sunflower oil and 57 for rapeseed oil).

3.3.5 Dairy industry

The dairy sector encompasses activities related to the treatment of milk for alimentary use and milk-derived products. It represents the most significant sector within the European food industry in terms of economic value, contributing approximately € 18 billion to the EU trade surplus and employing around 45,000 persons [38]. The industry is characterized by a substantial concentration of production capacity, with five major dairy-producing countries—France, Germany, the Netherlands, Italy and Poland [39].

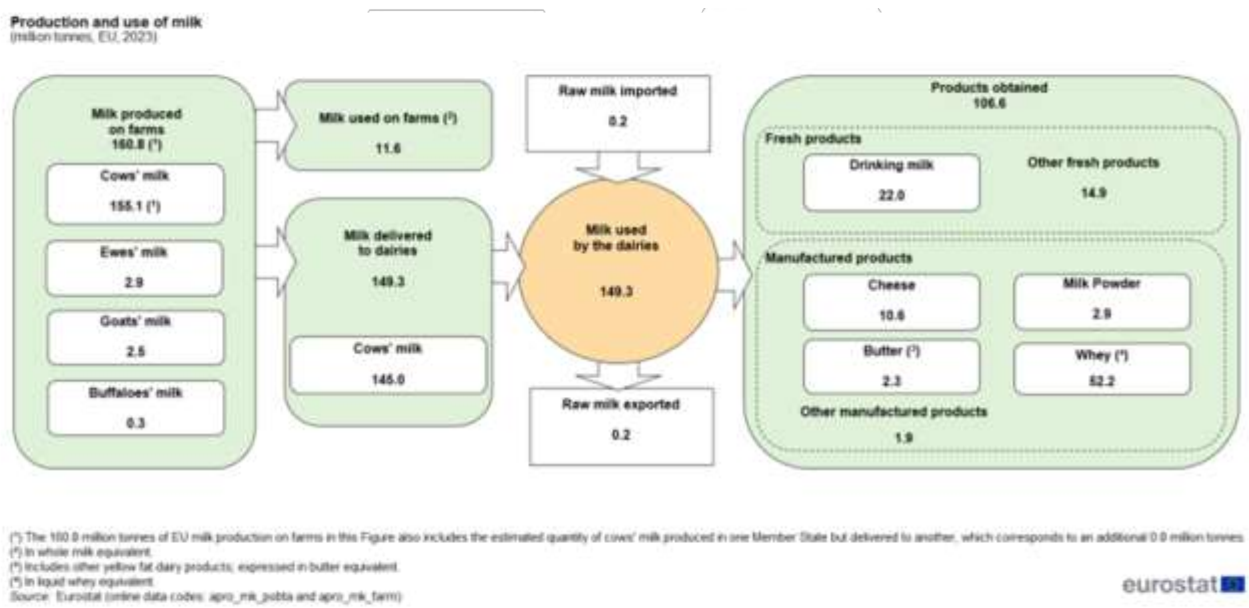

Figure 27 European dairy industry production [39]

As illustrated in the Figure 28 flow chart, the dairy industry follows a complex process structure starting from raw whole milk. This milk undergoes initial cooling and storage (at ≤6°C) before proceeding through thermization and separation processes. The production chain then branches into multiple pathways:

- Fluid Milk Processing: Involves pasteurization (72-75°C), cooling, and packaging. Different heat treatments produce pasteurized milk (72°C for 15s), sterilized milk (115°C for 20 min), or UHT milk (138-150°C for 1-4s).
- Cream Processing: Split from whole milk during separation, cream undergoes pasteurization (80-90°C or 72-110°C), potentially followed by deodorization, ripening, churning, and packaging to produce retail cream or butter.
- Cheese Manufacturing: Involves pasteurization, curd formation (30-45°C), whey separation, pressing, salting, and ripening. Fresh, soft, and hard cheeses require different ripening conditions and durations.

- Milk Powder Production: One of the most energy-intensive processes, involving pasteurization, thermal concentration/evaporation (72-150°C), and spray drying (90-95°C).
- Condensed Milk Production: Requires evaporation, cooling, packaging, and sterilization (100-140°C).
- Whey Processing: A by-product of cheese production that can be further processed into whey powder and protein concentrates.

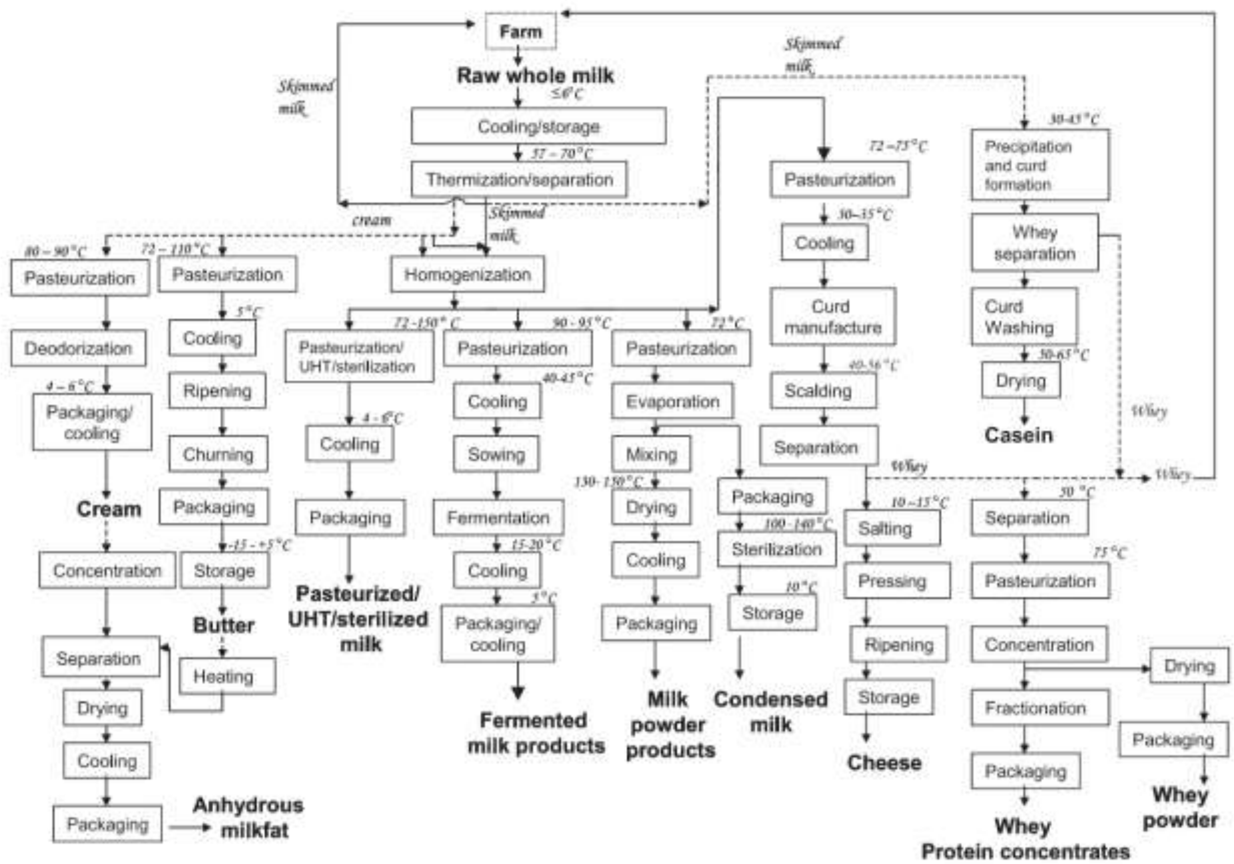

Figure 28 The European dairy industry [40]

Energy plays a crucial role in dairy processing, primarily for heat treatments that control bacterial growth and extend shelf life. Key energy-demanding processes include[40]:

1. Heat Treatment: Pasteurization, UHT treatment, and sterilization requiring temperatures from 72°C to 150°C.
2. Concentration/Evaporation: Accounting for up to 45% of energy use in milk powder production.

3. Drying: Particularly energy-intensive, consuming 51% of the energy in milk powder processing.
4. Cleaning-in-Place (CIP): Essential for maintaining hygiene standards and preventing fouling, representing 9.5-26% of energy use depending on the product.

a) Suitable processes for HTHP

The European dairy industry presents two significant opportunities for High-Temperature Heat Pump integration within critical thermal processes. The first opportunity exists in milk pasteurization, which operates within the 80°C to 110°C temperature range using steam as the primary heating medium. This process requires 58 kWh of thermal energy per tonne of processed milk and generates valuable waste heat from associated cooling operations.

The second viable application is in milk powder spray drying, which demands higher operating temperatures of 130-150°C and represents one of the most energy-intensive dairy processes at 1.57 MWh per tonne of product[40]. Spray drying operations produce significant waste heat streams from both evaporation and cooling processes, creating ideal conditions for HTHP implementation. Both processes present technically feasible scenarios for HTHP integration due to their temperature requirements, continuous operation characteristics, and the presence of recoverable waste heat streams.

b) Estimation of HTHP market potential

The European dairy industry's production infrastructure comprises approximately 12,000 processing facilities [41], creating substantial market potential for HTHP technology. The milk pasteurization subsector maintains an installed thermal capacity of 1.25 GW across facilities with an average of 100 kW thermal systems, processing 150 million tonnes of milk annually and consuming 8.7 TWh of thermal energy.

This infrastructure presents a market potential of 1,843 HTHP units at 675 kW capacity[32].

The milk powder spray drying segment, though smaller in production volume at 2.9 million tonnes annually, represents significant energy demand at 4.6 TWh per year with an installed subsector capacity of 650 MW. Heat pump integration analysis indicates this segment could support 964 HTHP installations at 675 kW capacity [24]. These implementations would leverage available waste heat from cooling and

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evaporation processes, significantly reducing primary energy consumption while maintaining the critical temperature requirements of both processes.

For milk powder, the process dataset reported by Marina et al. shows a total process heat demand of 5.64 TWh/yr, of which 5.20 TWh/yr lies within the 15–200 °C range. The heat demand is split between a large hot-air drying load (3.1 TWh/yr) associated with air heating over 9–220 °C (partly exceeding 200 °C), and a steam demand at 180 °C (2.1 TWh/yr). The associated waste heat amounts to 2.06 TWh/yr, entirely reported as condensate streams across several temperature levels (notably 81 °C, 75 °C, and additional condensate flows between 69 °C and 45 °C). On an aggregated basis, the dataset yields a waste heat-to-process heat ratio of 0.16, increasing to 0.17 when the comparison is restricted to 15–200 °C process heat. In terms of unit sizing, the dataset reports duties of 6.3 MW for the air heating demand and 3.7 MW for the 180 °C steam demand; the resulting demand weighted average duty is 5.4 MW on a total basis and 5.3 MW when restricting to the 15–200 °C segment. Applying the same unit estimation approach used in this deliverable, the dataset implies 160 units, corresponding to 80 units for the air heating load and 80 units for the steam demand.

3.3.6 Canned fruits and vegetables industry

The processed fruit and vegetable sector represents a distinctly European industry, with the majority of raw materials sourced from European agricultural production.

The European Association of Fruit and Vegetable Processing Industries [42] serves as the principal representative body for this sector, encompassing over 500 companies across 11 European Union member states. The association's membership spans the full spectrum of processed fruit and vegetable products:

- frozen vegetables, 3.3 million tonnes
- canned vegetables, 2.1 million tonnes
- dehydrated vegetables, 50,000 tonnes
- canned deciduous fruit and compotes, 1 million tonnes
- jams and fruit spreads, 485,000 tonnes

PROFEL member companies collectively employ more than 80,000 individuals, generating a combined annual turnover of approximately €22 billion[42].

The processed fruit and vegetable sector generated €47 billion in trade value representing approximately 6% of Europe's total food processing industry [43].

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Figure 29 PROFEL association key numbers [42]

Industrial vegetable and fruit canning processes share fundamental operational similarities despite distinct thermal processing requirements. We are going to describe the vegetable canning process.

Industrial Vegetable Canning Process

The industrial canning of vegetables follows a systematic multi-stage process designed to ensure product quality, safety, and preservation (Figure 30). The process commences with raw product receiving and cold storage, where incoming vegetables are maintained at controlled temperatures to preserve freshness prior to processing.

Preparation and Cleaning Phase

The initial processing stage involves preparation activities including cutting, vacuum cleaning, and washing operations. During this phase, vegetables undergo sorting and sizing to ensure uniformity, while visual inspection procedures verify quality

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standards. The vacuum cleaning step removes debris and contaminants before the comprehensive washing process.

Pre-Processing Treatment

Following the cleaning phase, vegetables enter a vacuum hydration process, which prepares the product for subsequent thermal treatment. The blanching operation represents a critical step where vegetables are briefly exposed to high temperatures to deactivate enzymes, preserve color, and partially cook the product. This is immediately followed by rinsing to halt the cooking process and remove any residual processing aids.

Final Processing and Packaging

The processed vegetables then proceed through chopper or slicing operations to achieve the desired final form, with additional rinsing and visual inspection steps ensuring quality control. The filler stage places the prepared vegetables into containers, followed by closing operations that seal the packages. The retorting process applies the final sterilization treatment through controlled heat and pressure, effectively eliminating pathogenic microorganisms and ensuring product safety.

Completion and Distribution

The final stages encompass cooling to ambient temperature, labelling for product identification and regulatory compliance, casing for protection during transport, and transfer to warehouse facilities for distribution.

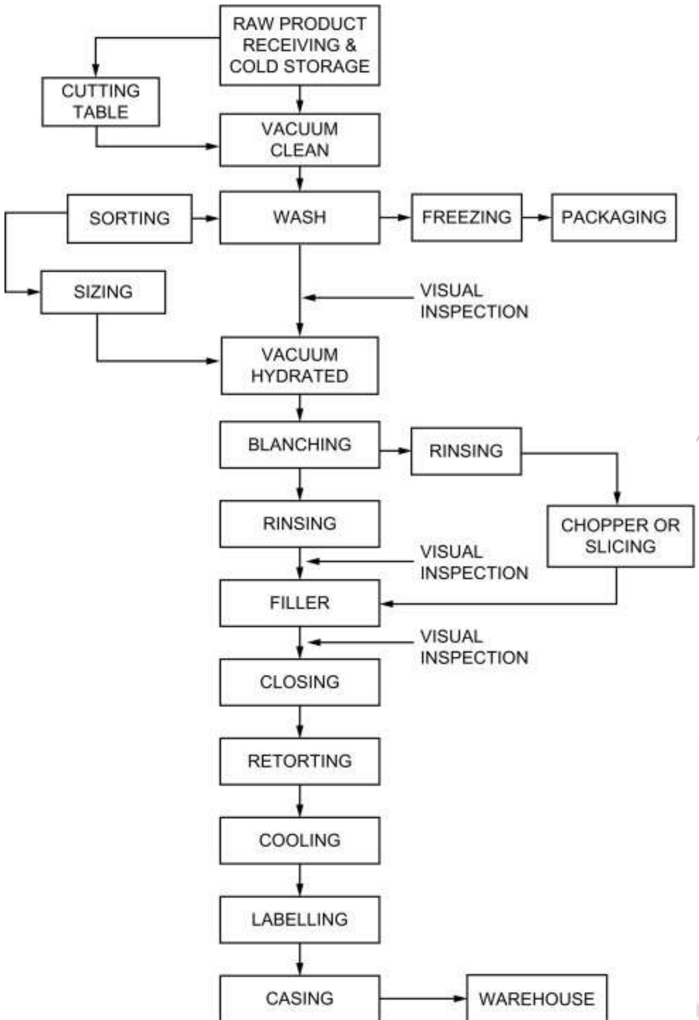

Figure 30 Canned vegetables industrial production process diagram [44]

The production of canned fruit is similar to the canned vegetables one, with some differences in energy intensity of the processes.

a) Suitable processes for HTHP

Scalding/blanching process represents highly suitable application for HTHP technology in industrial vegetable canning facilities. These process, which operate at steam temperatures of 120°C for scalding and require thermal treatment for enzyme inactivation and surface preparation, consume 0.17 MWh per tonne of processed vegetables [21] based on current industry data.

