D8.1 Evaluation of industrial application potential

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TABLE OF CONTENT

LIST OF TABLES

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101083558

LIST OF FIGURES

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LIST OF ABBREVATIONS

ACRONYM	DESCRIPTION
DAC	Direct Air Capture
DACCS	Direct Air Capture with Carbon Storage
EU	European Union
GHG	Greenhouse Gases
KPI	Key Performance Indicators
LPG	Liquefied Petroleum Gas
ORC	Organic Rankine Cycle
RES	Renewable Energy Sources
SWOT	Strengths, Weaknesses, Opportunities, Threats (analysis)

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EXECUTIVE SUMMARY

The present document presents an initial evaluation of the integration of the HOCLOOP concept directly on the industrial level, both in present and future industrial energy systems. The following three main topics are approached, described, and evaluated:

- Overview of the HOCLOOP concept and its industrial relevance.
- Key findings on its potential applications in selected industrial sectors and processes.
- Strategic insights on feasibility, sustainability impact, and market potential.

1. Introduction

1.1. Objectives

The main objective of Deliverable 8.1 is to evaluate and conduct a preliminary assessment of the integration of the HOCLOOP concept into both existing and future industrial systems. While geothermal energy is already planned for district heating within 4th generation systems or for stable renewable electricity production, its potential extends beyond these conventional applications. WP8 aims to explore new opportunities for integrating borehole closed-loop systems into various industrial sectors. This will be achieved through a structured approach involving identifying and selecting suitable industrial systems as well as assessing synergies between innovative geothermal solutions and industrial processes and the potential application. Deliverable 8.1 concentrates on reviewing the current state of industrial heat demand in the European Union with the particular emphasis on HOCLOOP regions as well as evaluating the industrial processes which may be suitable for integration with closed-loop geothermal system.

1.2. HOCLOOP system

The concept behind the HOCLOOP project is the construction of geothermal wells using a dual-channel drill-string for deep horizontal closed-loop circulation, providing enhanced efficiency. Unlike existing closed-loop systems, this innovative design is expected to significantly reduce costs for geothermal projects. By eliminating the need for a geothermal reservoir such as a hot aquifer, the technology expands the accessibility of geothermal energy beyond traditional locations. It is adaptable to local geological conditions and supports new community energy models, promoting sustainability and energy transition. Additionally, it allows for the use of alternative fluids, and for more efficient energy production compared to conventional systems. The conventional geothermal solution requires at least two wells and depends on high reservoir permeability and connectivity to maintain stable hydraulic and thermal properties. It also necessitates the use of brine with appropriate chemistry, making it susceptible to scaling, precipitation, and corrosion in surface installations. Moreover, low reservoir permeability, rapid injectivity decline, and the risk of unproductive wells are common challenges. These issues can lead to induced seismicity, efficiency loss, or environmental pollution. In contrast, the HOCLOOP solution

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operates with a single well in a closed-loop system, ensuring stable thermal output over time and eliminating the need for brine. This design effectively prevents scaling, avoids rock-fluid interactions, and eliminates the risk of unproductive wells. In addition, it minimizes seismic risks, reduces maintenance costs, increases geothermal accessibility, and has a minimal environmental footprint, leading to higher acceptance and broader applicability.

1.3. Methods

The assessment of HOCLOOP's industrial application follows a structured approach that evaluates technical and environmental factors to determine its feasibility across different industrial sectors. This methodology ensures the identification of industries where the HOCLOOP closed-loop geothermal system can be effectively implemented for process heating applications. The methodology is indicator-based as it relies on a set of quantifiable criteria to evaluate the feasibility of HOCLOOP's implementation and compare its applications.

One of the primary considerations in this assessment is the temperature requirements of different industrial processes. Low-temperature applications are found in industries such as food, beverages, and textiles, where processes like drying, pasteurization, and washing are common. Medium-temperature applications are more relevant for sectors such as pulp and paper, where heat-intensive processes like drying and bleaching are necessary. High-temperature applications are generally unsuitable for HOCLOOP, as they require combustion-based heating, which is essential in industries such as steel, cement, and glass.

Beyond temperature requirements, the selection of suitable industries is influenced by their overall heat demand. Sectors with continuous or seasonal heat needs are prioritized to ensure the efficient utilization of the geothermal system. Focus is given to industries that currently rely heavily on fossil fuels for their process heat, as these offer significant potential for decarbonization through the integration of HOCLOOP technology. Additionally, industries that primarily use steam or hot water for their heating processes are considered prime candidates, as these energy sources can be effectively replaced with geothermal heat. Although, the potential use of alternative working fluids in a closed-loop system is also considered.

Geographical and geological factors are other key determinants. Preference is given to industries located in areas where subsurface conditions are favorable for horizontal closed-loop heat exchange. Regions with established district heating networks or industrial parks are considered for their potential to integrate HOCLOOP into existing infrastructure. Another factor is related to the potential of the selected industries to reduce CO_2 emissions. Industries with high direct emissions resulting from fossil-fuel-based heating systems are prioritized.

The assessment begins with data collection and heat demand analysis to determine sectoral energy consumption trends, temperature requirements, and peak load demands, which is further discussed in the following sections. Based on this data, industries are classified according to their compatibility with HOCLOOP's operational characteristics. The expected outcome of this assessment is the identification of key industrial processes where HOCLOOP can provide sustainable and cost-effective process heat.

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2. Industrial Sectors Selection and Screening Criteria

2.1. Selection Rationale

The selection of industrial systems for HOCLOOP integration is based on a structured evaluation framework, ensuring alignment with technical feasibility, economic viability, and environmental impact. The methodology follows four key criteria:

- Temperature Requirements of Processes

Industrial processes can be categorized based on their thermal energy demand, differentiating between low-temperature (<100°C), medium-temperature (100–400°C), and high-temperature (>400°C) applications. The suitability of HOCLOOP for direct heat supply or hybrid configurations is assessed based on temperature compatibility with process requirements. Special attention is given to sectors where geothermal energy can provide stable and continuous heat supply, such as food processing, chemical manufacturing, and pulp & paper industries.

- Direct and Indirect Applications of HOCLOOP

HOCLOOP's potential for direct applications for providing primary process heat is examined, particularly in industries with steady thermal demand, such as drying processes or steam generation. The feasibility of waste heat recovery and hybrid integration with existing energy systems (e.g., industrial heat pumps) as a form of indirect applications is analyzed to maximize efficiency and reduce energy losses. Case studies of industrial processes are reviewed to assess synergies between HOCLOOP and heat recovery strategies. The parameters at the outlet of the well force the possible direct or indirect application. If the temperatures are high enough, steam-based systems can be deployed, if not, indirect installations such as heat pumps must be assessed.

- Industrial Demand and Market Potential in the EU

A market analysis will be conducted to identify sectors with high thermal energy consumption and a strong interest in decarbonization solutions. The heat demand profile within selected industries in evaluated regions will be presented. Moreover, EU industrial policies, incentives, and regulatory frameworks promoting geothermal integration will be reviewed to determine economic drivers and barriers and further included in SWOT analysis.

- Potential for CO_2 Emission Reduction

A CO_2 emission reduction potential will be assessed based on carbon footprint estimation to quantify the reduction in CO_2 emissions achieved by replacing fossil fuel-based heat sources with HOCLOOP. The analysis will be location-based to underline the differences in configurations assessed for different regions. It will be based on the amount of CO_2 avoided which can be obtained with HOCLOOP system applied under different operational scenarios.

2.2. Industrial Heat Demand Landscape in EU and Selected Regions

The industrial sector is the largest consumer of thermal energy in the European Union (EU), accounting for a significant portion of overall energy demand. Industrial heat consumption is driven by various manufacturing and processing activities that require different temperature ranges, from low-temperature heating to high-temperature processes. Industrial heat is largely invisible to consumers but

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represents about 40% of global final energy demand and 10% of the world's CO_2 emissions.

The EU industrial sector represents approximately 30% of total final energy demand, with more than 60% of this energy used for process heat generation. Heat consumption accounts for around 1800 TWh. Key industries that require substantial heat input include:

- Iron and steel (e.g. blast furnaces, reheating processes);
- Chemical and petrochemical (e.g. steam reforming, refining, synthesis reactions);
- Pulp and paper (e.g. drying and pulping);
- Food and beverage (e.g. pasteurization, sterilization, drying);
- Textile industry (e.g. dyeing, finishing processes);
- Ceramics and glass (e.g. kiln operations, annealing).

Although industrial heat is typically associated with very high-temperature processes, like manufacturing steel and cement or melting glass and cooking bricks, half of it is used at well below 400 °C, across a vast range of sectors, namely food and beverage, chemicals, pulp and paper, and textiles. Typical breakdown of heat temperature used in industry is presented in Figure 1.

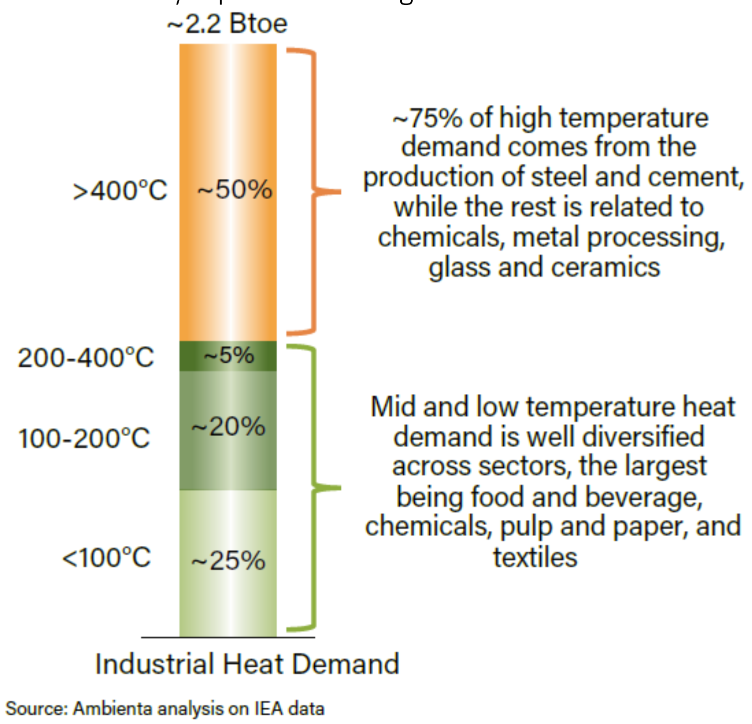

Figure 1. Temperature breakdown for industrial heat [1]

Of the global final energy demand, process heat occupies approximately 66%, whereas high-temperature processes demand more than a half of it (Figure 2). In industry, nowadays, about 75% of heat is produced by burning fossil fuels, mostly natural gas, in a boiler, furnace or combined heat and power plant [1].