Cooking process in vegetable canning present equally compelling opportunities for HTHP implementation, operating at the same steam temperatures of 120°C for sterilization and thermal processing, also consuming 0.17 MWh per tonne of processed vegetables [21].

This process is also shared in canned fruit industry, with the same steam temperature (120ºC), consuming 0.11 MWh per tonne of processed fruits [21].

The same numbers are applicable also to the retort process, which represents the critical sterilization stage in vegetable and fruit canning where sealed containers are subjected to high-temperature steam treatment, typically at 120ºC (0.17 MWh/tonne) for vegetables and at 120ºC (0.11 MWh/tonne), to eliminate pathogenic microorganisms and ensure product safety and shelf stability.

b) Estimation of HTHP market potential

For an industry processing 2.1 million tonnes of canned vegetables and 1 million tonnes of canned deciduous fruit and compotes annually, the implementation of HTHP technology for these thermal processes offers significant operational benefits.

The scalding, cooking and retort operations combined represent almost 1.3 TWh of annual thermal energy demand, with a installed capacity of 180 MW.

The technology's ability to utilize waste heat streams from cooling operations elsewhere in the facility, combined with the precise temperature control capabilities essential for maintaining HACCP compliance, positions HTHP systems as strategically advantageous investments for the sector.

The average installed capacity potential per factory would be around 360 kW, considering 500 units installed.

3.3.7 Ethanol

The European ethanol sector represents a significant component of the renewable energy landscape, producing 6,420,000 litres (5,100,000 tonnes) annually [45] from diverse agricultural feedstocks.

The EU ethanol industry utilizes a diversified feedstock portfolio comprising cereals (62.4%), sugar from beets and molasses (25.4%), and other organic materials (12.2%) [45]. Primary feedstocks include wheat, maize, barley, rye, triticale, and various intermediates from sugar beet and cereal starch processing.

Ethanol applications span multiple sectors, with industrial and fuel applications accounting for 70% of demand and food applications representing 30%. The material's solvent properties, miscibility characteristics, and antiseptic qualities drive demand across pharmaceuticals, cosmetics, and industrial processes.

The ethanol production process is divided into 4 main stages (Figure 31):

- Feedstock preparation
- Fermentation
- Distillation
- Purification

Feedstock Preparation

The production process initiates with substrate-specific preparation methods. Sugar beet processing involves acidification of raw juice to optimize hydrolysis conditions and create favorable environments for yeast development. Grain processing requires milling, liquefaction, and enzymatic saccharification to convert starch macromolecules into fermentable sugars. This multi-stage process combines thermal treatment with enzymatic action to achieve optimal glucose yields.

Fermentation Process

Alcoholic fermentation utilizes Saccharomyces species yeasts operating under controlled anaerobic conditions. The process maintains temperatures between 30-35ºC and pH levels below 4.5 to prevent bacterial contamination. The biochemical conversion follows the established stoichiometric relationship: $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$. Fermentation systems employ cylindrical closed tanks with CO_2 recovery capabilities, operating in continuous, semi-continuous, or batch configurations depending on production requirements.

Distillation and Purification

The distillation process separates ethanol from the fermented mixture through thermal separation techniques. Systems utilize either pot stills or column stills, with column distillation representing the predominant technology for large-scale operations. The process achieves alcohol concentrations of 95% through multi-stage rectification, followed by dehydration using molecular sieves, azeotropic distillation, or membrane separation technologies to produce anhydrous ethanol.

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Source: [198, FoodDrinkEurope 2015]

Figure 31 Ethanol production process [26]

a) Suitable processes for HTHP

Ethanol distillation processes represent exceptionally well-suited applications for high temperature heat pump technology due to their substantial thermal energy requirements and favorable thermodynamic characteristics. The distillation stage accounts for 50% of total energy demand in ethanol production facilities[46], with specific thermal energy demands of 1 MWh/tonne [47], representing significant opportunities for heat pump integration and energy recovery. The close proximity of boiling points between ethanol and water creates optimal conditions for direct vapor recompression systems, which have demonstrated superior economic performance compared to alternative heat pump configurations.

These processes benefit from the inherent availability of ethanol vapor as an appropriate heat transfer medium, enabling efficient heat pump operation through the compression of overhead vapors to provide reboiler heating. The small temperature differential between overhead vapors and bottom products allows vapor recompression systems to transfer substantial quantities of thermal energy with minimal work input, while the ability to optimize operating pressures enhances separation efficiency and reduces reflux requirements.

Furthermore, the established practice of replacing conventional steam and cooling water systems with integrated condenser-reboiler configurations demonstrates the technical maturity and commercial viability of heat pump integration in industrial distillation processes, making ethanol production facilities prime candidates for advancing HTHPs deployment in European industrial applications.

b) Estimation of HTHP market potential

The ethanol production sector presents considerable opportunities for high temperature heat pump deployment within distillation operations. With annual thermal energy requirements reaching 5 TWh across the industry, the distillation process constitutes a major demand center for industrial heat pump applications. The current installed capacity of 734 MW throughout the sector illustrates the magnitude of thermal infrastructure that could potentially incorporate HTHP technology.

Based on the average installed capacity of 11.3 MW per factory in distillation operations, the market potential spans 65 industrial facilities[45] suitable for HTHP implementation. This translates to a potential deployment of 147 heat pump units (assuming max size 5 MW) across the sector, representing a total addressable market of 735 MW of HTHP capacity, assuming full market penetration within installations that satisfy the technical and economic requirements for heat pump deployment.

The annual production capacity of 5 million tonnes of ethanol [45]establishes a robust and consistent demand foundation for HTHP systems. Considering the process energy intensity characteristics and the presence of recoverable waste heat streams, this market segment presents advantageous conditions for achieving competitive economics with HTHP technology, particularly as carbon pricing mechanisms and energy efficiency mandates continue to accelerate industrial decarbonization efforts across the renewable fuels manufacturing sector.

3.3.8 Other food and beverage industries

Whey powder

In the Marina et al. dataset [6], whey powder production has a total process heat demand of 4.68 TWh/yr, of which 4.38 TWh/yr lies in the 15–200 °C range. The heat demand is shared between air heating for drying (reported air temperatures 9–220 °C) and steam at 180 °C.

Waste heat is estimated at 1.74 TWh/yr, largely as condensate between 81 and 45 °C, giving a waste heat-to-process heat ratio of 0.16 (or 0.17 when focusing on the 15–200 °C segment).

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In terms of unit sizing, the dataset reports duties of 3.9 MW for the air-heating demand and 3.6 MW for the steam demand, resulting in an overall weighted average duty of 3.8 MW.

Using the unit estimation method applied in this deliverable, the combined market potential across the drying and steam demands is 177 HTHP units. The indicative installed capacity by the 15–200 °C demand is 626 MW.

Wheat starch

Wheat starch shows one of the larger heat demands within this group, with 8.46 TWh/yr of process heat and 7.63 TWh/yr in the 15–200 °C range [6]. Heat demand is dominated by air heating, mainly in the 50–160 °C band, consistent with drying as the principal heat sink. A smaller fraction is associated with higher-temperature air heating (104–540 °C), although only 235 GWh/yr falls below 200 °C.

Waste heat totals 2.92 TWh/yr, including 2.57 TWh/yr within 15–200 °C, and is primarily reported as condensate. This yields a waste heat-to-process heat ratio of 0.34 both on a total basis and for the 15–200 °C segment.

Duties are 28.6 MW for the main drying demand and 4.1 MW for the higher temperature air demand.

The dataset indicates a weighted average duty of 25.6 MW overall and 27.9 MW for the 15–200 °C segment.

Applying the unit estimation method results in 45 HTHP units (37 units for the main drying load plus 8 units linked to the sub 200 °C share of the higher-temperature air demand), corresponding to an indicative installed capacity of 1.1 GW. With a maximum size per unit of 5MW the total of HTHP units potential is 248 units.

Corn starch

Corn starch has a total process heat demand of 7.75 TWh/yr, with 5.84 TWh/yr in the 15–200 °C range[6]. The profile is again driven by air-based drying, with 5.30 TWh/yr in the 50–160 °C band. A second air-heating demand is reported for 104–540 °C; 540 GWh/yr of this lies below 200 °C.

Waste heat is estimated at 2.46 TWh/yr, including 2.19 TWh/yr within 15–200 °C, mainly as condensate. The waste heat-to-process heat ratio is 0.32 overall and increases to 0.37 for the 15–200 °C segment.

Duties are 17.6 MW for the main drying demand and 8.1 MW for the high temperature air demand, with a weighted average duty of 14.6 MW overall and 16.7 MW for the 15–200 °C segment.

The unit estimation method yields 86 HTHP units (43 units for the main drying demand and 43 units for the sub-200 °C share of the higher-temperature air demand), corresponding to an indicative installed capacity of 834 MW. If the maximum size per unit is limited to 5MW, the potential is 221 HTHP units.

Potato starch

Potato starch production has a process heat demand of 1 TWh/yr, entirely within the 15–200 °C range and supplied as air heat at 50–160 °C, consistent with a drying application [6].

Waste heat is reported at 310 GWh/yr, with 270 GWh/yr in the 15–200 °C range, mainly as condensate around 50–10 °C. This corresponds to waste heat-to-process heat ratios of 0.30 overall and 0.27 for the 15–200 °C segment, with an duty of 14.1 MW.

Applying the unit estimation approach gives a market potential of 10 HTHP units (29 units if maximum size limited to 5MW), corresponding to an indicative installed capacity of 144 MW.

Soy oil

Soy oil crushing shows a process heat demand of 2.17 TWh/yr, fully within 15–200 °C and provided as steam at 180 °C [6].

Waste heat is estimated at 906 GWh/yr and is characterized as condensate at several temperature levels (around 175 °C, 105 °C, 100 °C, and 66 °C), with a waste heat-to-process heat ratio of 0.06.

The duty associated with the steam demand is 19.4 MW.

Using the unit estimation method applied in this deliverable results in a market potential of 16 HTHP units, corresponding to an indicative installed capacity of 310 MW. The number of HTHP potential units is 29 if maximum size limited to 5MW.

Potato processing

Potato processing (blancher and dryer) has a process heat demand of 3.84 TWh/yr, fully within 15–200 °C, delivered as steam at 150 °C (620 GWh/yr) and 190 °C (3.22 TWh/yr)[6].

Waste heat is estimated at 2.07 TWh/yr, including 1.88 TWh/yr in the 15–200 °C range, reported mainly as condensate across multiple temperature bands.

Despite the sizeable waste heat volume, the aggregated waste heat-to-process heat ratio is 0.07 (and similarly 0.07 for the 15–200 °C segment).

Duties are 1.8 MW for the 150 °C steam demand and 9.2 MW for the 190 °C demand; with a weighted average duty of 8 MW.

Applying the unit estimation method yields 99 HTHP units (49 units linked to the 150 °C demand and 50 units linked to the 190 °C demand), corresponding to an indicative installed capacity of 548 MW. HTHP units potential rise to 141 units if maximum size is limited to 5MW.

3.4 Textile industry

The textile manufacturing process follows a complex, multi-stage production chain that transforms raw materials into finished garments. Based on the provided materials, this process can be divided into four major stages (Figure 32) [48]:

- yarn formation
- fabric formation
- wet processing
- fabrication

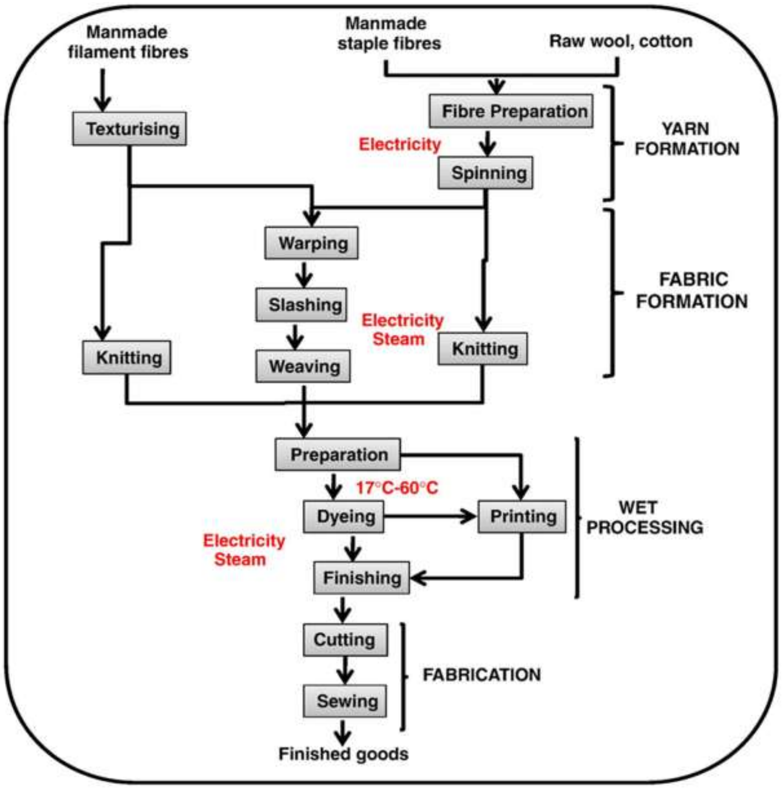

Figure 32 Processing flow of textile products with energy indication [48]

Yarn Formation Stage

The process begins with three potential input materials: manmade filament fibers, manmade staple fibers, or natural fibers (raw wool and cotton). Each pathway requires specific processing:

For manmade filament fibers, the first step is texturizing to create specific properties in the synthetic fibers. For natural fibers and manmade staple fibers, the process includes fiber preparation, which requires electricity as its primary energy source. This preparation involves cleaning, blending, and arranging fibers in a uniform manner.

Following preparation, the fibers undergo spinning—a crucial step that converts fibers into yarn by twisting them together. This stage is energy-intensive, consuming approximately 11-18% of the total energy used in textile production. According to the research, ring spinning alone accounts for 37% of energy demand in the spinning sector, while open-end machines consume about 20%.

Fabric Formation Stage

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Once yarn is produced, it enters the fabric formation stage through one of two primary pathways:

1. Weaving pathway: The yarn first undergoes warping (arrangement of longitudinal threads), followed by slashing (applying sizing agents to strengthen yarns), and then weaving, where perpendicular threads (warp and weft) are interlaced to create fabric. This process requires both electricity and steam.
2. Knitting pathway: Alternatively, yarn can be processed directly through knitting, where interlocking loops are created with a single thread or multiple threads. Knitting generally consumes less energy than weaving.

Energy demand in fabric formation typically represents 23% of the total energy used in textile manufacturing [48].

Wet Processing Stage

The wet processing stage is the most resource-intensive phase, consuming 35-60% of the total energy used in textile production. This stage includes:

1. Preparation: Initial treatment of fabrics to remove impurities and prepare for dyeing.
2. Dyeing: Applying color to textiles at temperatures ranging from 17°C to 60°C. This process requires substantial thermal energy (generated from steam) and electricity.
3. Printing: Optional decoration of fabrics with patterns.
4. Finishing: Final treatments that impart specific properties to the fabric (such as softness, water repellency, or flame resistance).

Fabrication Stage

The final manufacturing stage involves:

1. Cutting: Precision cutting of fabric according to patterns.
2. Sewing: Assembly of cut pieces into finished garments.

These operations primarily consume electricity for machinery operation.

a) Suitable processes for HTHP

The drying process in textile manufacturing represents a prime application for HTHPs, requiring steam at temperatures of 150°C. With an energy intensity of 1.2 MWh per tonne of fabric processed [49], drying operations constitute a significant thermal energy demand that can be efficiently served by heat pump technology. This application is particularly favorable due to the availability of waste heat from cooling processes within the same facilities, creating an optimal scenario for heat recovery and upgrading. HTHPs can capture this low-grade waste heat and elevate it to the required process temperatures, significantly reducing primary energy demand and associated carbon emissions while maintaining the quality requirements of textile processing.

Dyeing and washing processes requires steam at 120°C, with an energy intensity of 2 MWh per tonne of processed fabric [49], these wet processing operations consume substantially more thermal energy than drying alone, making them prime candidates for efficiency improvements. The technical synergy is particularly advantageous as these processes generate significant waste heat through their associated cooling operations, creating a circular energy opportunity.

b) Estimation of HTHP market potential

The textile industry presents a substantial market opportunity for HTHP deployment, with an annual fabric production of 2 million tonnes requiring approximately 2.4 TWh of thermal energy for drying processes alone. While the subsector has a massive installed thermal capacity of 343 MW, the fragmented nature of the industry—comprising thousands of small and medium enterprises—creates an ideal environment for modular HTHP solutions.

The dyeing and washing segment of textile manufacturing presents a compelling market opportunity for HTHP integration, consuming approximately 4 TWh of thermal energy annually to process 2 million tonnes of fabric. The subsector's substantial installed thermal capacity of 571 MW reflects the energy-intensive nature of these processes, yet the distributed structure of the industry—characterized by numerous small facilities rather than centralized production—creates an advantageous landscape for modular HTHP deployment.

Market analysis suggests an average installed power of 14 kW per company across the 65,010 textile companies considered (both processes). However, this value reflects a sector wide average diluted by the large number of very small enterprises and therefore does not represent a realistic capacity for an individual HTHP installation, which typically targets concentrated thermal loads at site level. To avoid under sizing the technology, this deliverable adopts a representative unit capacity of 350 kW [32]. On this basis, the market potential is estimated at 2,609 HTHP units, primarily addressing the needs of small and micro enterprises, which constitute a substantial share of European textile production sites.

3.5 Automotive industry

The automotive industry generates over 7% of EU GDP[50], making it a cornerstone of European economic activity. Recent analysis reveals that the sector generated approximately 1.9 trillion Euro in gross economic potential in the shift to electric vehicles value added for the European economy in 2023, representing about 8% of the region's total GDP [50].

The painting process is promising for electrification with the use of high temperature heat pumps.

The process goes through four different phases (Figure 33).

Initial Preparation Phase

The process begins with the body-in-white structure entering the washer for thorough cleaning, followed by pretreatment to prepare the metal surfaces for coating adhesion. The body then proceeds through cathodic electrodeposition (CED), which provides the primary corrosion protection layer, followed by baking to cure this foundation coating.

Surface Conditioning and Primer Application

After the initial baking cycle, the body undergoes sanding to achieve proper surface smoothness, followed by sealer application and sound damper installation where required. The process includes a drying stage before thorough cleaning to remove any contaminants. Primer surfacer application then provides the base for subsequent color coats, followed by another baking cycle to cure the primer layer.

Color Coating and Finishing

The final coating sequence begins with cleaning to ensure surface readiness, followed by base coat application. A flash-off period allows proper solvent evaporation before clear coat application. The clear coat provides durability and gloss characteristics. A final baking cycle cures the complete coating system.

Quality Control and Completion

The process concludes with comprehensive inspection to identify any defects. Bodies requiring correction proceed through repair operations, with potential routing back

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to cleaning stages for spot repairs when necessary. Successfully completed bodies receive final waxing treatment before proceeding to the assembly shop.

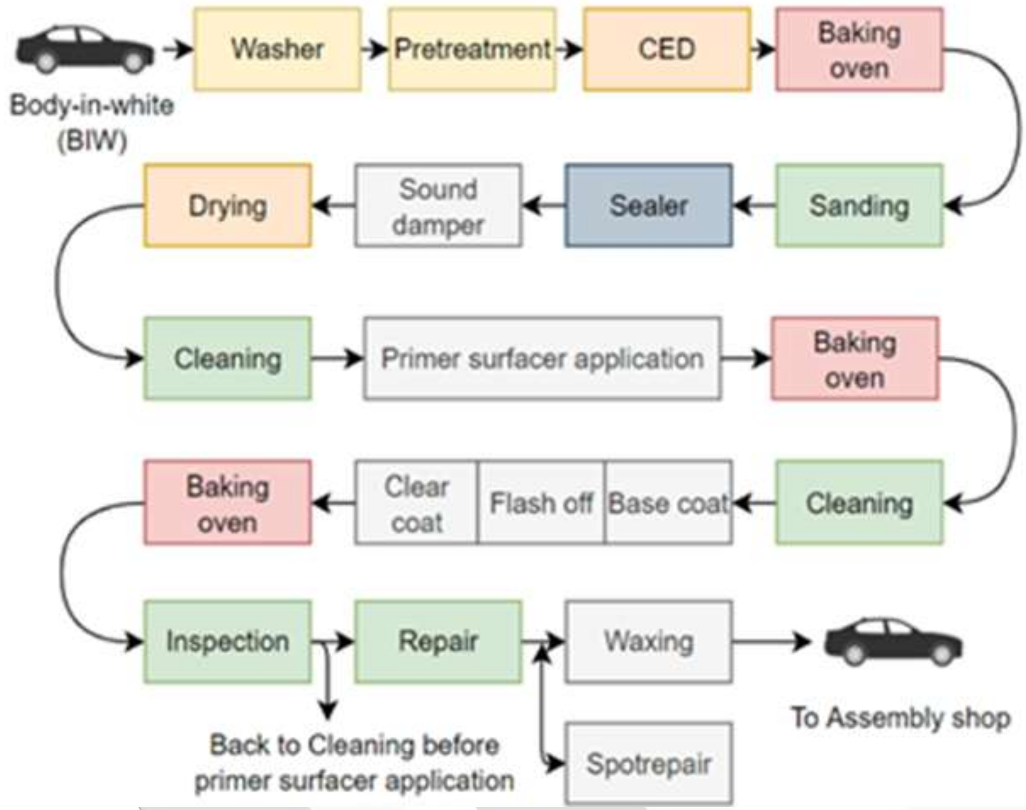

Figure 33 Car painting process diagram [51]

a) Suitable processes for HTHP

The car body preparation for painting process presents significant opportunities for HTHPs implementation due to its specific thermal characteristics and operational requirements. The process operates at temperatures between 170-180°C using steam [21] as the primary heating medium.

The energy intensity of 479 kWh per tonne [21] of production creates a compelling business case for HTHP deployment. The availability of waste heat from cooling processes within the same industrial facility provides an ideal heat source for HTHP systems, enabling effective heat recovery and thermal upgrading that transforms low-grade waste heat into useful process steam.

The continuous nature of automotive manufacturing operations, with consistent thermal energy demands throughout production cycles, ensures optimal HTHP utilization rates.

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b) Estimation of HTHP market potential

The market analysis reveals substantial potential for HTHP deployment within the automotive body preparation process. With annual thermal energy requirements totaling 2.2 TWh across the industry, the process represents a significant demand center for industrial heat pump applications. The current installed capacity of 308 MW across the subsector demonstrates the scale of thermal infrastructure that could potentially benefit from HTHP integration.

Based on the average installed capacity of 3.15 MW per factory, the market potential encompasses approximately 100 industrial units suitable for HTHP deployment. This represents a total addressable market of 308 MW of HTHP capacity, assuming complete market penetration within facilities that meet the technical and economic criteria for heat pump implementation.

The annual production volume of 4.6 million tonnes of car bodies provides a substantial and stable demand base for HTHP systems. Given the energy intensity characteristics and the availability of waste heat streams, this market segment offers favorable conditions for achieving competitive economics with HTHP technology, particularly as carbon pricing and energy efficiency regulations continue to drive industrial decarbonization initiatives across the European automotive manufacturing sector.

3.6 Chemical and Petrochemical industry

The chemical and petrochemical industry represents the largest industrial energy consumer within the European Union, accounting for approximately 598 TWh per year, corresponding to around 21% of total industrial final energy demand.

The sector is characterised by a broad range of products, including basic chemicals, polymers, fertilizers, solvents, fuels and specialty chemicals. Despite the diversity of outputs, the underlying industrial structure is dominated by a limited number of highly energy-intensive unit operations.

Both chemical manufacturing and petroleum refining share similar process configurations, particularly in separation and thermal processing steps. Among these, distillation constitutes the principal separation technology and is recognised as the most energy-intensive unit operation in the chemical industry [6].

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a) Suitable processes for HTHP

The thermodynamic characteristics of the chemical and petrochemical industry reveal a substantial share of process heat demand below 200°C. This temperature range is particularly relevant because it defines the upper boundary of current and emerging HTHP technologies.

Distillation columns require simultaneous heat rejection at the condenser and heat input at the reboiler. In conventional configurations, low-temperature heat rejected in the condenser is typically dissipated, while external steam is supplied to the reboiler. This configuration presents a structurally favourable opportunity for heat pump integration. By upgrading the rejected condenser heat and reintroducing it at the reboiler temperature level, an HTHP can significantly reduce the requirement for externally supplied steam.

The physical proximity of condenser and reboiler streams further enhances technical feasibility. Numerous studies have identified the integration of heat pumps within distillation columns as an effective measure for reducing specific energy demand [6].

The typical operating temperature of many distillation processes falls below 200°C, making them technically compatible with HTHP systems.

b) Estimation of the HTHP market potential

The market estimation for the chemical and petrochemical sector uses the bottom-up methodology developed by Marina et al. (2021) [6].

This methodology is based on process-level data, including temperature profiles, specific heat demand per unit of product, and production statistics. Individual process analyses are subsequently upscaled to the EU28 level using relevant production volumes.

In the chemical sector, generalized data were collected for distillation columns used in the manufacture of 26 chemical products. In the refinery sector, data were compiled for nine major distillation-based processing steps in crude oil transformation [6]

The analysis considers only applications with sink temperatures up to 200°C and temperature lifts within technically feasible limits.

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For applications limited to sink temperatures up to 150ºC, which correspond to commercially available or near-commercial HTHP technology, the estimated market potential in the EU28 amounts to approximately 8.1 GW of installed heating capacity in the chemical sector, distributed across 1,164 heat pump units. These units could supply approximately 70 TWh/yr of process heat, with an associated electricity demand of around 16.4TWh/yr. Under this scenario, approximately 85% of the process heat demand below 150ºC could be covered by heat pump technology [6].

When extending the technical boundary to sink temperatures up to 200ºC, reflecting anticipated technological developments, the market potential increases to approximately 9.1 GW of installed heating capacity across 1,291 units in the chemical sector. In this case, around 78.6 TWh/yr of process heat could be supplied by heat pumps, corresponding to roughly 80% of the process heat demand below 200ºC. The associated electricity requirement is estimated at 18 TWh/yr [6].

The refinery sector presents a more limited potential due to its higher share of very high-temperature processes. Nevertheless, a technical potential of up to 500 MW of installed heat pump capacity has been identified for refinery applications below 200 ºC , corresponding to 69 potential heat pump units, capable of supplying approximately 3.9 TWh/yr of process heat, with an associated electricity demand of 1.67 TWh/yr. Under this scenario, heat pumps could cover approximately 6% of the refinery sector's process heat demand below 200 ºC [6].

Most units identified in the market assessment fall below 10 MW of heating capacity, with an average capacity of approximately 5.5 MW and a median capacity of 3 MW. This indicates that the chemical HTHP market is primarily composed of modular mid-scale installations rather than a small number of very large units.

3.7 Bottom-up analysis results

The combined market potential across all analyzed sectors represents 42.6 GW of potential HTHP capacity, with around 19,500 potential installations ranging from 224 kW to more than 5 MW units.

The potential market for the different sectors and processes analysed is the following:

- Papermaking: 21 GW (4,208 units with 5 MW avg)
- Food & Beverage: approximately 10.4 GW across multiple subsectors
- Textile: 913 MW (2,609 units with 350 kW avg)
- Automotive: 308 MW (100 units with 3.14 MW avg)

- Chemical and Petrochemical (1,360 units, 5.5 MW avg)

Most sectors require temperatures between 120-180°C, perfectly in the range of HTHP technology developed in SPIRIT.

- Suitable processes for HTHPs can be divided into the following categories:
- Most Promising: Drying processes (paper, textiles, food), steady thermal loads, available waste heat
- High Potential: Distillation/evaporation (sugar, ethanol), ideal for vapor recompression
- Specific Applications: Specialized processes (automotive painting, dairy pasteurization)

Potential market is fragmented in the size of the units:

- Large Units (>5 MW): Paper, sugar, automotive, large chemical plants focus on custom solutions
- Medium Units (1 MW-5 MW): Food processing, medium breweries, standardized modular systems
- Small Units (<1 MW): Textiles, microproduction, mass-produced standardized units

Full deployment could substitute more than 240 TWh of annual fossil fuel demand across these sectors, representing significant progress toward EU industrial decarbonization goals.

Taken together, the dataset-based process representation and the market potential results indicate that the food and beverage sector offers a large number of mid-scale HTHP opportunities linked to drying, evaporation and steam utilities, but that realizable coverage is constrained by waste heat availability and integration requirements. For deployment planning, this highlights the importance of site specific heat integration (to minimize temperature lift), identification of stable waste heat sources, and consideration of utility system interfaces (steam and hot air networks) to enable practical electrification via heat pumps.

The results of the bottom-up will be used in the Market penetration scenarios section of the report to draw market penetration scenarios of HTHPs for the different sectors analysed.

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4. PESTLE ANALYSIS

4.1 Introduction

The PESTLE analytical framework enables organizations to systematically evaluate six critical categories of external environmental factors that influence business operations and strategic decision-making processes (Figure 34).[52]

Figure 34 Graphic representation of PESTLE analysis aspects

Political Factors encompass the governmental and regulatory landscape within which organizations operate. This dimension includes government policies, regulatory frameworks, taxation systems, trade restrictions, and overall political stability. Political factors fundamentally shape the business environment and exert direct influence on organizational operational efficiency and profitability. The regulatory environment established by political institutions creates the foundational conditions under which enterprises must conduct their activities.

Economic Factors comprise the macroeconomic conditions that affect market dynamics and consumer behavior. Key economic indicators include GDP growth rates, inflation levels, exchange rate fluctuations, interest rates, and unemployment statistics. These economic variables directly determine consumer purchasing power and spending patterns, thereby influencing market demand and business performance across sectors.

Social Factors represent the demographic and cultural characteristics of the market environment. This category encompasses cultural norms, demographic trends, population growth patterns, educational attainment levels, and prevailing societal attitudes. Social factors significantly influence consumer preferences and purchasing behaviors, ultimately determining market demand patterns and product acceptance within specific demographic segments.

Technological Factors address the innovation landscape and technological infrastructure that shapes competitive dynamics. This dimension includes research and development activities, technological advancement rates, automation capabilities, and innovation adoption patterns. Technological developments drive industry transformation and fundamentally determine organizational competitiveness through their impact on operational efficiency and market positioning.

Legal Factors constitute the regulatory and compliance framework governing business operations. This category encompasses legislative requirements, intellectual property protections, employment law, health and safety regulations, and industry-specific compliance standards. Legal factors establish the mandatory operational parameters within which organizations must function to maintain regulatory compliance and avoid legal risks.

Environmental Factors reflect the ecological considerations and sustainability imperatives increasingly central to business strategy. This dimension includes climate change impacts, environmental regulations, sustainability requirements, and corporate social responsibility expectations. Environmental factors now significantly influence operational methodologies and strategic planning as organizations integrate sustainability principles into their business models.