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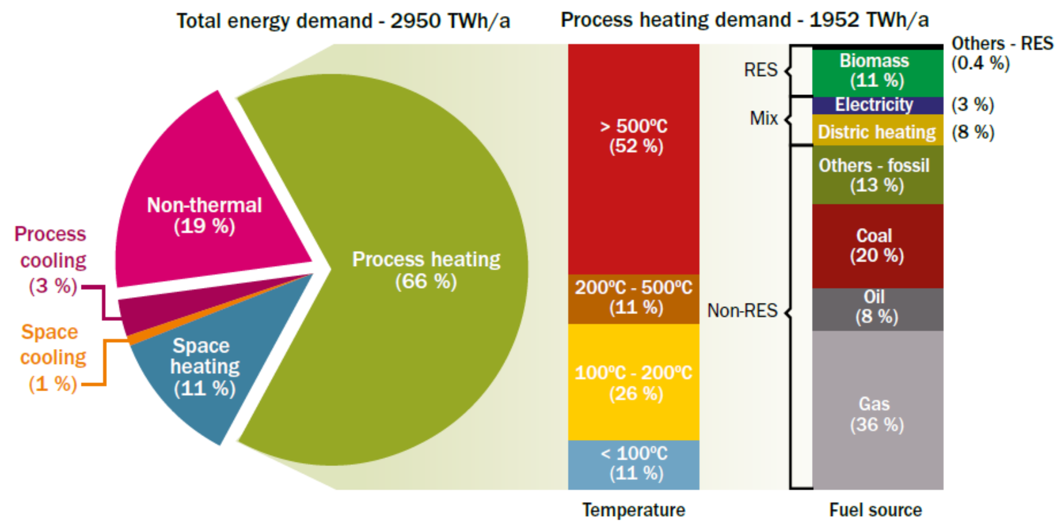

Figure 2. Breakdown of the final energy demand in European industry [2]

The Industrial sector uses a wide variety of processes employing different types and designs of heating equipment. Process heating methods used in manufacturing operations largely depend on the industry, and many companies use multiple operations. Figure 3 presents the heat consumption in 2021 in different sectors in the EU with the sources.

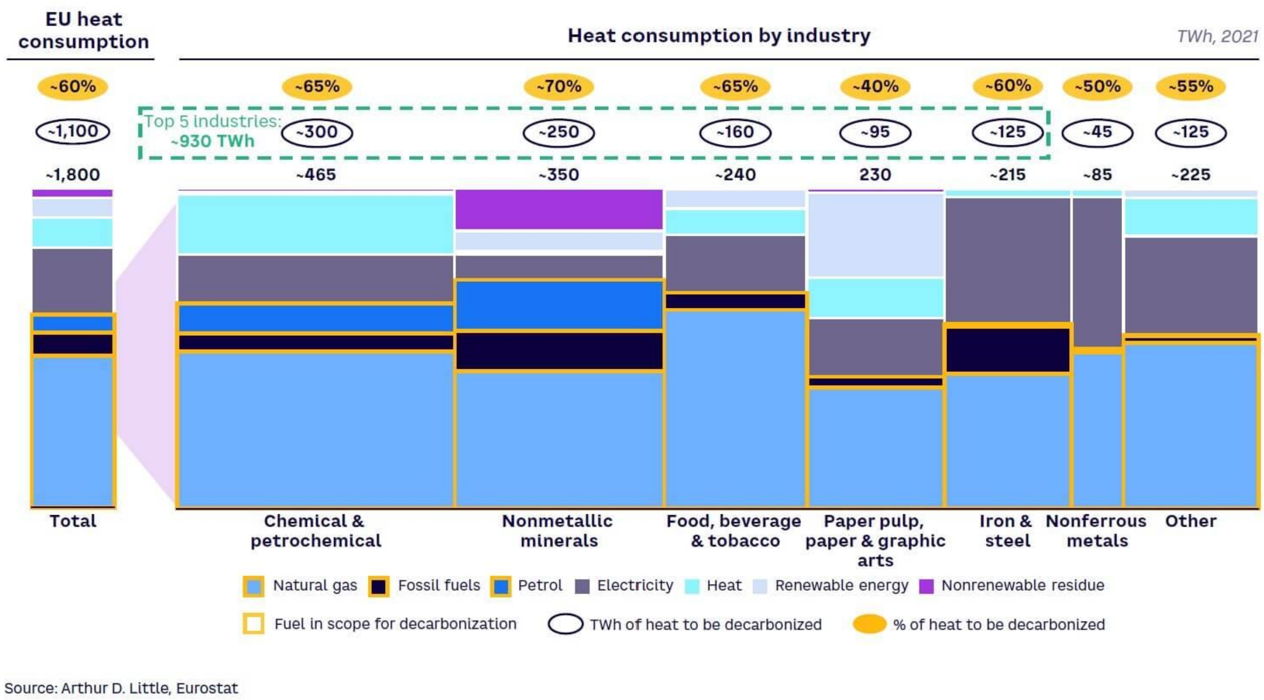

Figure 3. Heat consumption by industry in the EU, 2021 [3]

Industries require a reasonable amount of heat to drive processes, such as pasteurization, drying, cooking, preheating of water, curing, etc. Some of these use electricity, whereas the electricity demands are usually met using fossil fuel-based thermal power plants [4]. Nevertheless, in sectors like iron and steel, chemical and petrochemical, as well as non-metallic minerals, high-temperature processes play a crucial role in (Figure 4).

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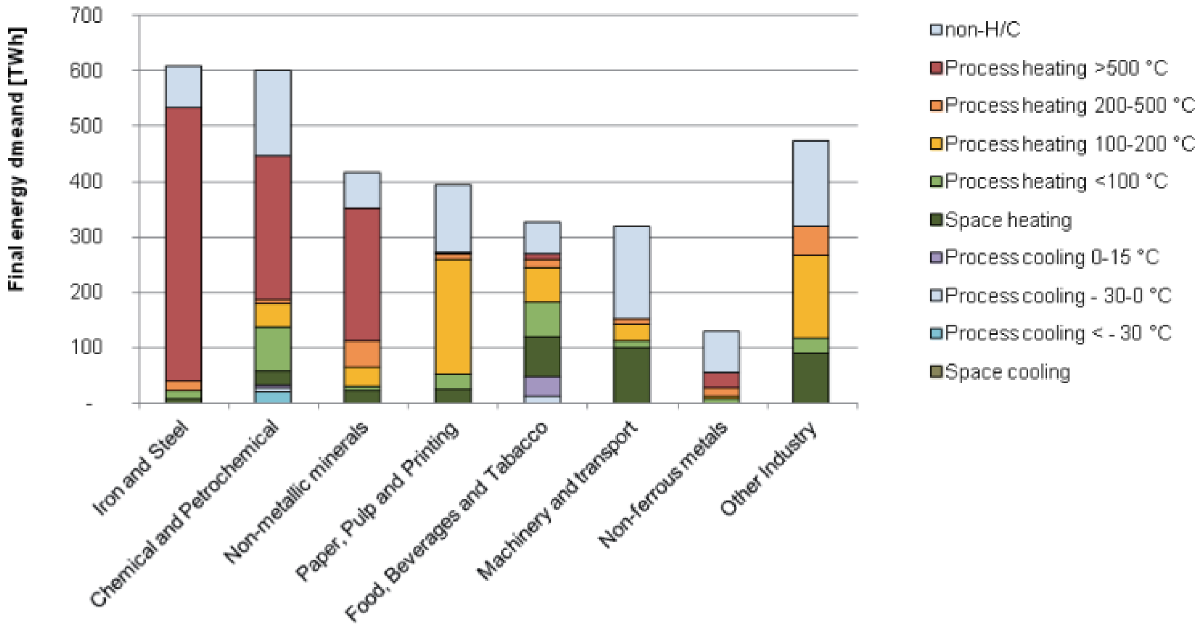

Figure 4. Sectoral final energy demand with the process temperatures breakdown [5]

Up to 70% of industrial energy demand consists of medium (150°C – 400°C) and high temperature (above 400°C) process heat, most of which cannot be electrified due to technical constraints. Low-carbon alternatives such as heat pumps and solar thermal struggle to meet the high-temperature requirements, while biomass – currently the main alternative – faces hurdles such as sustainable sourcing and high costs. Nevertheless, low-temperature processes are clearly visible in sectors such as pulp and paper or food and beverages.

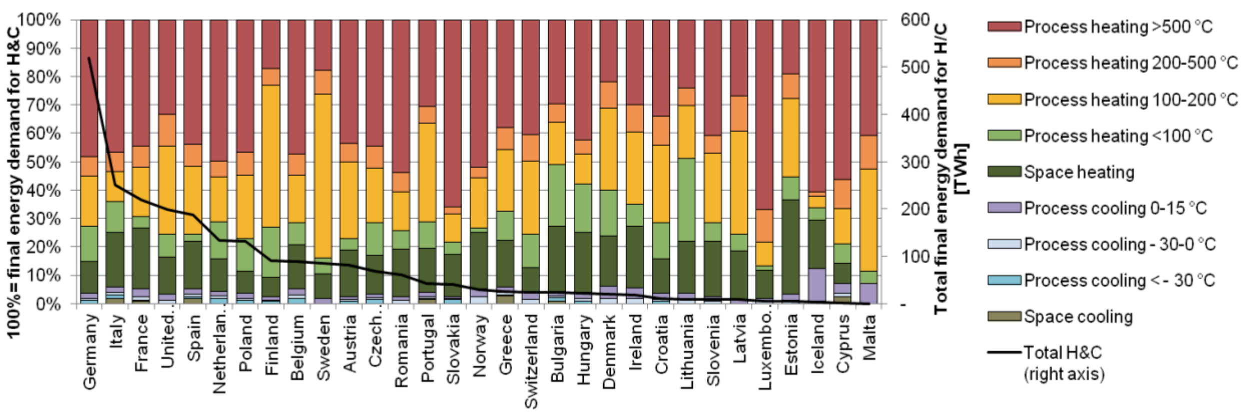

Figure 5. Heating and cooling demand in the EU countries [5]

Figure 5 illustrates the final energy demand for heating and cooling across European countries, showing both the relative distribution of different heating and cooling needs and the total energy demand. Process heating, particularly above 200°C, dominates the energy demand in most countries, with higher temperature requirements in industrialized countries like Germany, Italy, and France. Space heating also represents a significant share, especially in northern Europe as a result of the colder climate conditions. Cooling demand, though present, remains relatively low compared to heating, with process cooling being more relevant in southern countries.