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For every aspect are taken into consideration different indicators to be analysed (Figure 35); the analysis has been developed in collaboration with the development of deliverables of Tasks 5.2. 5.3 and 5.5 of the SPIRIT project, interviews with Industrial Associations representatives and members, Heat Pumps manufacturers, collaboration with Push2Heat project, literature research and workshops on the HTHP topic and internal discussions within the consortium.

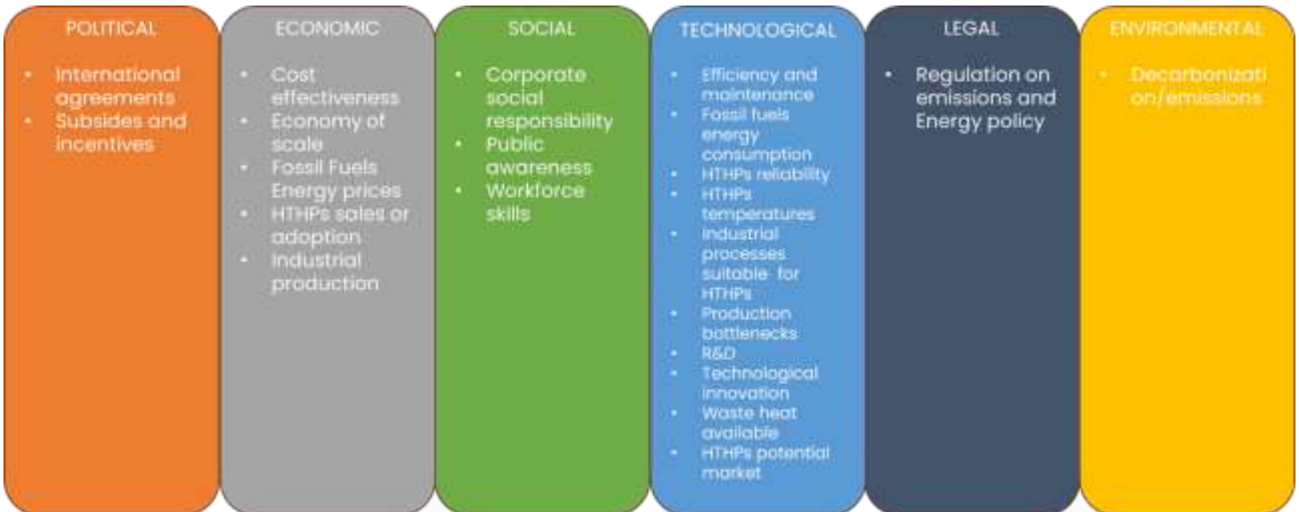

Figure 35 HTHPs PESTLE factors

In the following paragraphs all factors will be explained and described, motivating their role in shaping the market conditions of HTHPs technology.

4.2 Political Factors

4.2.1 International Agreements

The political framework for HTHPs deployment is increasingly shaped by international and European climate and energy policy commitments aimed at reducing greenhouse gas emissions from energy-intensive sectors. At the global level, the Paris Agreement establishes the objective of limiting global temperature increase to well below 2 °C and pursuing efforts to limit warming to 1.5 °C, which has catalyzed national and regional industrial decarbonisation strategies and reinforced the role of electrification and energy efficiency in industrial heat supply [53].

Within the European Union, these objectives are translated into binding policy targets through the European Green Deal and the European Climate Law, which commit the EU to climate neutrality by 2050 and to a net reduction of at least 55 % in greenhouse gas emissions by 2030 compared to 1990 levels. These targets directly affect industrial heating policies by increasing regulatory pressure to reduce fossil fuel use in process heat applications and by prioritizing low-carbon alternatives [32]. In this context, industrial heat pumps are recognized as a key enabling technology for decarbonizing process heat, particularly at low- and medium-temperature levels, with ongoing policy and technological efforts aimed at extending their applicability to higher temperature ranges[53]. Collectively, these policy commitments create an increasingly favorable framework for the adoption of electrified heat solutions in industry, while raising the long-term regulatory and economic risks associated with continued reliance on fossil fuel-based heat supply [53].

4.2.2 Subsidies and Incentives

Government financial support mechanisms have become instrumental in accelerating HTHPs possible adoption. The European Union allocates €86.7 billion through REPowerEU specifically for heat pump deployment [54], while individual member states offer substantial direct subsidies.

Industrial Heat Pump Subsidies in Europe - Country Summary

Table 5 Industrial heat pumps subsides recap [44]

Country	Main Programs	Type of Support	Maximum Amount	Heat Pump Types	Key Requirements
Austria	- Heat Recovery ≥100kW - Heat Pump ≥100kW - Innovative Climate Programs	Grant	- Based on company size % - Up to €4.5M (pilots)	All types	- GWP <2,000 - Min SPF 3.8 - Nominal capacity ≥100kW
Belgium	**Wallonia:** Tax deduction, Energy transition aids	Tax deduction, Grant, Multiple	- 20.5% tax deduction - €1M max (Flanders)	All types	- GWP <2,000 - Min SPF 3.8

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Country	Main Programs	Type of Support	Maximum Amount	Heat Pump Types	Key Requirements
	Flanders: Ecology premium+, Green investment **Brussels:** Economic Transition Fund		- €1.5M (Brussels)		
Bulgaria	Energy Efficiency Fund	Loans	€30,000 - €3M	All types	-
Czech Republic	HEAT - Modernisation	Grant	Project-based	All types	Heat source change required
Denmark	Energy Efficiency Business Subsidy	Grant	€1,300 - €15M	All types	Based on CO_2 savings
Finland	- Energy Aid - R&D programs	Grant, Loan	- 10-50% of costs - Project limits vary	All types	Min €10,000 investment
France	- Fonds Chaleur - CEE certificates - Green loans	Grant, Certificates, Loans	- Up to 65% costs - € 50,000-5M loans	- Geothermal - Waste heat recovery	-

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Country	Main Programs	Type of Support	Maximum Amount	Heat Pump Types	Key Requirements
Germany	- Process Heat Program - Energy Efficiency - District Heating - Innovation programs	Grant, Loan	**€ 20M max**	- Air/water/ground - Max 50% excess heat	- COP ≥2.0 - Quality grade ≥0.4
Greece	New Development Law	Multiple	€ 10M max	All types	Green transition focus
Hungary	- White Certificates - TAO tax discount	Certificates, Tax incentives	30-70% corporate tax	All types	Ecodesign requirements
Ireland	- EXEED grant - Renewable Heat Support	Grant	- € 3M (EXEED) - 40% HP costs	Air/water/ground source	-
Italy	- White Certificates (TEE) - Transition 5.0	Certificates, Tax credit	5-45% tax credit	All types	Min 3-5% energy savings
Latvia	- White Certificates	Certificates, Loan	Up to € 5M	All types	-

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Country	Main Programs	Type of Support	Maximum Amount	Heat Pump Types	Key Requirements
	- Energy efficiency loan				
Lithuania	Fossil fuel reduction	Grant	€200,000 max	Air/water/ground	- GWP <150 - Ecodesign compliance
Luxembourg	Energy efficiency program	Grant	Program-specific	All types	-
Netherlands	- SDE++ - VEKI - EIA tax deduction	Grant, Tax deduction	- €30M (VEKI) - 40% tax deduction	- Waste heat recovery - Geothermal - Air-water	Based on CO_2 reduction
Norway	- Central heating - Climate initiatives - Industry 2050	Grant	- €250/kW ground - €200/kW water - €30M max	All types	Existing facility required
Poland	- Energy Plus - White Certificates	Loan, Certificates	~€133,000-940,000	All types	Energy efficiency focus

Country	Main Programs	Type of Support	Maximum Amount	Heat Pump Types	Key Requirements
Portugal	- Decarbonising Industry - Green Industry Support	Grant	- €200,000 (simplified) - €15M (full projects)	All types	-
Slovakia	Green by Business	Grant	€70,000 max	All types	SMEs only
Slovenia	Efficient Energy Use	Grant	20% of costs	All types	-
Spain	Order ITU/1434/2023	Grant, Loan	Project-based	All types	Emission reduction focus
Sweden	Climate Step (Klimatklivet)	Grant	20-70% of costs	All types	Based on CO_2/SEK
Switzerland	- Industrial heating subsidy - Decarbonization roadmaps	Grant	- 40% of costs - €25,000 roadmaps	All types	Min 95°C output required
UK	Industrial Energy Transformation Fund (IETF)	Grant	€590M total fund	Waste heat recovery, Environmental source	Industrial process use

Notes:

GWP = Global Warming Potential (refrigerant requirement)

SPF = Seasonal Performance Factor

COP = Coefficient of Performance

SME = Small and Medium-sized Enterprises

Many programs have specific eligibility criteria based on company size, with higher support percentages for smaller companies

Several countries offer multiple programs that can sometimes be combined

Amounts shown are maximum available; actual support depends on project specifics

4.3 Economic Factors

4.3.1 Cost Effectiveness

The economic viability of HTHPs presents a complex picture in which higher initial investments can be offset over time by reduced operating expenditures. Investment costs vary widely across technologies and applications: specific investment costs between 200 and 1500 €/kW [53], indicating that upfront investment can constitute a significant adoption barrier in some industrial cases. In addition to equipment cost, site-specific integration measures may be required (e.g., adapting utility systems originally designed around steam), which can add to total project costs and affect feasibility[53].

Operational economics can favor heat pumps where boundary conditions are suitable. Typical practical COP for vapor-compression high-temperature heat pumps are reported in the range of 2–5, indicating that multiple units of useful heat can be delivered per unit of electrical energy input [53]. For selected applications in the food industry, payback periods of 5–6 years have been reported when comparing heat pump-based solutions to conventional natural-gas boilers, based on results from validated techno-economic simulation models [53]

Nevertheless, the overall economic performance of industrial heat pump installations remains strongly site-specific and depends on factors such as energy prices, annual operating hours, and the availability and temperature level of suitable heat sources. Reported annual operating hours vary significantly across industrial sectors, ranging from 3,000–5,000 hours per year for small companies to more than 8,000 hours per year for energy-intensive industries, with the economic viability of investments often being proportional to these operating hours[56].

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4.3.2 Economy of Scale

Economies of scale could play a relevant role in the economics of HTHPs, both at the level of individual installations and across the manufacturing supply chain. At the project level, larger industrial installations can achieve lower specific investment costs, as major system components such as compressors, heat exchangers, and auxiliary equipment do not scale linearly with installed capacity. The review of commercially available and near-market HTHP technologies shows that multi-megawatt systems are technically feasible and increasingly deployed in industrial applications, indicating improved cost efficiency compared to small-scale, highly customized units [53].

At the manufacturing level, cost reductions are associated with learning effects, standardization, and increased production volumes as deployment expands, with increased production volumes expected to reduce equipment costs by 20% by 2050 [56]. Long-term technology projections for industrial process heat explicitly account for cost reductions driven by economies of scale and accumulated operational experience, while also highlighting that cost uncertainties remain significant for technologies with limited market diffusion, particularly at higher temperature levels [56].

Given the current limited deployment of HTHPs (we are currently in Cat. 2 of Figure 36), economies of scale are not yet realized. As a result, cost reductions linked to scaling effects are expected to materialize progressively and will depend on actual deployment rates, technological maturation, and the development of stable supply chains, rather than being uniformly achievable in the short term [53], [56].

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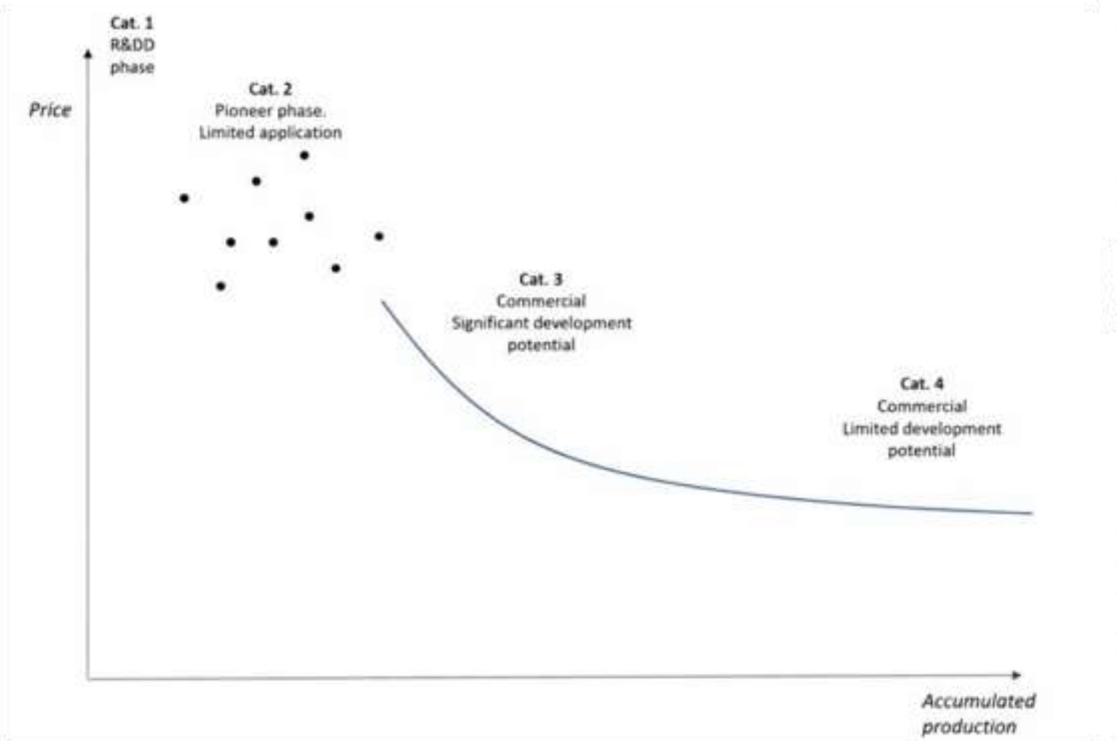

Figure 36 Technological development phases. Correlation between accumulated production volume (MW) and price (adapted from [56])

4.3.3 Fossil Fuels and Energy Prices

The economic attractiveness of HTHPs is strongly dependent by the relative prices of electricity and fossil fuels. The competitiveness of electrically driven heat pump systems compared to natural gas heat supplies relies primarily on the electricity-to-gas price ratio, as well as on the achievable COP under given operating conditions. In general, higher fossil fuel prices relative to electricity prices improve the economic case for electrified process heat solutions.

Based on a simplified energy cost comparison between electrically driven HTHP and natural gas boilers, and assuming typical performance values for industrial applications (COP 2.5–3.5 and boiler efficiency 90% [53]), the breakeven electricity-to-gas price ratio is in the order of 3. This value is indicative and strongly dependent on application-specific temperature levels, operating hours, and the availability and quality of suitable heat sources. Consequently, variations in process integration, waste heat recovery potential, and system design can significantly shift this threshold in practice.

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Volatility in fossil fuel markets (exemplified by the 2022 energy crisis) represents an additional economic driver for electrification. Fluctuating gas prices increase the economic risk associated with conventional boiler-based heat generation, whereas electrically driven solutions can benefit from more predictable cost structures, particularly when electricity is procured through long-term contracts or increasingly supplied by renewable sources. This dynamic strengthens the relative attractiveness of HTHPs for industrial process heat.

Carbon pricing mechanisms further influence the relative economics of heat supply technologies, with EU carbon prices at €60-90 per tonne of CO_2 emitted. By increasing the effective operating costs of fossil fuel combustion, carbon pricing improves the competitiveness of low-carbon alternatives such as heat pumps. As a result, the economic case for HTHPs is increasingly shaped by the combined effects of energy price dynamics and climate policy instruments, rather than by technology performance alone.

4.3.4 Industrial Production and Adoption Scales

Industrial heat pump adoption remains nascent compared to residential applications, with current installations representing less than 1 % of industrial heating capacity [32]. Current industrial deployments are limited relative to total industrial heat demand and are primarily concentrated in applications with low-to-medium temperature requirements, where technical feasibility and economic robustness are already well established [32], [53]. HTHPs represent a more recent development stage and are therefore less widely deployed than conventional industrial heat pumps operating at lower temperatures [53].

Early adoption is mainly observed in industrial sectors characterized by process heat demand below approximately 120–150 °C, including food and beverage processing, papermaking production, and selected chemical processes. These sectors combine compatible temperature levels with relatively continuous production profiles and, in many cases, the availability of suitable waste heat streams, which facilitates heat pump integration and improves overall system performance [32], [56]. Market evidence indicates that the majority of currently installed industrial heat pump capacity is concentrated in these temperature ranges, while higher-temperature applications remain largely limited to demonstration and early commercial projects [32], [53].

Achieving wider deployment and meaningful scale requires addressing several sector-specific barriers. Industrial facilities are often designed around centralized steam-based utility systems, and the integration of heat pumps may require additional investments in heat distribution infrastructure, such as hot-water circuits or modified process interfaces [56].

Furthermore, production continuity requirements, strict reliability constraints, and conservative investment practices in capital-intensive industries tend to slow the adoption of novel technologies [53], [56]. As a result, industrial heat pump deployment is progressing incrementally, with adoption initially focused on applications where operational risk is low and system integration can be achieved without major disruption to existing production processes [32], [53].

4.4 Social Factors

4.4.1 Corporate Social Responsibility

Corporate social responsibility (CSR) and broader Environmental, Social, and Governance (ESG) considerations are increasingly influencing investment decisions in energy-intensive industries. Market analyses indicate that industrial companies face growing pressure from investors, customers, and business partners to demonstrate measurable progress in reducing greenhouse gas emissions and improving energy efficiency, particularly for emissions directly associated with industrial operations and energy use [32]. Within this context, technologies enabling the reduction of fossil fuel consumption for process heat are gaining strategic relevance.

Supply-chain-driven decarbonisation requirements further reinforce these dynamics. Large multinational corporations increasingly impose emission-reduction and energy-efficiency expectations on suppliers as part of sustainability reporting and procurement strategies, indirectly incentivizing the adoption of low-carbon heat solutions across industrial value chains [32]. The electrification of process heat through industrial heat pumps, including HTHPs, can therefore contribute to improved alignment with corporate sustainability objectives.

From a social and reputational perspective, the deployment of industrial heat pumps can support companies in strengthening their sustainability profiles, enhancing transparency in energy and emission reporting, and maintaining competitiveness in markets where environmental performance increasingly influences customer and investor perceptions. These benefits, while secondary to economic and technical considerations, can play a supporting role in adoption decisions, particularly for companies with strong ESG commitments [32], [53].

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4.4.2 Public Awareness

Awareness of industrial heat pump technologies, particularly HTHPs, remains limited compared to residential heat pump applications. Market analyses indicate that industrial heat pump deployment is still at an early stage, and that knowledge of technical capabilities, temperature ranges, and integration concepts is uneven across industrial stakeholders, especially outside early-adopter sectors [32]. This limited awareness is partly related to the historically dominant role of fossil fuel–based steam systems in industry and the relatively recent commercial availability of industrial heat pump solutions [53].

At the same time, broader societal and policy attention to industrial greenhouse gas emissions has increased, leading to higher expectations for industrial decarbonisation and transparency in energy use. This creates a gap between societal pressure for emission reductions and the level of familiarity with available electrification technologies within parts of the industrial community [32].

Addressing this awareness gap is an important enabling factor for wider deployment. Experience from early projects highlights the role of demonstration installations, technology showcases, and knowledge exchange between industrial peers in building confidence and improving understanding of heat pump capabilities and integration strategies [53]. Increased dissemination of operational experience and best-practice examples can therefore support informed decision-making and facilitate broader uptake of industrial heat pump technologies.

4.4.3 Workforce Skills

The availability of appropriately skilled professionals represents a critical enabling factor for the deployment of HTHPs in industrial applications. Industrial heat pump projects require a combination of competencies that go beyond those typically needed for conventional heating systems, including expertise in thermodynamics, refrigeration technology, process engineering, electrical and instrumentation systems, and industrial safety. This multidisciplinary skill requirement reflects the complexity of designing, integrating, commissioning, and operating HTHPs within existing industrial processes [53].

Results from an internal workshop on professional figures and skills for the industrial heat pump value chain highlight that workforce needs span the entire lifecycle of HTHP projects, from research and development to manufacturing, installation, operation, and maintenance. Key professional profiles identified include thermodynamic and process engineers, mechanical and electrical engineers, application and commissioning engineers, as well as technicians with specific certifications related to pressure equipment, electrical systems, welding, and occupational safety. The workshop also emphasized the importance of system integration skills, particularly for adapting heat pumps to steam-based utility systems and complex industrial process environments.

In addition to technical expertise, industrial HTHP deployment requires project management, procurement, and regulatory compliance capabilities, reflecting the capital-intensive and highly regulated nature of industrial energy systems. Skill gaps in these areas can slow project development, increase perceived technical risk, and constrain market uptake, particularly in regions or sectors with limited prior experience in industrial heat pump integration. Addressing workforce skill shortages through targeted training, certification schemes, and knowledge transfer from early projects is therefore an important social factor influencing the pace and scale of HTHP adoption [56].

4.5 Technological Factors

4.5.1 Efficiency and Maintenance

The efficiency of HTHPs has improved significantly as a result of advances in compressor technology, working fluids, and system design. For industrial applications, electrically driven HTHPs typically achieve COP that depend strongly on temperature lift, heat source characteristics, and integration design, with higher efficiencies observed at lower temperature levels and smaller temperature lifts [53].

From an operational perspective, HTHPs differ from combustion-based heating systems in that they eliminate on-site fuel combustion and associated components. This reduces wear mechanisms linked to burners, flue gas handling, and corrosion, while shifting maintenance requirements toward compressors, heat exchangers, control systems, and refrigerant circuits [53], [56]. However, the operation and maintenance of industrial heat pumps require specialized technical expertise, particularly for troubleshooting, performance optimization, and integration with complex industrial processes, which can represent an operational challenge in facilities without prior experience [56].

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4.5.2 HTHPs Reliability and Temperature Capabilities

Commercially available industrial heat pump systems have demonstrated reliable operation for process heat supply at temperatures above 100 °C in industrial environments [53]. Ongoing technological development focuses on extending temperature capabilities through advanced compressor concepts, new and alternative working fluids, and multi-stage or cascade cycle configurations. While technologies capable of delivering heat at temperatures well above 160 °C are under development and demonstration, applications above approximately 200 °C remain limited and are not yet widely available as standard commercial solutions[53].

4.5.3 Fossil Fuel Energy Consumption

HTHPs enable a reduction in fossil fuel use in industrial process heating by replacing on-site combustion with electrically driven heat generation. By upgrading low-temperature heat sources using electricity, HTHPs reduce direct fossil fuel consumption and shift energy demand toward electricity, whose carbon intensity can decrease over time as power systems decarbonize [53], [56].

For an overall estimation of the fossil fuel energy consumption reduction potential, reference is made in *Section 5.4 Energy savings and CO_2 emissions*

4.5.4 Industrial Processes Suitable for HTHPs

Approximately 29% of industrial process heat demand in Europe occurs at temperature levels below 200°C. Suitable processes are found across multiple industrial sectors, including food and beverage processing, paper and pulp production, selected chemical processes, textile and pharmaceutical manufacturing and other industries characterized by low- to medium-temperature heat demand [53], [56], [11].

Process suitability depends not only on temperature level but also on load profiles, heat source availability, and system integration complexity. Continuous or semi-continuous processes with stable heat demand and accessible waste heat streams generally offer more favorable conditions for heat pump integration than highly intermittent or batch-operated processes, which may require additional system design measures [56]

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4.5.5 Production Bottlenecks and R&D

The scaling-up of HTHP deployment is influenced by manufacturing capacity, component availability, and project-specific engineering requirements. Large industrial heat pump systems are often customized for specific applications, which can result in longer lead times compared to standardized equipment [32], [53]. Key components such as large compressors, specialized heat exchangers, and control systems can represent critical bottlenecks, particularly as demand increases.

Research and development activities continue to focus on improving system efficiency, expanding feasible temperature ranges, increasing component reliability, and developing application-specific solutions. Public research programs and collaborative European initiatives support these efforts by facilitating demonstration projects, reducing technological risk, and accelerating the transition from pilot installations to broader commercial deployment [32], [53].

4.5.6 Technological Innovation and Market Potential

Technological innovation in the HTHP sector is driven by advances in working fluids, compressor technologies, and system architectures. The use of alternative low-GWP refrigerants, multi-stage and cascade configurations, and transcritical cycles enables higher temperature operation and improved performance under demanding industrial conditions [53]. In parallel, digital tools for system modelling, monitoring, and optimization are increasingly used to support design and operation, contributing to performance optimization and operational reliability.

From a technological perspective, the potential application space for HTHPs covers a wide range of industrial heat demands below 200 °C. The realization of this potential depends on continued technological development, cost reductions, and the ability to integrate heat pumps effectively into existing industrial processes [53], [56].

4.5.7 Waste Heat Availability

The availability of waste heat represents a key enabler for efficient HTHP operation. Many industrial processes generate low-grade waste heat at temperatures typically between approximately 30 and 80 °C, which can serve as a heat source for heat pump systems [53]. The integration of HTHPs with suitable waste heat streams can significantly improve system performance by reducing temperature lift and electricity input requirements.

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Industries with simultaneous heating and cooling demands, or with multiple processes operating at different temperature levels, offer particularly favorable conditions for waste heat utilization. In such cases, heat pump integration can enhance overall energy efficiency and improve the economics of industrial heat supply, provided that system design and process integration are carefully addressed [53], [56]

4.6 Legal Factors

4.6.8 Regulations on Emissions

Regulatory frameworks governing greenhouse gas emissions increasingly favour the adoption of low-carbon heating technologies in industry. Emission pricing mechanisms and climate-related regulatory requirements raise the cost of fossil fuel–based process heat and increase compliance risks for installations relying on on-site combustion. These dynamics improve the relative competitiveness of electrified heat supply options, including HTHPs, particularly in energy-intensive sectors subject to carbon pricing and emission reporting obligations [53], [56].

In parallel, evolving regulatory expectations create long-term uncertainty for continued reliance on fossil fuel-based industrial heat supply. As emission constraints tighten and climate policies are progressively strengthened, industrial facilities face increasing pressure to adopt technologies that reduce direct emissions and limit exposure to future regulatory costs [32], [56].

4.6.9 Energy Policy

Energy policy frameworks increasingly support the electrification of industrial energy use as part of broader decarbonisation strategies. Policies promoting energy efficiency, renewable energy deployment, and the electrification of end uses create favourable conditions for industrial heat pumps by aligning electricity system development with industrial decarbonisation objectives [32], [56]

At the system level, investments in electricity infrastructure and market design reforms (such as measures encouraging flexible electricity demand) can improve the economic and operational integration of electrically driven heat technologies. As the share of renewable electricity increases, the carbon reduction potential of electrified industrial heating solutions is further enhanced, strengthening the policy rationale for heat pump deployment in industrial applications [32], [53], [56].

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4.7 Environmental Factors

4.7.1 Decarbonization and Emissions

HTHPs offer significant decarbonisation potential for industrial process heat by replacing fossil fuel–based heat generation with electrically driven systems. Scenario analyses indicate that the substitution of conventional fossil fuel technologies with HTHPs can lead to direct CO_2 emission reductions ranging approximately from 36% to 80%, depending primarily on the carbon intensity of electricity supply and the extent of technology deployment (see 5.4 Energy savings and CO_2 emissions). These reductions arise from the elimination of on-site combustion and from the high efficiency of heat pump systems.

Lifecycle considerations further support the environmental benefits of HTHPs. While manufacturing and installation contribute to overall environmental impacts, lifecycle assessments indicate that the operational phase dominates total emissions, due to the large cumulative energy throughput over system lifetime. As electricity systems decarbonise, the emission reduction potential of HTHPs increases proportionally, creating a reinforcing effect between power-sector decarbonisation and industrial electrification [53].

Additional environmental benefits can be achieved through integration with renewable energy sources and waste heat recovery. The use of renewable electricity enhances emission reductions, while natural refrigerants such as carbon dioxide and ammonia reduce direct GHG emissions associated with refrigerant leakage. Combined with improved end-of-life material recovery and recycling, these factors position HTHPs as a cornerstone technology for low-carbon and resource-efficient industrial heat supply [53], [56].

5. MARKET PENETRATION SCENARIOS

5.1 Market potential

Table 6 presents comprehensive market data for HTHP applications across the industrial sectors considered. The results confirm pronounced heterogeneity across industrial applications. Under the standardized sizing framework (minimum 200 kW, maximum 5,000 kW), the total addressable market amounts to 19,516 potential units, corresponding to an aggregate installed thermal capacity of 42.6 GW. When the same demand is expressed without applying minimum/maximum unit-size constraints (i.e., reflecting the factory distribution as reported in the underlying datasets), the implied stock increases to 108,106 units, underscoring the sensitivity of unit counts to packaging assumptions

The analysis applies a standardization framework that constrains industrial heat pump units between 200 kW minimum and 5,000 kW maximum capacity[1]. This approach reflects practical manufacturing and deployment considerations, where smaller applications are consolidated to achieve economies of scale, while larger applications are segmented to maintain manageable unit sizes and reduce technical complexity.

The installed power minimum threshold significantly impacts market structure across sectors. In textile dyeing and washing applications, where the natural factory requirement averages only 14 kW, the standardization creates a market of around 2,600 single unit installations at 350 kW each[32]. This represents substantial oversizing relative to actual demand, potentially affecting economic viability but ensuring standardized deployment approaches. This also implies that one unit would typically serve multiple processes and/or a broader site heat demand beyond the specific processes considered.

[1] For chemical and petrochemical sector this constraint has not been applied.

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Conversely, high capacity applications require segmentation. Papermaking drying remains the clearest example: with natural factory requirements of 29,387 kW across 716 locations, the 5,000 kW maximum constraint results in 6 units per facility, creating a concentrated market of 4,208 units.

A similar modularization logic applies to other large-load processes, including sugar juice evaporation (average 18,750 kW per factory, around 4 units per factory, 330 units in total) and ethanol distillation (average 11,292 kW per factory, around 2 units per factory, 147 units). Several additional drying-intensive applications also fall in this segmented category: wheat starch drying (average 25,600 kW per factory, 5 units per factory, 248 units) and corn starch drying (average 14,600 kW, 3 units per factory, 221 units), with potato starch drying representing a smaller niche (144 MW, 29 units). The same segmentation logic applies to soy oil crushing (average 19,400 kW per factory, 4 units per factory, 62 units; 310 MW) and to potato processing (blancher and dryer) (8,000 kW per factory, 2 units per factory, 141 units; 548 MW), reflecting factory-scale demands above 5 MW.