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HOCLOOP selected regions

Poland

Heating and cooling in Poland account for 56% of the country's total final energy demand, slightly above the European average of 50%. Over half of this energy is consumed for space heating in buildings, while process heating in industry and the service sector constitutes the second-largest share [5]. Poland's industrial sector is heavily reliant on fossil fuels, particularly coal, leading to a high-carbon energy profile. The country's district heating systems predominantly use fossil fuels, with over 80% of the energy sourced from such fuels.

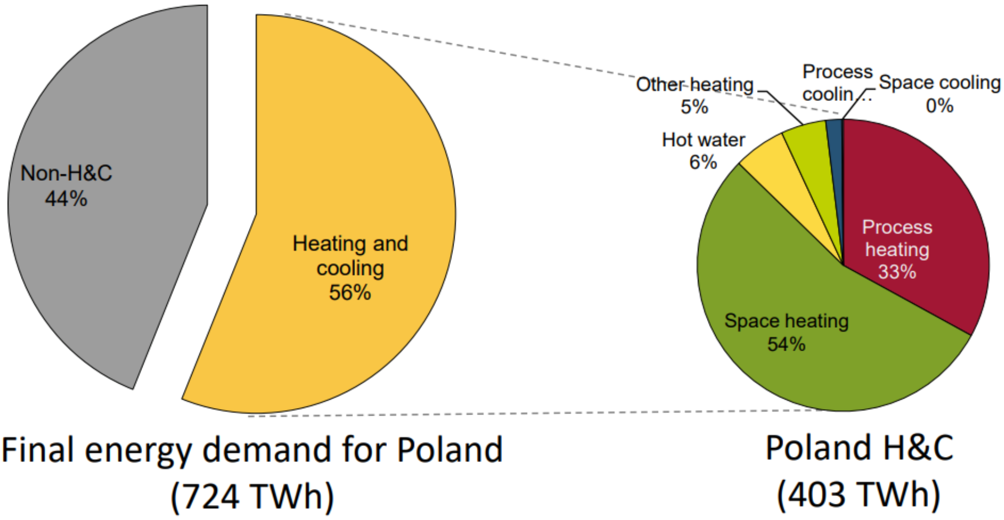

Figure 6. Heating and cooling energy demand in Poland [5]

Germany

Industrial process heat represents nearly 70% of the final energy demand in Germany's industrial sector, making up over 20% of the country's total final energy consumption.

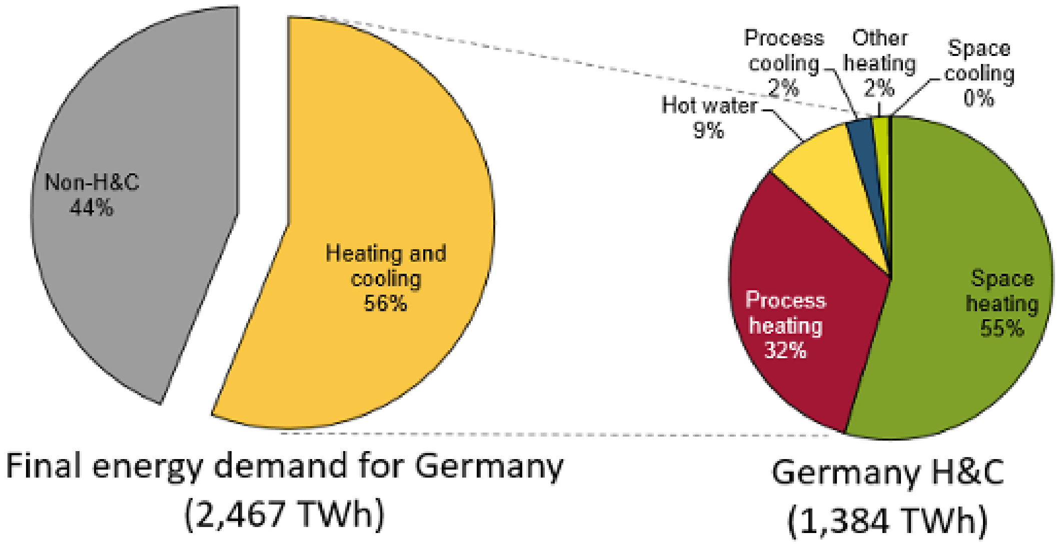

Figure 7. Heating and cooling energy demand in Germany [6]

The sector remains heavily reliant on fossil fuels, particularly natural gas, which supplies almost 50% of the required process heat, while coal accounts for 24% [7]. Currently, renewable energy and electricity

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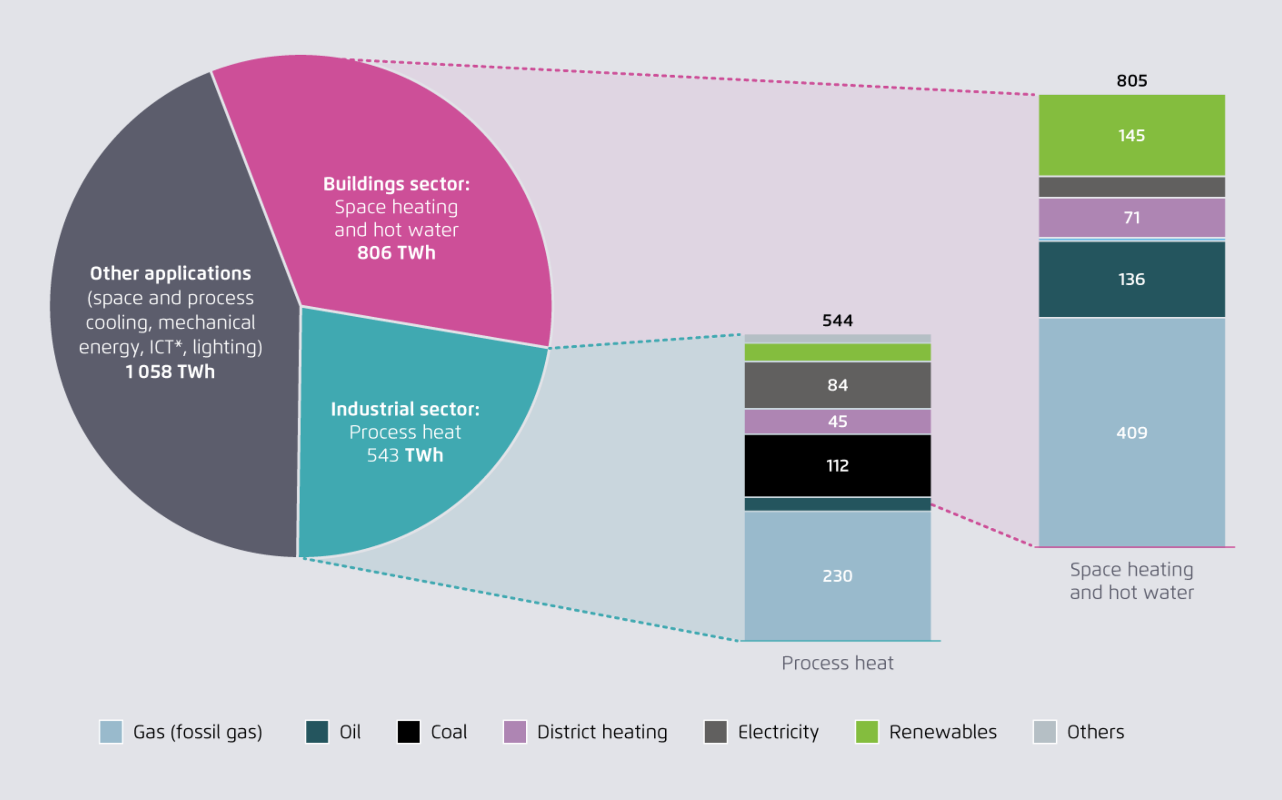
play only a minor role in industrial heating. In 2021, Germany's industrial process heat consumption reached approximately 544 TWh (Figure 8) [8].

Final energy consumption by application in Germany 2021 (left)
Energy sources of supply (right)

Figure A



Agora Energiewende based on AGEB (2022b). *Information and communication technology

Figure 8. Final energy consumption by application in Germany [8]

Industrial process heating is considered one of the most challenging sectors to decarbonize due to its diverse and highly specialized applications across industries such as paper, textiles, steel, cement, and glass. While many processes operate at low- and medium-temperature levels (e.g., drying, steam generation), around 50% of industrial heat demand in Germany exceeds 400°C, making it particularly difficult to decarbonize. High-temperature heat requires high energy densities, which further complicates the transition to cleaner alternatives [9].

Italy

Heating and cooling account for the largest share of energy consumption in Italy, making up 54% of the country's final energy demand, slightly above the European average of 50%. Over half of this energy is dedicated to space heating in buildings, while process heating in industry and the service sector represents the second-largest share [10].