Table 6 HTHPs potential market, average size and stock market potential for the sectors analyzed

Industrial application	Installed power market potential (MW)	Number of factories	Average installed power per factory (kW)	Average installed power per unit (min size 200kW, max size 5,000kW)	Units per factory	Units market potential (min size 200kW, max size 5,000kW)	Units market potential (no min and max sizes)
Papermaking drying	21,041	716	29,387	5,000	6	4,208	4,208
Sugar juice evaporation	1,650	88	18,750	5,000	4	330	330
Milk pasteurization	1,244	12,000	104	675	1	1,843	12,000
Milk powder spray drying	651	12,000	54	675	1	964	12,000
Ethanol distillation	734	65	11,292	5,000	2	147	147
Animal feed pelleting conditioning	718	3,200	224	224	1	3,200	3,200
Beer brewing	2,159	10,000	216	675	1	3,199	10,000
Oilseed flakes cooking	151	180	839	839	1	180	180
Canned fruit and vegetables (5 proceses)	182	500	364	364	1	500	500
Wheat starch drying	1,100	-	25,600	5,000	5	248	45
Corn starch drying	834	-	14,600	5,000	3	221	86
Potato starch drying	144	-	14,100	5,000	3	29	10
Soy oil crushing	310	-	19,400	5,000	4	62	16
Potato processing blancher and dryer	548	-	8,000	5,000	2	141	99
Textile dyeing and washing and drying (2 processes)	913	65,010	14	350	1	2,609	65,010
Automotive car body preparation	308	98	3,143	3,143	1	98	98
Whey powder drying	308	-	3,800	3,800	1	177	177
Chemical and petrochemical industry	9,600	-	5,500	-	1	1,360	-
Total	**42,595**	**103,857**				**19,516**	**108,106**

In the food and beverage sector, several high volume opportunities emerge. Milk pasteurization represents a major opportunity by unit volume, with 1,843 potential installations averaging 675 kW each [32], contributing 1,244 MW to total market capacity. Milk powder spray drying remains a significant medium-scale opportunity, with 964 potential installations at 675 kW average unit size [32], contributing 651 MW. Beer brewing presents 3,199 potential units (standardized sizing) at 675 kW [32]average unit size[32] and contributing 2,159 MW. Canned fruit and vegetables (five processes) contributes 182 MW across 500 units.

Whey powder drying contributes 308 MW with 177 units (average factory demand 3,800 kW). Animal feed pelleting conditioning remains a high-volume market with 3,200 units, contributing 718 MW, with an average unit size of 224 kW (close to the minimum threshold). Oilseed flakes cooking remains comparatively small (151 MW, 180 units, average 839 kW),

The textile sector presents substantial opportunities for heat pump deployment across two primary operational areas, encompassing around 2,600 potential heat pump installations with an average thermal capacity of 360 kW per unit, contributing 913 MW to the total market potential.

The automotive car body preparation sector presents a specialized, high-capacity market segment characterized by 98 potential installations with substantial individual thermal requirements around 3,150 kW per unit. This application contributes 308 MW to the total market.

Finally, Table 6 includes an aggregated estimate for the chemical and petrochemical industry, representing 9,600 MW of installed power market potential and around 1,360 units (with average unit sizing not standardized in the same way due to process heterogeneity). This sector materially increases the overall capacity potential and should be treated as a high-level market envelope rather than a fully standardized bottom-up count.

5.2 Technology Diffusion Model

To forecast the adoption trajectory of high-temperature heat pumps in the European industrial sector, this study employs a logistic growth model (also known as the Verhulst-Pearl model), for modeling innovation adoption with market saturation constraints. [57], [58], [59]

The logistic growth model is expressed mathematically as:

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$$y(t) = \frac{L}{1 + e^{-k\cdot(t-t_0)}}$$

Where:

- $y(t)$ is the cumulative number of adopters (HTHP units installed) at time t
- L is the maximum market potential in units
- k is the growth rate parameter (determining the steepness of the adoption curve)
- t_0 is the inflection point (time at which adoption reaches 50% of market capacity)
- t is time (in years)
- e is the Euler number

This S-shaped function that derives from the equation captures three distinct phases characteristic of technology diffusion:

- slow initial adoption as early adopters overcome barriers
- rapid growth as mainstream acceptance occurs through imitation effects
- saturation as the market approaches its natural limit.

In the context of residential heat pump adoption, the logistic growth model provides valuable insights for policy design and market development strategies.

The growth rate parameter determines the steepness of the adoption curve and reflects the speed of diffusion through the market. For our analysis, k is 0.1451 and is derived from historical data regression of European residential HP market annual growth rates reported for the 2005-2023 period: this value suggests a moderate adoption rate (Figure 37).

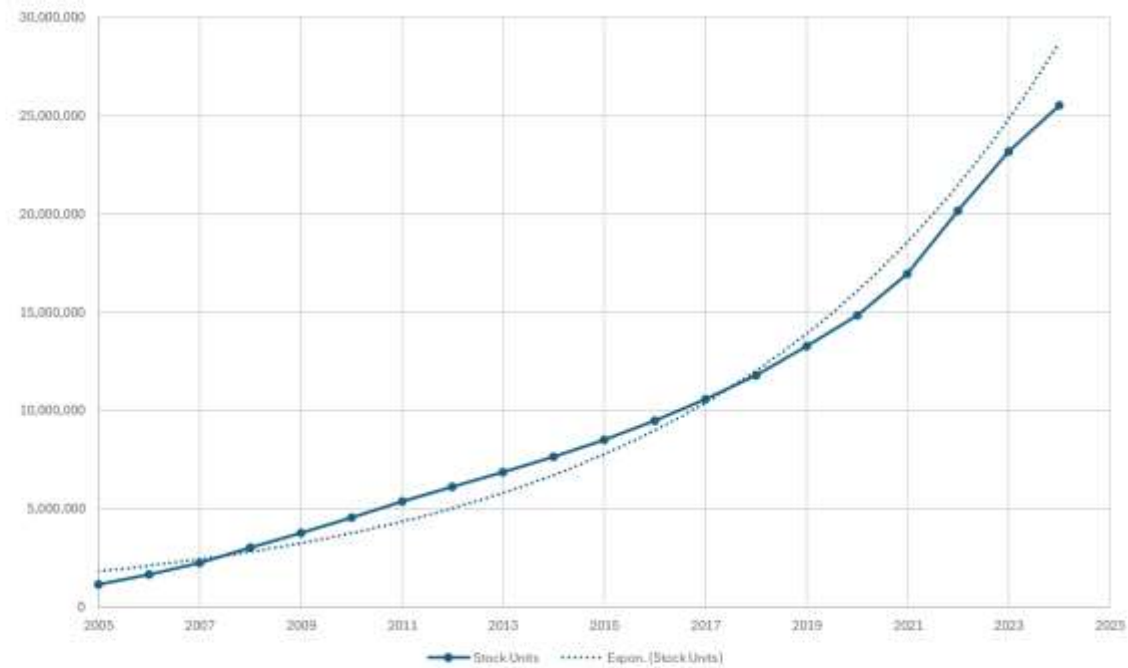

Figure 37 Residential heat pumps stock units (Actual data and Exponential trendline)

A 50-year logistic growth model was developed to forecast the diffusion of domestic heat pumps in Europe, calibrated to align with the historical data available. To define the upper bound of the model, a market saturation level of 90 million installed units was assumed [60]. The initial condition was set using a baseline of 130,000 heat pumps installed in Europe in 1990 [61].

The growth rate parameter (k) was initially derived from observed market data and subsequently refined through numerical optimisation. The optimisation process was carried out using machine-based calculations to minimise the deviation between the modelled curve and the historical data points. The resulting calibrated growth rate was $k = 16.59\%$, with the inflection point occurring in 2029, corresponding to the transition from accelerating to decelerating market growth (indicated by the green marker in Figure 38).

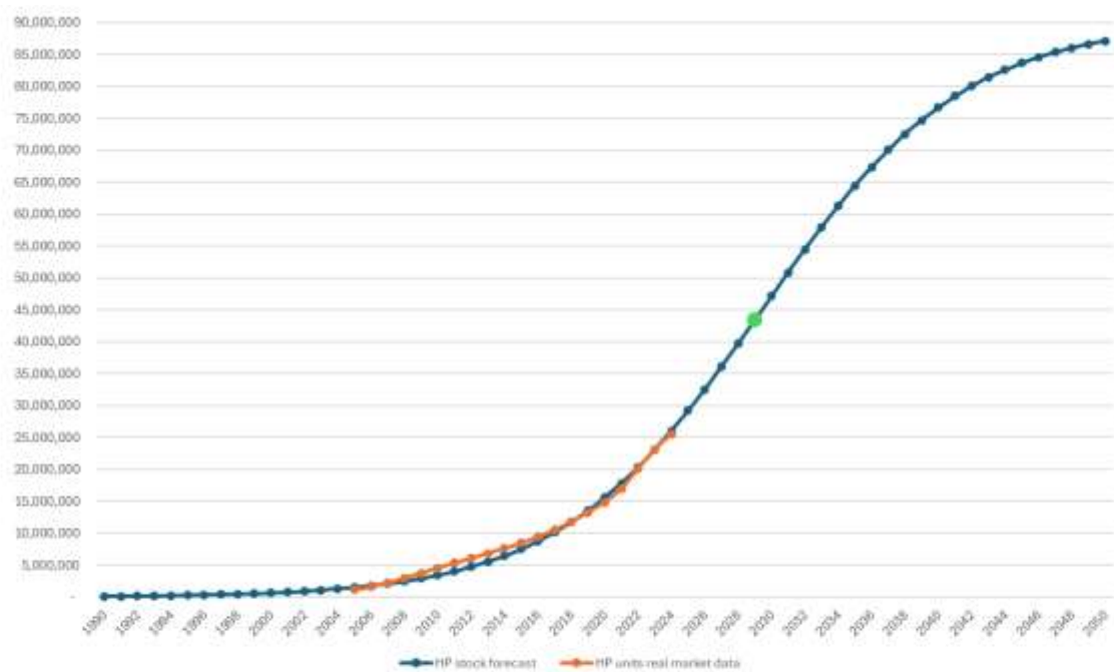

Figure 38 Residential heat pumps adoption curve calculation based on actual data

The inflection point represents the temporal midpoint of adoption when the market reaches 50% penetration. This parameter is calculated using the initial condition constraint, given:

$$y(t_0) = y_0$$

(initial installed base at t_0), we can solve for t_0:

$$t_0 = -\left(\frac{1}{k}\right) \cdot \frac{\ln(L - y_0)}{y_0}$$

5.3 Adoption of the technology forecast

Based on the previous calculations and methodology, we developed the forecast curve for HTHP units

For each forecast we specify three growth curves:

- a Business As Usual (BAU) Industrial Heat Pumps trend path anchored to observed data and forward projections for current lower-temperature industrial heat pumps, with a 6.1% Compound Annual Growth Rate(CAGR) [32]
- a Residential HP-replication path that applies the historical diffusion of residential heat pumps (implemented as a 16.59% CAGR [62], [63]) to the industrial context called BAU Residential HP trend.

- an Accelerated path representing stronger policy support and faster learning, modeled as a 20% CAGR. This structure lets us bound plausible outcomes while making explicit how different adoption tempos would translate into both unit stocks and aggregate installed capacity.

The logistic growth modeling we developed projects a maximum addressable market of 19,516 HTHP units, starting from a current baseline of 1% of total annual sales. This value has been estimated by interviews with experts in the sector and market data reports [32] it is in the range of 8-20 units sold for the first year.

Under three distinct scenarios, the market demonstrates markedly different penetration rates (Table 7).

Table 7 HTHP units scenarios inputs

Inputs	BAU (Ind. HP trend)	BAU (Ind. HP trend)	Res. HP trend	Res. HP trend	Accelerated growth	Accelerated growth
Max Market Size (units)	19,516	19,516	19,516	19,516	19,516	19,516
Initial number (units)	8	20	8	20	8	20
Growth rate	6.10%	6.10%	16.59%	16.59%	20.00%	20.00%
Midpoint (years)	128	113	47	42	39	34

The BAU scenario based on industrial heat pump trends shows the most conservative adoption pathway, with a 6.10% annual growth rate reaching the market inflection point between 113 and 128 years. This trajectory reflects the substantial technical and economic barriers characteristic of industrial process heating applications, including high upfront costs, process integration complexity, limited availability of high-temperature models and relatively long payback periods in energy-intensive sectors (Figure 39).

In contrast, the Residential Heat Pump trend scenario, with a 16.59% growth rate and 42-47 years midpoint, represents a more optimistic adoption curve that assumes industrial sector learning from the relatively successful residential heat pump deployment across Nordic and Western European countries.

The Accelerated Growth scenario, achieving a 20% annual growth rate with market inflection at 34-39 years, models the potential impact of enhanced policy support mechanisms, including increased capital subsidies, streamlined permitting processes, carbon pricing mechanisms, and mandatory fossil fuel phase-out regulations aligned with the European Green Deal's 2030 and 2050 decarbonization targets for industrial emissions.

Figure 39 presents the three scenarios. The lower and upper markers indicate the minimum and maximum values obtained from the scenario calculations, reflecting

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uncertainty in the initial sales estimates for the first years. The bold colored curve shows the average of the lower and upper values.

The divergence among these scenarios becomes particularly pronounced beyond year 20, with the accelerated pathway reaching the range 2,768-6,050 units by year 30 (average 4,409 units), while the industrial BAU scenario remains between 49-123 units (average 86 units) over the same timeframe. The residential HP BAU scenario reaches at the end of the 30 years simulation a range between 1,098-2,345 installed units (average 1,721 units).

Midpoints are the critical inflection points where adoption reaches 9,758 units (50% of market capacity), they represent the moment when the technology transitions from early adopter phase to mainstream market acceptance.

These midpoints occur at vastly different timescales: from year 34 for accelerated growth and year 42 for residential trend adoption to year 113 for industrial heat pump trend, highlighting the temporal impact of policy choices and market conditions on technology diffusion dynamics.

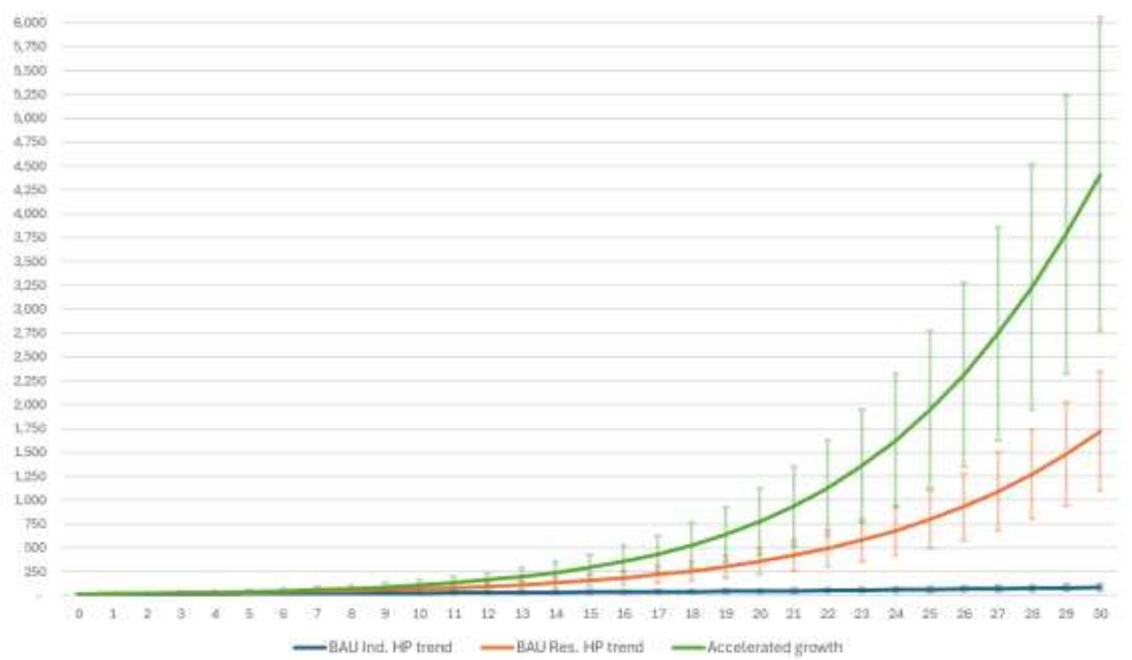

Figure 39 Deployment scenarios of HTHP units over a 30-year timeframe

5.4 Energy savings and CO_2 emissions

Figure 40 and Table 8 show the current final energy consumption (FEC) structure for the main industrial sectors considered: chemical and petrochemical, transport equipment, food and beverages, papermaking and printing and textile and leather as well as the total industry sector.