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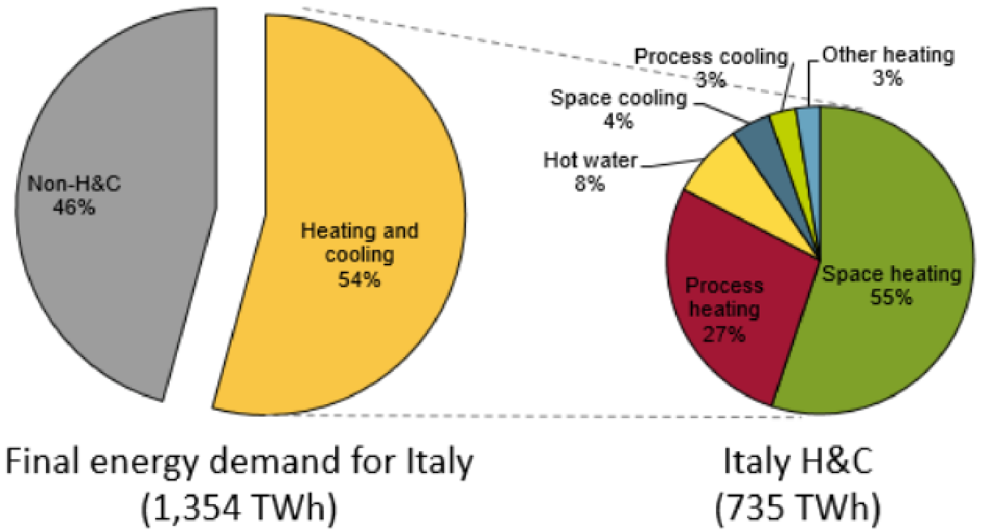

Figure 9. Heating and cooling energy demand in Italy [10]

<u>The Netherlands</u>

Heating and cooling in the Netherlands account for 5% of the EU28's total final energy demand, making it the largest energy-consuming sector in the country, representing 50% of the national final energy demand. Nearly half of this energy is used for space heating in buildings, while process heating in industry and the service sector forms the second-largest share. Cooling, including both process and space cooling, makes up less than 5% of the total heating and cooling demand and plays a minor role in the overall energy system. Process heating represents the second largest demand, the overwhelming majority of which is used by the industry sector in the Netherlands. [11].

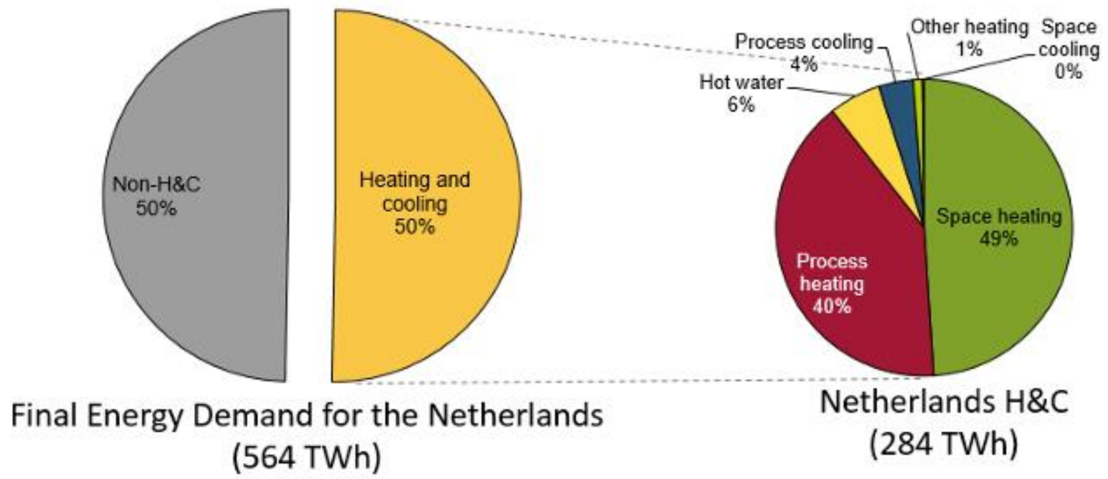

Figure 10. Heating and cooling energy demand in the Netherlands [11]

2.3. List of Industrial Sectors and Pre-Selected Processes

In this section, the industries were assessed with basis on heat demand category and previously described selection rationale. Those which fit into temperature ranges of HOCLOOP possible application were chosen for further analysis. Subsequently, based on the temperatures and type of heating media as

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well as general commonness of occurrence within countries' economies, 10 specific industrial processes were appointed for further investigation (Table 3).

Industrial heat demand is typically classified into three categories based on temperature range and heating medium as presented in Table 1.

Table 1. Heat demand categories based on temperature range

Heat demand category	Temperature range (°C)	Heating medium	Examples of industries
Low-Temperature heat	50°C – 150°C	Hot water, steam, air	Food & Beverages, Textile, Pulp & Paper, Direct Air Capture (DACCS)
Medium-Temperature heat	150°C – 400°C	Steam, thermal oils	Chemical Processing, Refining, Drying Processes
High-Temperature heat	>400°C	Direct combustion, molten salts	Steel, Cement, Glass, Ceramics

HOCLOOP's operational range (50°C - 250°C) aligns well with low and medium-temperature industrial processes, making it a possible solution for sectors with significant heat demand in this range.

The mode of operation is an important feature that also affects the type of equipment used and ways alternative heat sources can be integrated at industrial facilities. During operation, the load being heated can either run through process heating equipment continuously or run in discrete steps for set conditions and time. This distinction between continuous and batch operations has implications for estimating heat demand on an accurate operating time scale.

A comparison of the various databases shows that there are wide variations in the reported amount of energy used by different processes and by the individual process steps. The large differences between the databases and the published information are in part due to the large number of manufacturing variables, including age of equipment, system configuration, and reporting systems.

<u>Rationale for Sector Selection</u>

The following table highlights the suitability of HOCLOOP for different industrial sectors, categorized by temperature needs [12]:

Table 2. Temperature ranges within industrial sectors and following feasibility for HOCLOOP integration

Industry sector	Heat demand temperature range	HOCLOOP feasibility
Pulp and paper	80 - 200°C	Suitable
Food and beverages	60 - 180°C	Suitable
Textile Industry	70 - 150°C	Suitable
Chemical processing	150 - 400°C	Partially suitable
Direct air capture	80 - 200°C	Suitable
Petrochemical Refining	300 - 600°C	Not suitable

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Steel Manufacturing	500 - 1200°C	Not suitable
Glass and Ceramics	700 - 1600°C	Not suitable

a) Food and beverages sector

Based on the Eurostat energy balance, the food, beverages, and tobacco industries encompass various processes, including bread baking and cheese manufacturing. Essential heat applications in this sector primarily involve steam generation and baking. Most of the fuel consumption occurs at temperatures below 200°C, except for certain operations like sugar production and specific high-temperature drying methods, such as milk powder processing [12].

b) Pulp and paper sector

The primary products of the paper, pulp, and printing industry are packaging paper and board. Major processes within this sector include paper manufacturing and pulping. More than 82% of the industry's fuel consumption is dedicated to generating heat below 200°C, with the vast majority of this heat supplied in the form of steam [12]. The pulp and paper industry is among the top five most energy-intensive industries globally and is the fourth largest industrial energy user. This industry accounts for approximately 6% of global industrial energy use and 2% of direct industrial CO_2 emissions. This critical and systematic review seeks to identify alternatives for mitigating the climate impacts of pulp and paper processes and products, thus making the pulp and paper industry more environmentally sustainable [13].

c) Chemical sector

The chemical industry produces over 30,000 chemicals for various sectors, including plastics, fertilizers, paints, and detergents. However, most CO_2 emissions come from just ten basic chemicals [14]. According to Eurostat, this sector ranges from large-scale chemical production to specialized pharmaceuticals. Key processes include steam cracking, ammonia production, steam generation, and carbon black production. Electrification potential is highest for ethylene, carbon black, and ammonia production, which together account for 74% of the industry's fuel demand and 53% of its total energy use. This potential extends to the broader chemical and petrochemical sector [12].

d) Textile sector

The textile and apparel industry accounts for about 2% of global greenhouse gas (GHG) emissions [15], making it a key sector in climate change discussions. As global demand rises and production shifts to lower-cost regions, adopting cleaner and more efficient manufacturing becomes crucial. The industry's complexity makes emissions reduction a global challenge across supply chains. Fabric preparation, dyeing, and finishing consume 50% of thermal energy, while 35% is lost in steam generation and distribution. Transitioning to low-carbon energy sources and electrified heating technologies offers significant potential for cutting fossil fuel use and emissions [16].

e) Direct air capture

Commercial-scale Direct Air Capture (DAC) requires substantial thermal and electrical energy, particularly for the regeneration process, which is a major energy-consuming step. Solid sorbent-based DAC systems operate at low temperatures (80–120°C), which can be supplied by waste heat, heat pumps, or electric heaters [17]. According to the International Energy Agency's Net Zero by 2050 Scenario, DAC technologies are expected to capture over 85 Mt CO_2 by 2030 and around 980 Mt CO_2 by 2050, marking a significant scale-up from the current 0.01 Mt CO_2 captured today [18].

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Based on the heat demand categorization and selection rationale, the following ten industrial processes have been identified as prime candidates for further HOCLOOP feasibility studies:

Table 3. Specific industrial processes for further studies [12,19]

Industry Sector	Industrial Process	Heat Demand Range	HOCLOOP Feasibility
Pulp and paper	Paper Drying	60-80°C	*Suitable*
	Pulp Bleaching	130-150°C	*Suitable*
Food and beverages	Pasteurization	60-80°C	*Suitable*
	Sterilizing	110-120°C	*Suitable*
Textile Industry	Fabric Dyeing	70-90°C	*Suitable*
	Bleaching	60-100°C	*Suitable*
Chemical processing	Solvent distillation	140-250°C	*Partially suitable*
	Polymerization	200-300°C	*Partially suitable*
Direct air capture	CO_2 Adsorption & Desorption	60-120°C	*Suitable*
All/others	Pre-heating of fluids	60-90°C	*Suitable*

These selected processes will undergo further evaluation in the following sections, assessing feasibility, integration potential, and economic viability of HOCLOOP technology.

3. Heat Demand Characteristics of Selected Industrial Processes

This section presents the characterization of heat demand for ten selected industrial processes, including Direct Air Capture with Carbon Storage (DACCS). While most processes operate under relatively stable conditions, leading to an assumption of constant heat demand profiles, some exhibit variations influenced by daily, weekly, or seasonal factors. These fluctuations are analyzed and represented accordingly. The results are illustrated through graphical representations and summarized, providing a clear overview of the thermal energy needs across different industrial applications.

a) Food and beverage sector

The most thermal energy-intensive processes within the food and beverage industry are evaporation and crystallization (180°C), baking (180°C), pasteurization (up to 150°C, but typically around 80°C), and drying (90°C), which often require removing large quantities of water, and typically rely on heat from fossil fuel combustions [20].

The following graphs (Figure 11 and Figure 12) present the heat demand characteristics within a typical week for two processes in the food and beverage sector: (i) pasteurization and (ii) sterilizing. Three typical daily periods were identified for the above-mentioned areas:

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- weekdays,
- Saturdays,
- Sundays and holidays.

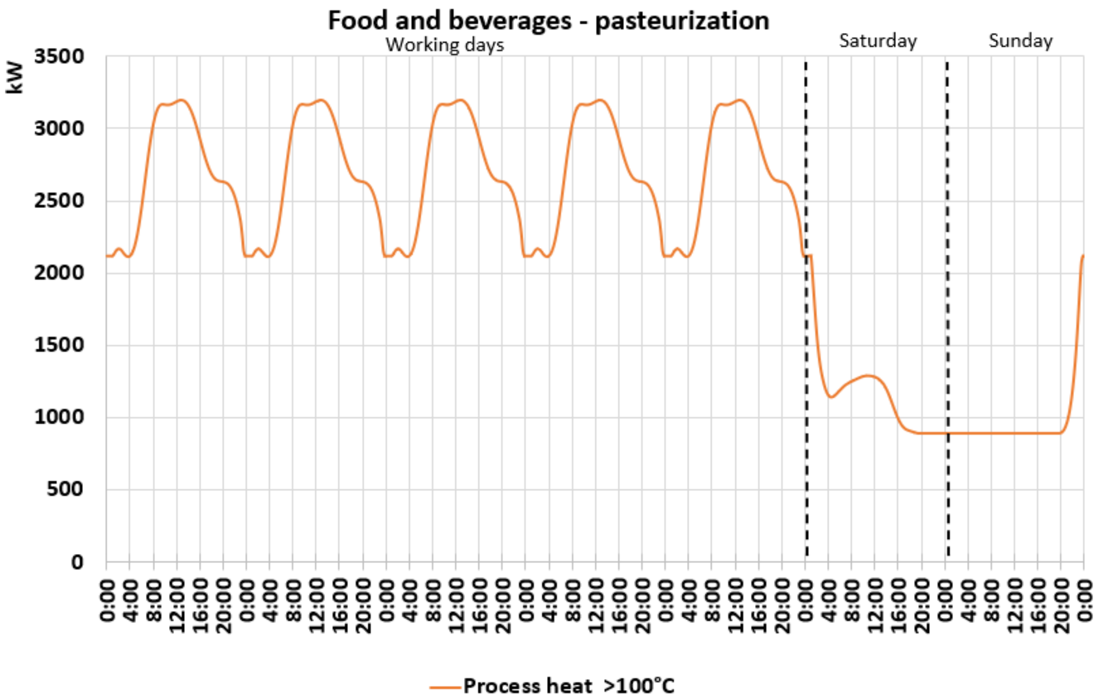

Figure 11. Heat demand profiles, food and beverage - pasteurization (based on data from [21])

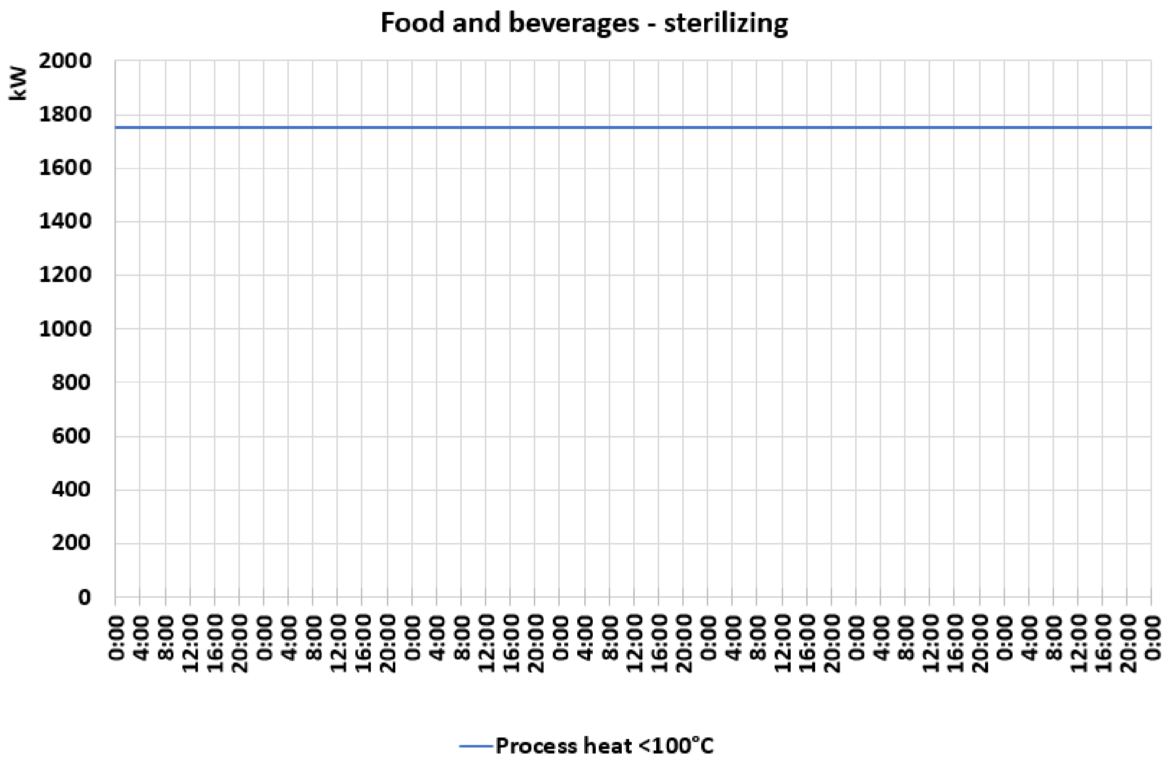

Figure 12. Heat demand profiles, food and beverage - sterilizing (based on data from [21])

b) Pulp and paper sector

The paper, pulp and printing sector's primary output is packaging paper and board. Key applications within the sector include paper production and pulping. Over 82 percent of this sector's fuel demand is used to generate temperatures below 200 °C, and nearly all of this heat is in the form of steam [22].

Three typical daily periods were identified for the heat demand profiles in pulp and paper industry, and they are presented below. They include two processes in pulp and paper sector: (i) paper drying and (ii) pulp bleaching.

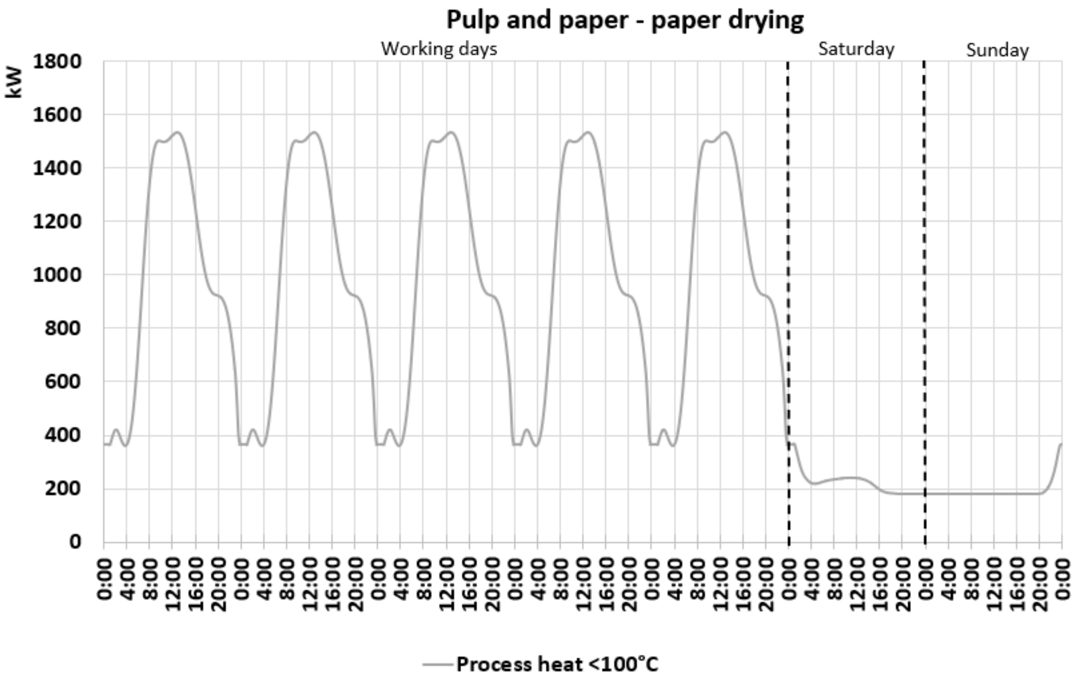

Figure 13. Heat demand profiles, pulp and paper – paper drying (based on data from [21])

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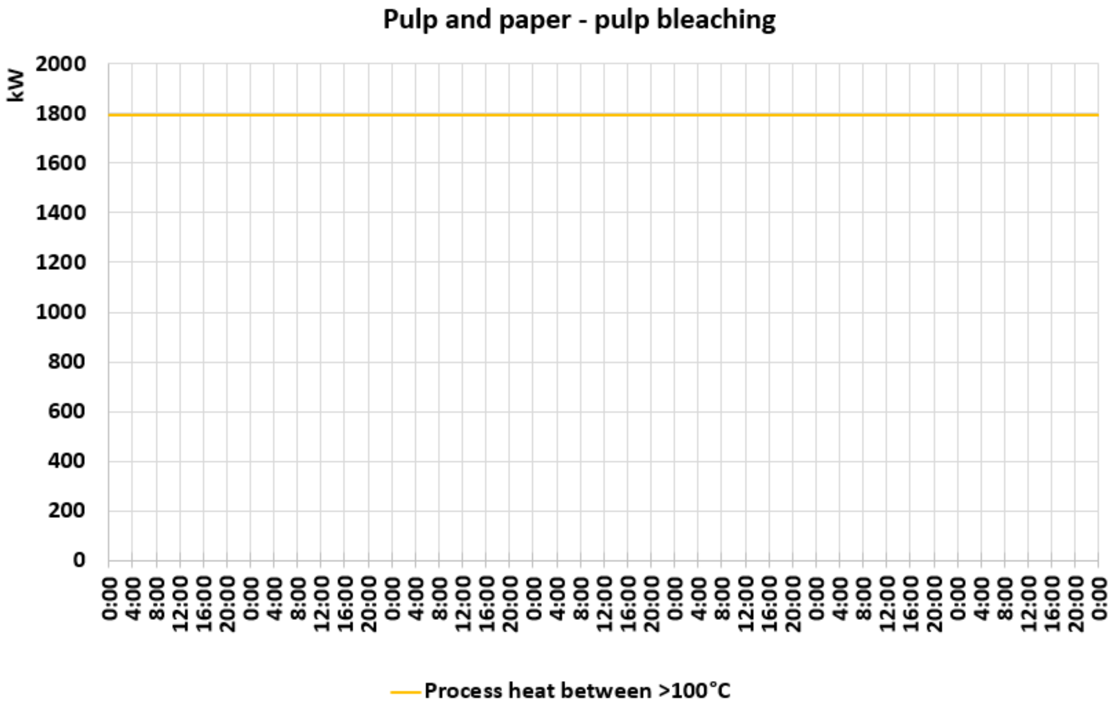

Figure 14. Heat demand profiles, pulp and paper – pulp bleaching (based on data from [21])

c) textile sector

The most common processes within the textile sector are bleaching, fixing, dyeing, drying, washing, and pressing. The first two are recognized with the highest required temperature. Bleaching is applied to remove natural colour, impurities, and stains from fibres and fabrics to achieve a uniform, white, or bright base for further processing, while fixing refers to the process of stabilizing dyes, pigments, or chemical treatments onto fabric and involves heat-activated chemical reactions that improve fabric properties. Nevertheless, within the latter one, the temperature ranges differ due to type and agent used. Moreover, most of them use hot air or infrared as a heat source therefore it was not included in the study. Figure 15 and Figure 16 present graphs with heat demand for fabric dyeing and bleaching processes during a typical week.