Each stacked bar indicates the share of energy coming from solid fossil fuels, natural gas and petroleum products, renewable biofuels and non-renewable waste, electricity, and derived heat [64].

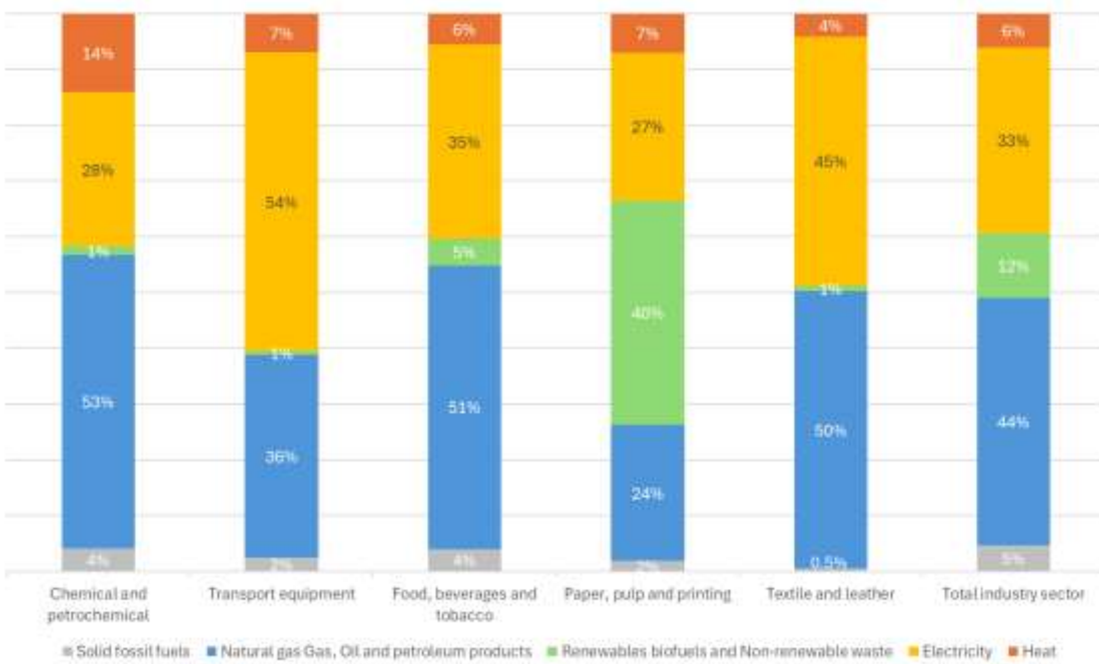

Figure 40 Share of industrial final energy consumption by fuel type, including electricity

Across all sectors, the dominant carrier is natural gas, oil and petroleum products, covering 36% to 53% of total final energy consumption. The food, beverages and tobacco sector, for instance, exhibits 51% reliance on gas and petroleum fuels, while the chemical and petrochemical sector reaches 53%.

Electricity represents a major share of final energy consumption across all industrial subsectors in the figure (27% to 54%) making it the co-dominant energy carrier together with natural gas.

Derived heat accounts for an additional 4–14% depending on the sector. Solid fossil fuels remain present, although to a lesser extent (2–7%).

Table 8 Share of industrial final energy consumption by fuel type, including electricity

Final energy consumption, energy use (including electricity)					
Industrial application	Solid fossil fuels	Natural gas Gas, Oil and petroleum products	Renewables biofuels and Non-renewable waste	Electricity	Heat
Chemical and petrochemical	4%	53%	1%	28%	14%
Transport equipment	2%	36%	1%	54%	7%
Food, beverages and tobacco	4%	51%	5%	35%	6%
Paper, pulp and printing	2%	24%	40%	27%	7%
Textile and leather	0.5%	50%	1%	45%	4%
Total industry sector	5%	44%	12%	33%	6%

Natural gas, oil and petroleum products in the figure refers to a combined category that includes *manufactured gases, peat and peat products, oil and petroleum products, and natural gas*.

However, manufactured gases contribute 0 or negligible amounts in all sectors shown, and peat and peat products account for less than 0.01%, making both effectively irrelevant to the sectoral energy mix [64].

Similarly, the category *Renewables and biofuels and non-renewable waste* is almost entirely composed of *Renewables and biofuels*, since *Non-renewable waste* contributes less than 1% across the sectors considered.

In order to calculate the final energy consumption specifically associated with process heat in the processes considered, and to estimate the corresponding CO_2 emissions, it is necessary to exclude electricity from the calculations.

Electricity is excluded to focus on fuel-based thermal supply for process heat and to avoid double-counting, noting that a limited share of process heat is already electrified in certain subsectors.

For this reason, only the energy carriers that are directly used for thermal processes are included when quantifying fuel-based process heat demand and its associated emissions (Table 9 and Figure 41).

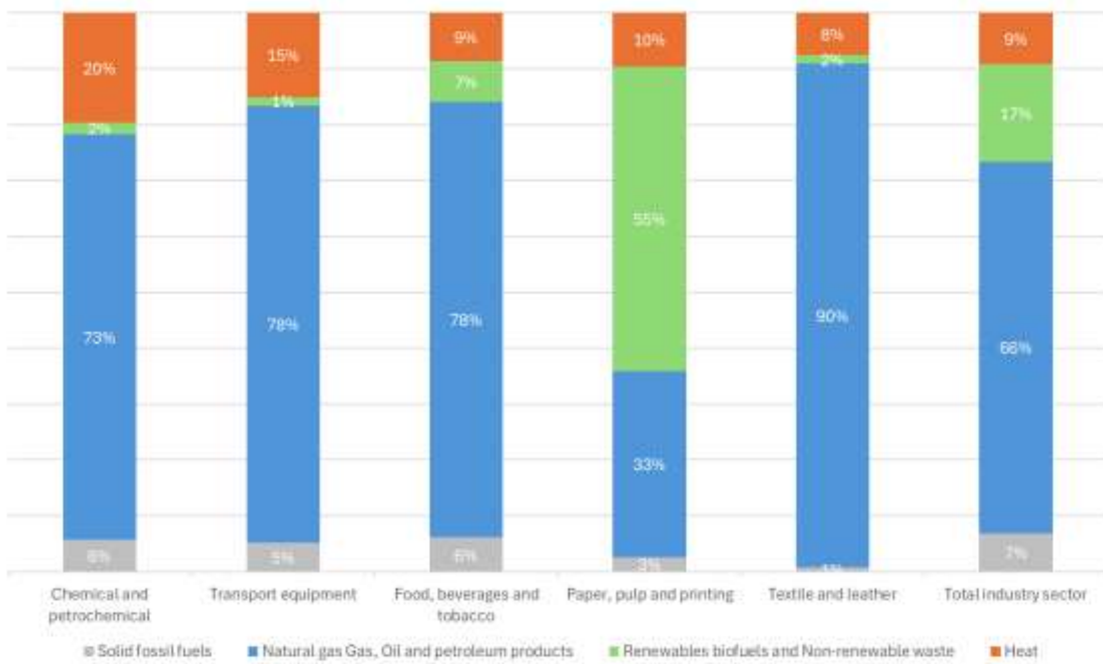

Figure 41 Share of industrial final energy consumption by fuel type, excluding electricity

Excluding electricity ensures that the analysis reflects the actual thermal energy supply mix and avoids overestimating both the energy flows and the emission reductions potentially achievable through fuel switching or the deployment of high-temperature heat pump technologies.

Table 9 Share of industrial final energy consumption by fuel type, excluding electricity

Final energy consumption, energy use (excluding electricity)				
Industrial application	Solid fossil fuels	Natural gas Gas, Oil and petroleum products	Renewables biofuels and Non-renewable waste	Heat
Chemical and petrochemical	6%	73%	2%	20%
Transport equipment	5%	78%	1%	15%
Food, beverages and tobacco	6%	78%	7%	9%
Paper, pulp and printing	3%	33%	55%	10%
Textile and leather	1%	90%	2%	8%
Total industry sector	7%	66%	17%	9%

These data enabled the calculation of the final energy consumption of the industrial processes considered. The analysis applies the energy use shares reported in Table 9.

Table 10 and Figure 42 present a comparison of the annual energy demand and final energy consumption of the industrial applications considered in our analysis under

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the current energy mix and under a scenario assuming full deployment of HTHPs operating at an average COP of 3[2].

Table 10 Energy demand and Final Energy Consumptions of selected industrial applications with current mix and with full adoption of HTHPs potential (TWh/yr)

Energy Demand and Final Energy Consumption (TWh/yr)			
Industrial application	**Energy demand**	**Current mix FEC**	**HTHP potential FEC**
Papermaking drying	124.3	147.3	49.1
Beer brewing	15.1	17.5	5.8
Milk pasteurization	8.7	10.1	3.4
Wheat starch drying	7.6	8.8	2.9
Sugar juice evaporation	6.6	7.7	2.6
Textile dyeing and washing and drying (2 processes)	6.4	7.3	2.4
Corn starch drying	5.8	6.7	2.2
Ethanol distillation	5.1	6.0	2.0
Animal feed pelleting conditioning	5.0	5.8	1.9
Milk powder spray drying	4.6	5.3	1.8
Potato processing	3.8	4.4	1.5
Automotive car body preparation	2.2	2.6	0.9
Soy oil crushing	2.2	2.6	0.9
Canned fruit and vegetables (5 proceses)	1.3	1.5	0.5
Oilseed flakes cooking	1.1	1.3	0.4
Potato starch drying	1.0	1.2	0.4
Chemical and petrochemical	159.4	200.7	66.9
Total	**360.2**	**436.7**	**145.6**

The total energy demand amounts to 360.2 TWh/yr: under the current situation the FEC is 436.7 TWh/yr, while in the HTHP scenario it is reduced to 145.6 TWh/yr, representing a 66.7% reduction in final energy consumption with full deployment of HTHPs

Final energy consumption for the current energy mix was calculated by applying the technology-specific energy mix shares from Table 11 to the total energy demand and adjusting for the corresponding conversion efficiencies (11).

[2] COP values are conservatively assumed to average 3 across applications, reflecting a mix of low- and medium-temperature HTHP deployments [53].

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Table 11 Emission factors and efficiency for different energy classes[65], [66]

Energy class	Emission factor (T CO2-eq/MWh)	Efficiency
Solid fossil fuels	0.375	0.900
Natural gas Gas, Oil and petroleum products	0.240	0.930
Renewables biofuels and Non-renewable waste	0.420	0.900
Electricity	0.187	
Heat	0.240	0.500

Across the applications assessed, full deployment of HTHPs reduces final energy consumption relative to the current mix in every case.

Papermaking drying remains the dominant application, with an energy demand of 124.3 TWh/yr with DEC decreasing from 147.3 TWh/yr (current mix) to 49.1 TWh/yr under the HTHP scenario.

Beer brewing shows an energy demand of 15.1 TWh/yr, with FEC moving from 17.5 TWh/yr to 5.8 TWh/yr. Milk pasteurization requires 8.7 TWh/yr, decreasing from 10.1 TWh/yr to 3.4 TWh/yr FEC, while wheat starch drying has an energy demand of 7.6 TWh/yr and FEC shifts from 8.8 TWh/yr to 2.9 TWh/yr.

Sugar juice evaporation totals 6.6 TWh/yr of demand, decreasing FEC from 7.7 TWh/yr to 2.6 TWh/yr, and textile dyeing and washing and drying shows 6.4 TWh/yr of demand, with FEC falling from 7.3 TWh/yr to 2.4 TWh/yr.

A similar pattern is observed in the mid-range processes. Corn starch drying has an energy demand of 5.8 TWh/yr, with final energy consumption decreasing from 6.7 TWh/yr to 2.2 TWh/yr. Ethanol distillation requires 5.1 TWh/yr, moving FEC from 6.0 TWh/yr to 2.0 TWh/yr, while animal feed pelleting conditioning shows 5.0 TWh/yr of demand and changes FEC from 5.8 TWh/yr to 1.9 TWh/yr. Milk powder spray drying totals 4.6 TWh/yr of demand, with final energy consumption decreasing from 5.3 TWh/yr to 1.8 TWh/yr. Potato processing has an energy demand of 3.8 TWh/yr, shifting FEC from 4.4 TWh/yr to 1.5 TWh/yr.

Smaller applications include automotive car body preparation and soy oil crushing, each with an energy demand of 2.2 TWh/yr and FEC decreasing from 2.6 TWh/yr to 0.9 TWh/yr. At the lower end, canned fruit and vegetables shows 1.3 TWh/yr of demand and FEC decreasing from 1.5 TWh/yr to 0.5 TWh/yr. Oilseed flakes cooking totals 1.1 TWh/yr, moving FEC from 1.3 TWh/yr to 0.4 TWh/yr, and potato starch drying shows 1.0 TWh/yr of demand, with FEC decreasing from 1.2 TWh/yr to 0.4 TWh/yr.

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Finally, the aggregated chemical and petrochemical category represents a major share of the portfolio, with an energy demand of 159.4 TWh/yr and final energy consumption decreasing from 200.7 TWh/yr to 66.9 TWh/yr under full HTHP deployment.

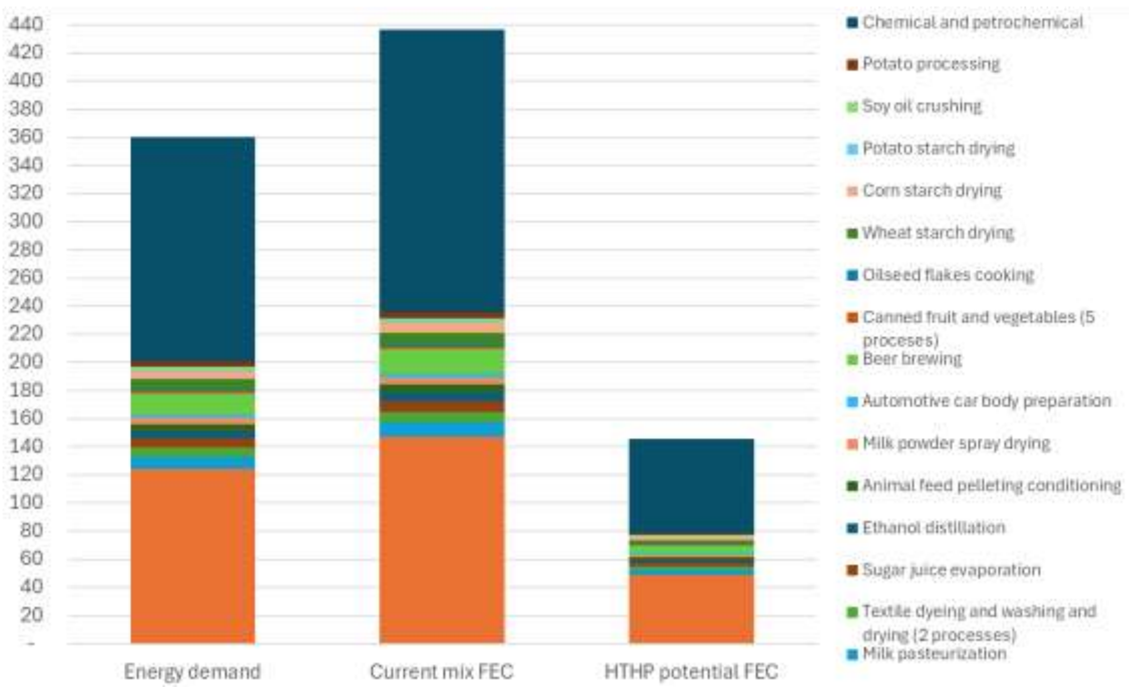

Figure 42 Energy demand, FEC of selected industrial applications with current mix and with full adoption of HTHPs potential (TWh/yr)

CO_2 emissions are calculated following the same methodological approach used for the estimation of final energy consumption. Specifically, the FEC shares of the different energy carriers were multiplied by the corresponding emission factors reported in Table 11.