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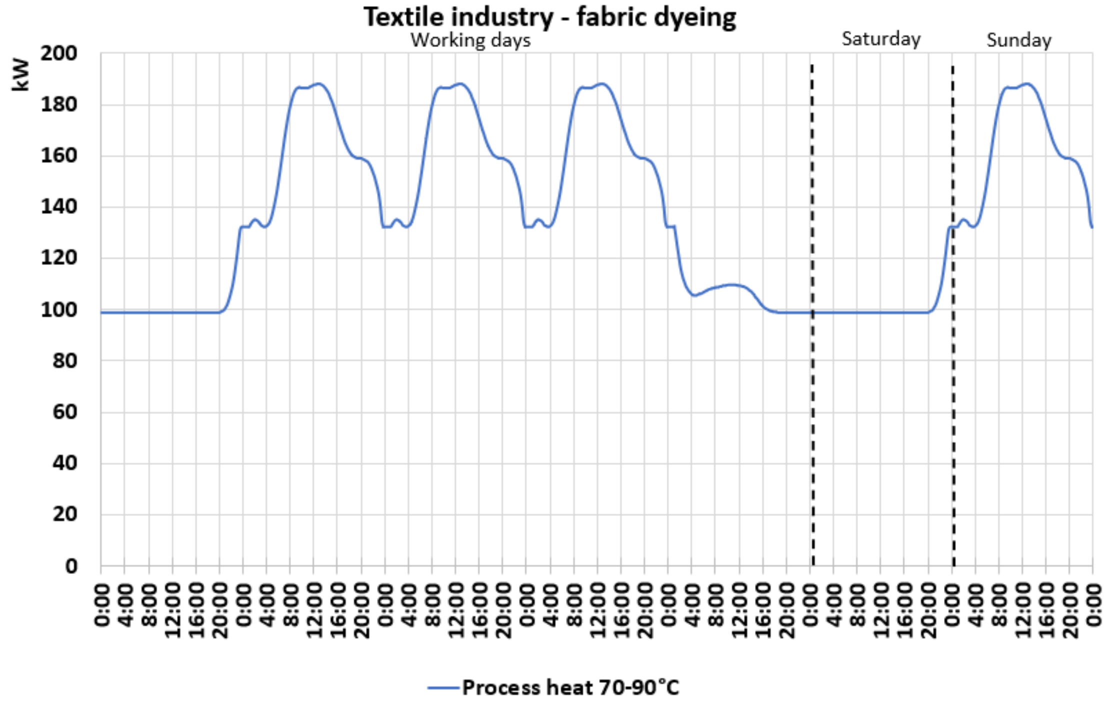

Figure 15. Heat demand profiles, textile industry – fabric dyeing (based on data from [21])

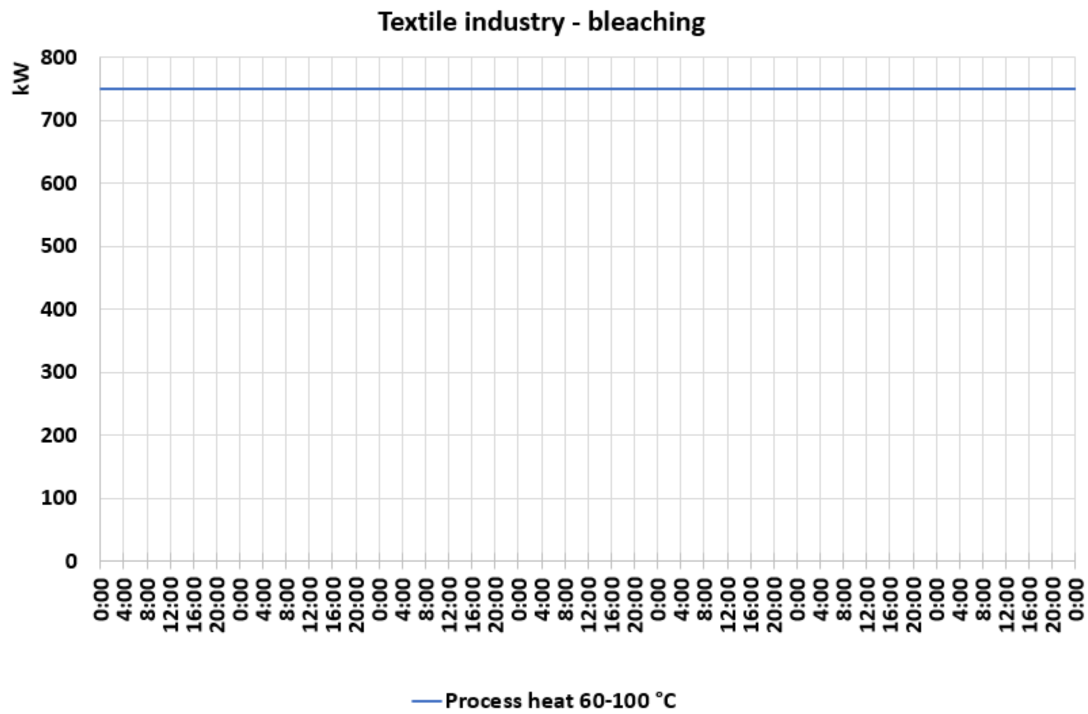

Figure 16. Heat demand profiles, textile industry - bleaching (based on data from [21])

d) chemical processing

The chemical industry is highly energy intensive, with processes like solvent distillation and polymerization requiring significant heat. Solvent distillation, essential for solvent recovery in industries such as pharmaceuticals and petrochemicals, operates at 80–250°C, depending on the solvent's boiling point. Polymerization, key to plastics and resin production, varies from 60–200°C, with higher

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temperatures needed for thermosetting polymers. Both processes rely on steam or direct heating, with energy demand influenced by reaction kinetics and solvent properties. Weekly heat demand profiles for both processes are presented below.

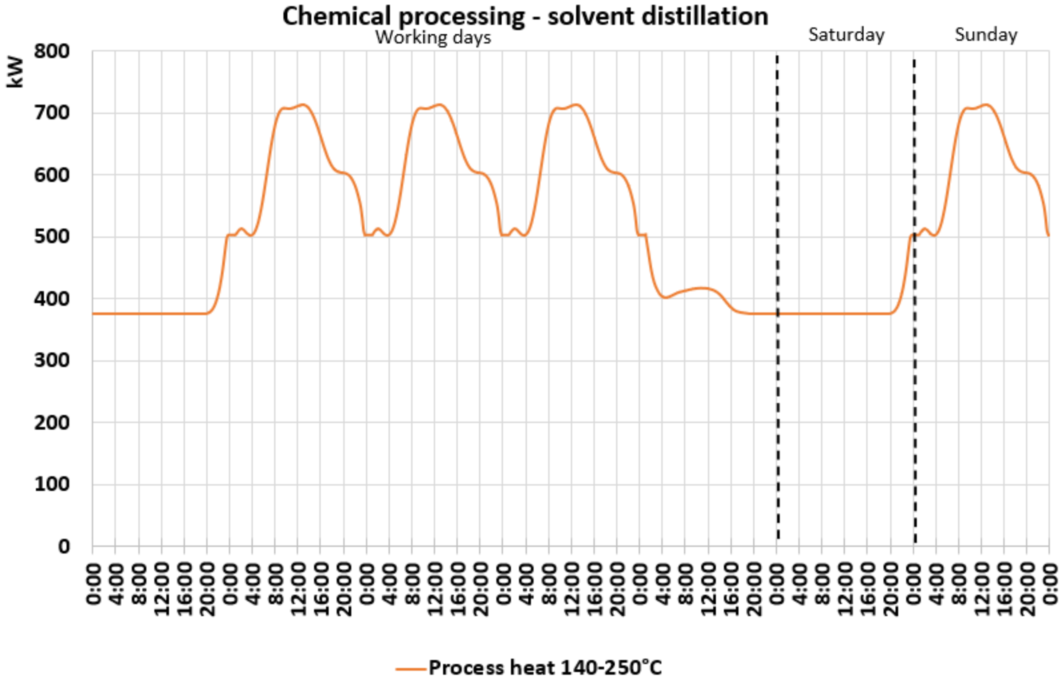

Figure 17. Heat demand profiles, chemical processing – solvent distillation (based on data from [21])

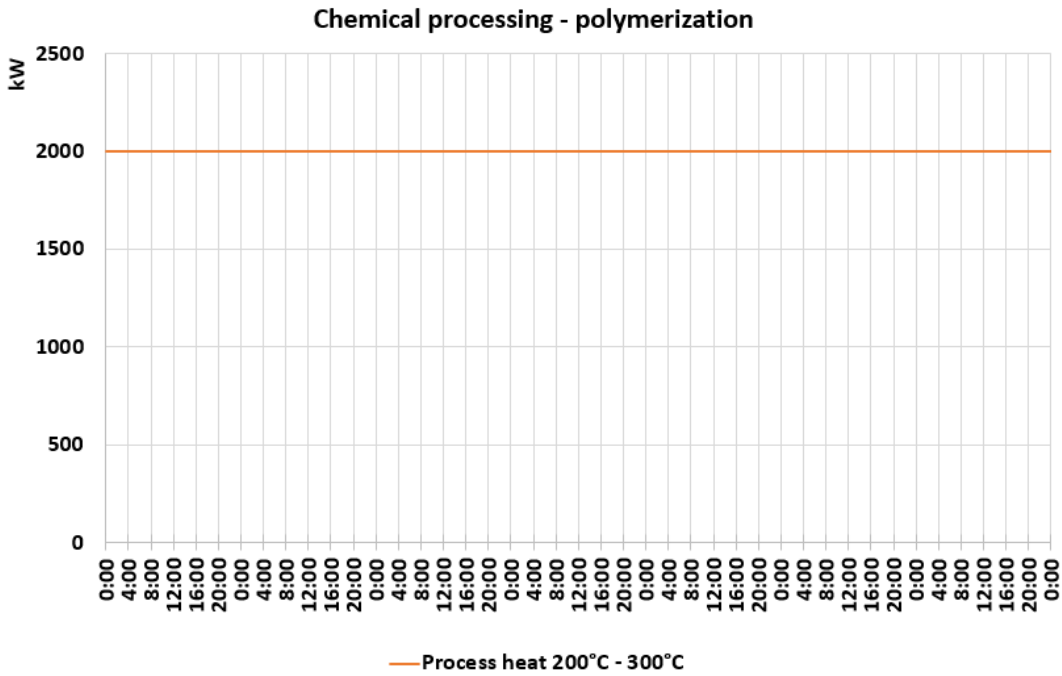

Figure 18. Heat demand profiles, chemical processing - polymerization (based on data from [21])

e) direct air capture

Direct Air Capture (DAC) with solid sorbents is an energy-intensive process that removes CO_2 from the atmosphere using chemically active materials. The key thermal requirement comes from the sorbent regeneration stage, where CO_2 is released by applying heat, typically up to 150°C, depending on the

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sorbent type. The process relies on steam or low-temperature heat sources, with energy demand influenced by the regeneration efficiency and cycle duration.

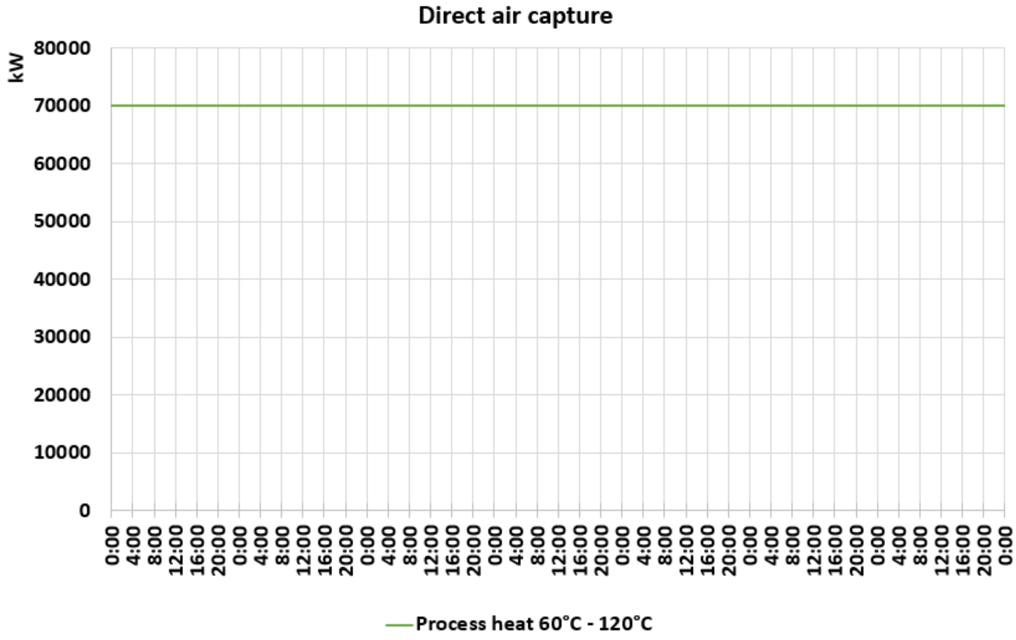

Figure 19. Heat demand profiles, direct air capture – solid sorbent (based on data from [21])

f) other

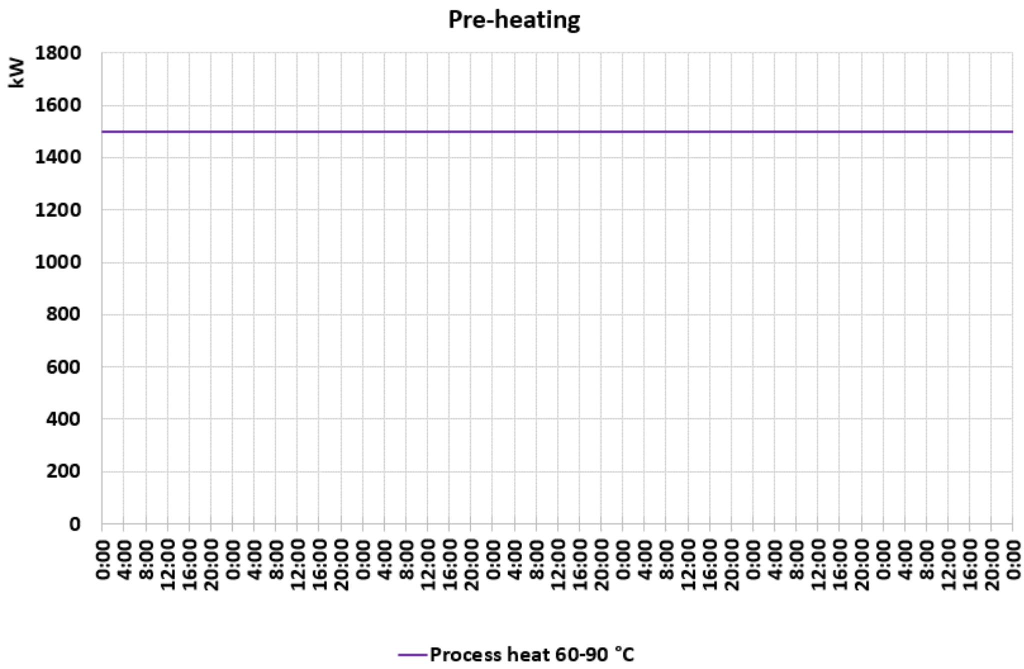

Figure 20. Heat demand profiles, other industries (based on data from [21])

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4. Feasibility of Direct and Indirect HOCLOOP Systems Application

Integration configurations

The HOCLOOP concept, based on geothermal energy, can be configured and integrated with various technologies to optimize its performance and enhance its application across different industrial sectors. This includes configurations that use systems such as Organic Rankine Cycles (ORC), flash steam systems, heat pumps and heat exchangers.

The Organic Rankine Cycle is an indirect cycle, where electric power is generated by the expansion of working fluid in ORC turbine. In such a unit, water in a closed-loop cycle is used as a heat source for heat collection from the reservoir and further transfer via heat exchanger. This unit may be deployed in HOCLOOP system either as a first step when medium temperatures are high enough or as a supporting carbon-neutral electricity source used for instance as a power supply for heat pump in a system.

Heat exchangers are devices designed to transfer heat between two or more fluids at different temperatures. They are commonly used to recover waste heat or provide heat for industrial processes. The HOCLOOP geothermal system can serve as a low-temperature heat source for a heat pump in industrial applications. If the desired temperature is much higher than the geological seam may provide, a heat pump then increases this temperature to a more usable level (up to 150°C, depending on the industrial application). The geothermal fluid circulating through the HOCLOOP loop can pass through heat exchangers that transfer its thermal energy to either water or air, depending on the industrial application. The heated fluid can then be used for heating, steam generation, or to drive ORC and flash steam systems.

Flash steam systems are used to utilize geothermal fluids at high pressure that undergo a pressure drop (or "flash") to produce steam. This process is typically used when the geothermal fluid is above its boiling point, and by reducing pressure, it generates steam that can be used for power generation or direct heating applications. For geothermal resources with high-temperature fluids (120°C to 300°C), a flash steam system is more suitable. This high-temperature heat can be converted into useful steam that can drive turbines for power generation or be used directly in industrial processes.

Different possible configurations are presented in Figure 21.

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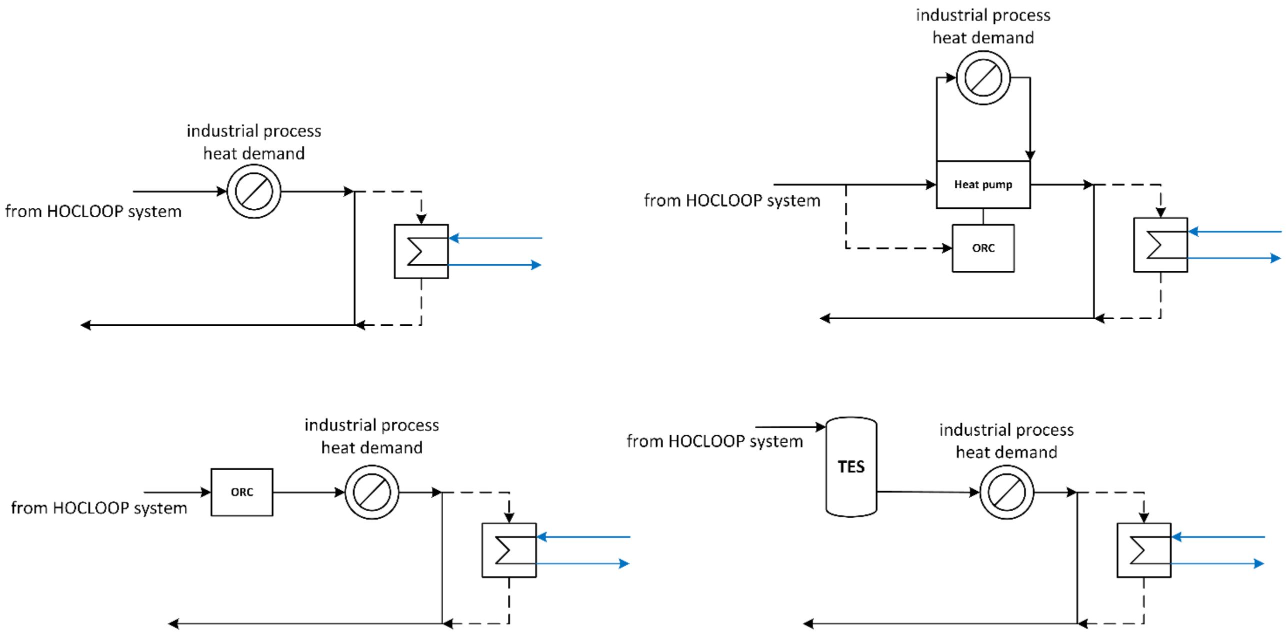

Figure 21. Different integration configurations for HOCLOOP system.