Table 12 and Figure 43 summarize the estimated CO_2 emissions for each industrial application under the current energy mix and under the HTHP potential scenario.

In aggregate, emissions decrease from 123.8 Mtonnes CO_2-eq/yr in the current mix to 27.2 Mtonnes CO_2-eq/yr with HTHPs. This corresponds to an absolute reduction of 96.6 Mtonnes CO_2-eq/yr, equivalent to a 78% decrease across the applications included in the assessment.

Table 12 CO_2 emissions of selected industrial applications with current mix and with full adoption of HTHPs potential (MTonnes CO_2-eq/yr)

CO2 emissions (MTonnes CO_2-eq/yr)		
Industrial application	**Current mix FEC**	**HTHP potential**
Papermaking drying	50.3	9.2
Beer brewing	4.6	1.1
Milk pasteurization	2.6	0.6
Wheat starch drying	2.3	0.5
Sugar juice evaporation	2.0	0.5
Textile dyeing and washing and drying (2 processes)	1.8	0.5
Corn starch drying	1.8	0.4
Ethanol distillation	1.6	0.4
Animal feed pelleting conditioning	1.5	0.4
Milk powder spray drying	1.4	0.3
Potato processing	1.2	0.3
Automotive car body preparation	0.7	0.2
Soy oil crushing	0.7	0.2
Canned fruit and vegetables (5 proceses)	0.4	0.1
Oilseed flakes cooking	0.3	0.1
Potato starch drying	0.3	0.1
Chemical and petrochemical	50.5	12.5
Total	**123.8**	**27.2**

The emissions profile is strongly concentrated in two applications. Chemical and petrochemical is the largest contributor, with 50.5 Mtonnes CO_2-eq/yr under the current mix, declining to 12.5 Mtonnes CO_2-eq/yr under the HTHP potential. Papermaking drying is nearly as significant, with 50.3 Mtonnes CO_2-eq/yr in the current mix and 9.2 Mtonnes CO_2-eq/yr under the HTHP scenario. Together, these two categories account for the majority of total emissions in both cases, and therefore drive the largest share of the overall reduction potential identified.

Beyond these two dominant applications, a second tier of processes contributes emissions on the order of a few megatonnes CO_2-eq per year.

Beer brewing is the largest within this group, with emissions decreasing from 4.6 to 1.1 Mtonnes CO_2-eq/yr. Milk pasteurization follows, moving from 2.6 to 0.6 Mtonnes CO_2-eq/yr. Wheat starch drying is of similar magnitude, declining from 2.3 to 0.5 Mtonnes CO_2-eq/yr, while sugar juice evaporation decreases from 2.0 to 0.5 Mtonnes CO_2-eq/yr.

In the textile sector, textile dyeing and washing and drying shows 1.8 Mtonnes CO_2-eq/yr in the current mix and 0.5 Mtonnes CO_2-eq/yr under HTHP potential.

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A comparable emissions level is reported for corn starch drying, which decreases from 1.8 to 0.4 Mtonnes CO_2-eq/yr, and for ethanol distillation, which declines from 1.6 to 0.4 Mtonnes CO_2-eq/yr. Animal feed pelleting conditioning shows emissions of 1.5 Mtonnes CO_2-eq/yr in the current mix, decreasing to 0.4 Mtonnes CO_2-eq/yr in the HTHP scenario. Milk powder spray drying follows with 1.4 declining to 0.3 Mtonnes CO_2-eq/yr. These mid-range applications, while individually much smaller than papermaking and chemical/petrochemical, collectively represent a meaningful share of the remaining emissions and contribute to the diversification of abatement potential across multiple sectors.

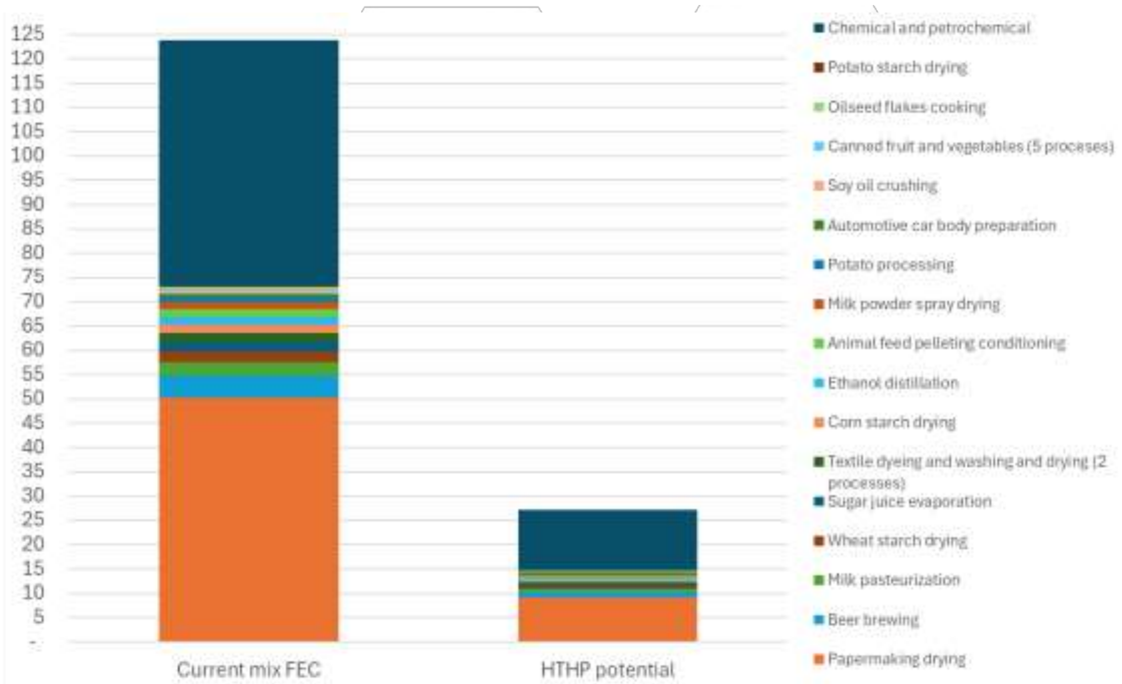

Figure 43 CO_2 emissions of selected industrial applications with current mix and with full adoption of HTHPs potential (T CO_2-eq/yr)

The remaining applications form a lower-emitting group, with values below approximately 1.5 Mtonnes CO_2-eq/yr each. Potato processing decreases from 1.2 to 0.3 Mtonnes CO_2-eq/yr. Automotive car body preparation shows 0.7 Mtonnes CO_2-eq/yr in the current mix and 0.2 Mtonnes CO_2-eq/yr under HTHPs; soy oil crushing exhibits the same pattern, also moving from 0.7 to 0.2 Mtonnes CO_2-eq/yr. Canned fruit and vegetables declines from 0.4 to 0.1 Mtonnes CO_2-eq/yr, while oilseed flakes cooking and potato starch drying each decrease from 0.3 to 0.1 Mtonnes CO_2-eq/yr under the HTHP potential.

Overall, the table indicates that emissions reductions are observed consistently across all applications when shifting from the current mix to the HTHP potential

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scenario. The largest absolute impacts are associated with chemical and petrochemical and papermaking drying, while the remaining processes contribute additional reductions at smaller but still relevant scales, together shaping the total reduction of 96.6 Mtonnes CO_2-eq/yr.

6. CONCLUSIONS

This deliverable has provided an integrated market analysis of high temperature heat pumps for industrial process heat in the European Union, assessing technical feasibility, market potential, and the possible role of HTHPs in industrial decarbonisation pathways to 2050. The analysis combines a top-down quantification of sectoral energy demand and temperature levels with a bottom-up assessment of selected processes, complemented by a review of waste heat availability, a PESTLE analysis of market conditions, and long term market penetration scenarios. Taken together, these elements offer a picture of where HTHPs can already contribute at scale, where deployment is likely to concentrate, and which constraints will shape adoption.

From a system perspective, EU industrial energy use remains dominated by process heat and is still largely supplied by fossil fuels. In 2022, total industrial final energy consumption amounted to around 2,790 TWh/yr, with demand strongly concentrated in a small number of sectors. The chemical and petrochemical industry (598 TWh/yr), non-metallic minerals (395 TWh/yr), paper, pulp and printing (378 TWh/yr), and food and beverage (324 TWh/yr) together account for more than 60% of total industrial energy use.

A key outcome of the top-down assessment is the temperature segmentation of process heat demand. While several energy intensive activities are dominated by very high temperature requirements beyond the current commercial envelope of HTHPs (and largely beyond the range demonstrated by prototype systems), a substantial share of industrial heat demand occurs below 200 °C, which defines the principal applicability window for near and mid term HTHP deployment. In particular, the paper, pulp and printing sector is identified as the largest consumer of low temperature process heat, with 260 TWh/yr below 200 °C, followed by food and beverage with 149 TWh/yr; additional contributions arise from chemicals (82 TWh/yr), non-metallic minerals (47 TWh/yr), machinery (31 TWh/yr), transport equipment (24 TWh/yr) and textiles (11 TWh/yr). Overall, these results indicate that the bulk of deployable potential is concentrated in a relatively small set of sectors combining high heat loads with large shares of low and medium temperature demand.

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The bottom-up analysis translates these sector level opportunities into a portfolio of concrete industrial applications and quantifies both their process heat demand and their installed power market potential. Across the applications included in the assessment, the total energy demand amounts to 360.2 TWh/yr, while the corresponding total installed power market potential reaches 42.6 GW. This portfolio is dominated by two large contributors: chemical and petrochemical applications, representing 159.4 TWh/yr of energy demand and 9,600 MW of installed power potential, and papermaking drying, with 124.3 TWh/yr of energy demand and 21,041 MW of installed power potential.

Beyond these two dominant applications, the analysis identifies a broader set of smaller but still relevant opportunities. The largest of these are beer brewing (2,159 MW), sugar juice evaporation (1,650 MW), milk pasteurization (1,244 MW), wheat starch drying (1,100 MW), textile dyeing, washing and drying (913 MW), corn starch drying (834 MW), ethanol distillation (734 MW), animal feed pelleting and conditioning (718 MW), and milk powder spray drying (651 MW). Additional contributions come from potato processing blancher and dryer (548 MW), soy oil crushing (310 MW), whey powder drying (308 MW), automotive car body preparation (308 MW), canned fruit and vegetables (182 MW), oilseed flakes cooking (151 MW), and potato starch drying (144 MW).

Taken together, these results confirm that, beyond the two largest application areas, additional opportunities exist across a broad range of food and beverage and manufacturing processes, giving the HTHP market a diversified application base even where individual process segments remain smaller in absolute scale.

At the process level, the most promising applications for HTHP integration are those such as drying, evaporation, boiling, washing, and low pressure steam generation, where thermal demand is often continuous and where compatible heat sources can be identified. Drying emerges as a recurring high potential use case due to its high specific heat demand and frequent availability of low temperature waste heat streams that can be upgraded. At the same time, the analysis confirms that feasibility remains process and site specific: required sink temperature, temperature lift, integration with existing steam and utility systems, spatial constraints, and annual operating hours materially affect both performance and economics. Detailed integration and system design studies therefore remain essential to translate sector level potential into investable projects, particularly for retrofits.

Waste heat availability strengthens the HTHP value proposition by improving achievable coefficients of performance and broadening feasible integration options.

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Sector level indicators show that waste heat can represent meaningful shares of process heat consumption in several sectors, but practical recoverability depends on temperature level, temporal availability, and integration constraints that cannot be fully captured by sector aggregates alone.

The PESTLE analysis highlights a generally favorable policy direction for industrial heat pump deployment, driven by EU climate and energy efficiency objectives, while also identifying barriers likely to shape adoption rates. High upfront investment costs, electricity price volatility, and retrofit complexity remain key constraints, particularly for smaller sites and for facilities built around legacy steam networks. Organizational factors (risk perception, internal capacity to develop integration projects, and skills availability) also influence adoption. On the technology side, ongoing advances in compressors, working fluids and system configurations are expanding the temperature range and improving reliability, with commercial solutions increasingly addressing mid temperature applications and higher temperature solutions progressing through demonstration, while widespread deployment beyond 200 °C remains outside near term commercial reach.

Building on the technical assessment, the market potential analysis confirms heterogeneity across industrial applications and quantifies the addressable market in terms of unit stock and installed thermal capacity. Under the standardized sizing framework (minimum 200 kW, maximum 5,000 kW), the total addressable market amounts to 19,516 potential units, corresponding to an aggregate installed thermal capacity of 42.6 GW. When the same demand is expressed without applying minimum/maximum unit size constraints (reflecting the factory distribution reported in the underlying datasets), the implied stock increases to 108,106 units, highlighting the sensitivity of unit counts to packaging assumptions; the standardized estimate is therefore used as the saturation level for the diffusion modelling.

To forecast adoption, the deliverable applies a logistic diffusion model with an initial condition corresponding to a baseline of around 1% of total annual sales, estimated through expert interviews and market reports and expressed as a range of 8–20 units sold in the first year. Three penetration scenarios are defined: a Business As Usual (BAU) pathway (6.1% CAGR), a residential heat pump replication pathway (16.59% CAGR), and an accelerated pathway (20% CAGR). By year 30, the accelerated scenario reaches 2,768–6,050 units (average 4,409 units), the residential trend reaches 1,098–2,345 units (average 1,721 units), and the industrial BAU reaches 49–123 units (average 86 units). The midpoint of adoption, corresponding to 9,758 units (50% of market capacity), occurs at year 34–39 for accelerated growth, year 42–47 for the residential trend, and year 113–128 for the

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industrial BAU pathway, highlighting the strong sensitivity of diffusion dynamics to policy choices, market conditions and learning rates.

In the scenario analysis, full HTHP deployment across the selected bottom-up application portfolio results in substantial reductions in final energy consumption. For the assessed applications, FEC decreases from 436.7 TWh/yr under the current supply mix to 145.6 TWh/yr under the full HTHP potential scenario (with an average COP of 3), corresponding to 291.1 TWh/yr of final energy savings (a 66.7% reduction in FEC for the assessed applications). Moreover, the scenario analysis confirms that large scale HTHP deployment can deliver substantial emissions benefits, especially when paired with low carbon electricity. For the selected industrial applications considered in the bottom-up analysis, total emissions decrease from 123.8 Mtonnes CO_2-eq/yr under the current mix to 27.2 Mtonnes CO_2-eq/yr under the full HTHP potential scenario: an absolute reduction of 96.6 Mtonnes CO_2-eq/yr, equivalent to a 78% decrease. Emissions are strongly concentrated in two applications that therefore drive the majority of the reduction potential: chemical and petrochemical decreases from 50.5 to 12.5 Mtonnes CO_2-eq/yr, and papermaking drying decreases from 50.3 to 9.2 Mtonnes CO_2-eq/yr. The remaining applications contribute additional reductions at smaller but still relevant scales, collectively diversifying the abatement potential across multiple industrial segments.

Overall, the combined evidence from the top-down segmentation, bottom-up application assessment, waste heat evaluation, market framework analysis, and diffusion scenarios shows that HTHPs could be a key enabling technology for decarbonizing low and medium temperature industrial process heat in Europe. While HTHPs cannot substitute high temperature fossil fuels heat demand in all sectors, their targeted deployment in suitable applications (particularly in chemical and petrochemical and papermaking drying, alongside a broader set of food and manufacturing processes) can deliver major final energy savings and deep CO_2 reductions. HTHPs should therefore be positioned as a core component within a broader portfolio of industrial decarbonisation strategies supporting the transition towards a climate neutral European industrial sector by 2050.

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