Table 4. Selected system designs for investigated heat demand processes

Industry Sector	Industrial Process	Heat Demand Range	Type of medium used	HOCLOOP Integration
Pulp and paper	Paper Drying	60-80°C	Steam	Indirect
	Pulp Bleaching	130-150°C	Water/Steam	Indirect
Food and beverages	Pasteurization	60-80°C	Water/Steam	Direct/Indirect
	Sterilizing	110-120°C	Steam	Indirect
Textile Industry	Fabric Dyeing	70-90°C	Water	Direct
	Bleaching	60-100°C	Water	Direct
Chemical processing	Solvent distillation	140-250°C	Steam	Indirect
	Polymerization	200-300°C	Steam	Indirect
Direct air capture	CO_2 Adsorption & Desorption	60-120°C	Steam	Indirect
All/others	Pre-heating of fluids	60-90°C	Water/Steam	Direct/Indirect

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5. EU Market Industrial Heat Demand and CO_2 Emission Reduction Potential for HOCLOOP Systems Application

The assessment was conducted to evaluate the EU market potential and the corresponding CO_2 emission reduction for selected industrial sectors and direct air capture. This analysis utilize back-of-the-envelope calculations to estimate heat demand and integration feasibility for HOCLOOP technology across key industries, including pulp and paper, food and beverages, textiles, chemical processing, and DAC. The attention is given to previously selected processes with direct or indirect integration with HOCLOOP installation by quantifying emission reductions for HOCLOOP applications.

The methodology for calculating GHG emission reduction from geothermal energy involves comparing the emissions from the replaced heating system with those from the geothermal system. First, the functional unit is defined as the annual heat demand in MWh_{th}. Next, the analysis identifies the specific energy source being replaced - such as coal, natural gas, or biomass - since the type of replaced system significantly affects the baseline emissions. Emission factors (Table 5) for the replaced and the geothermal systems are then applied to calculate total annual CO_2 emissions for each scenario. The difference between them represents the avoided emissions, which quantifies the carbon footprint reduction. If the geothermal system is self-sufficient - such as one using an ORC system to generate its own electricity - its emissions can be considered negligible, maximizing the reduction potential. This comparative approach ensures consistency and accuracy in evaluating the environmental benefit.

Table 5. Heat sources emissivity

Heat source	CO_2 emissivity [$kgCO_2/GJ$]
Coal	94.6
Biomass	0*
Gas	55.4
Oil	74.1
RES	0
Others (fossil fuels)	74.1
Electricity	76.4
District heating	100**

**biomass was assumed as zero-emission fuel, with a CO_2 emission factor from biomass combustion set at '0' with the key condition of sustainable biomass procurement*

***resulting from the mix of primary sources of energy in use*

Based on the average emissivity of each heat source and shares of each source in process heating demand in Europe, the average emissivity of heat supply is 65.3 $kgCO_2/GJ$. For the analyzed case studies

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within the project, the biomass was assumed to be zero-emission fuel, with a CO_2 emission factor from biomass combustion set at "0", where the key condition is sustainable biomass procurement.
The graph below shows the process heat sources breakdown with corresponding division into low-, medium- and high-temperature processes and emissivity with increasing penetration of HOCLOOP geothermal concept within the low-temperature area. The highest share of geothermal energy in the total demand significantly decreases the CO_2 emissivity of the European heat supply.

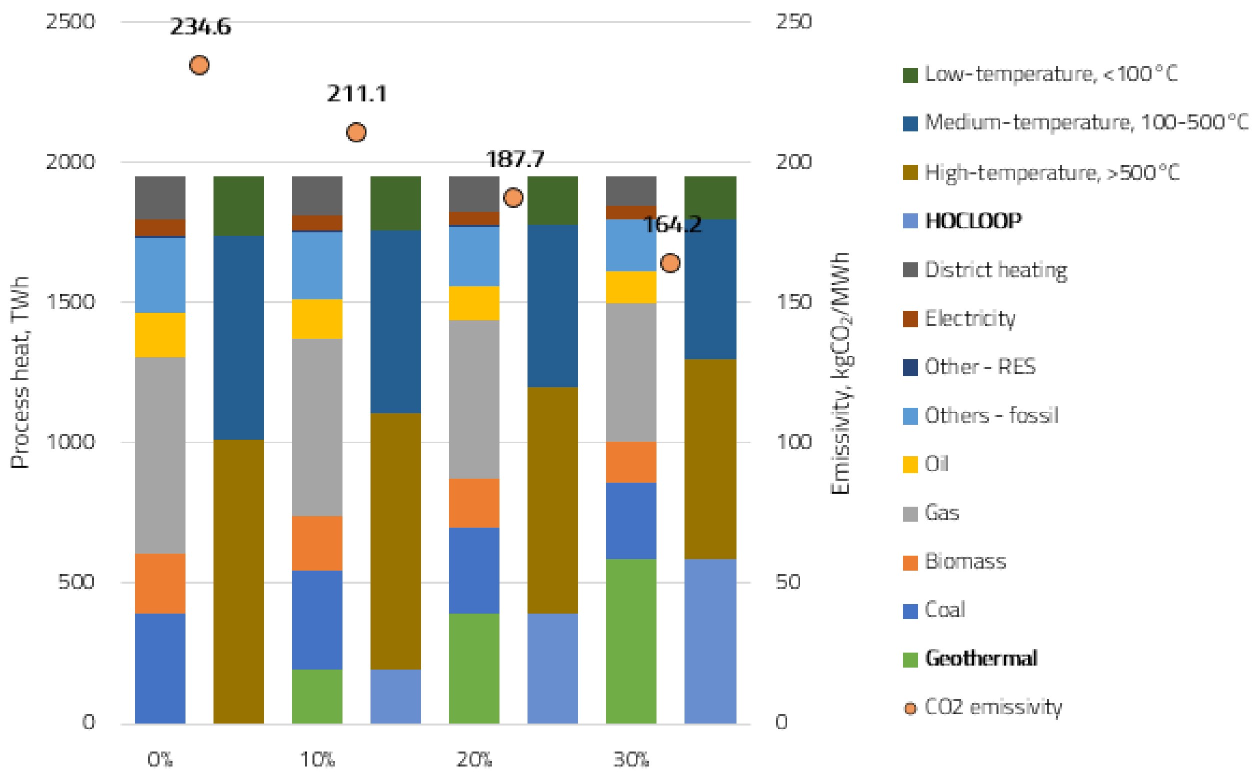

Figure 22. Process heat and emissivity with 0-30% penetration of HOCLOOP geothermal

To estimate the reduction potential for HOCLOOP applications in the following section Polish example with detailed data regarding the assessed industrial sector is presented.

Polish example study

For the purpose of the study, Polish example for food and beverage sector was performed. The basic technological variant (Business as Usual - BaU) assumes that the share of individual heat sources in the total final energy by 2050 remains unchanged. Moreover, the demand for heat is projected to remain at the same level, while any technological advancements e.g. energy efficiency increase result in a possible production boost.

The graph below shows the share of final energy consumption only for heat generation purposes for different sources. Conventional sources such as natural gas or coal have the highest share in total energy demand. Biomass share amounts to approximately 1% of total final energy consumption. The “other” sources include mainly the usage of LPG, diesel oil, liquid biofuels and other fuel oils.

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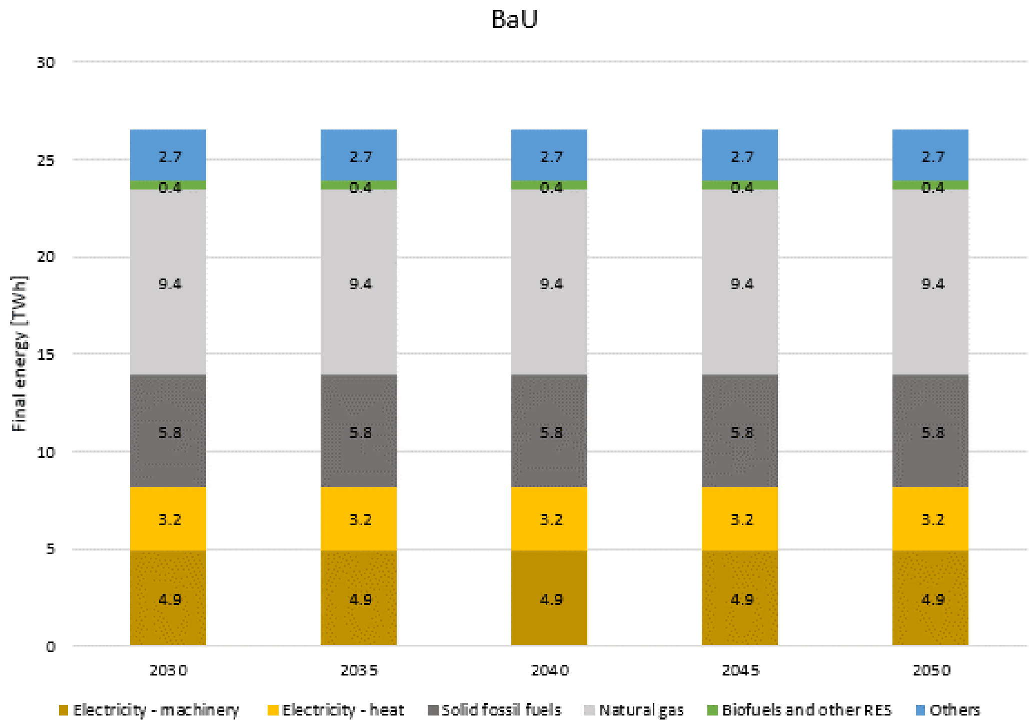

Figure 23. Final energy demand in food and beverage sector in Poland, BaU

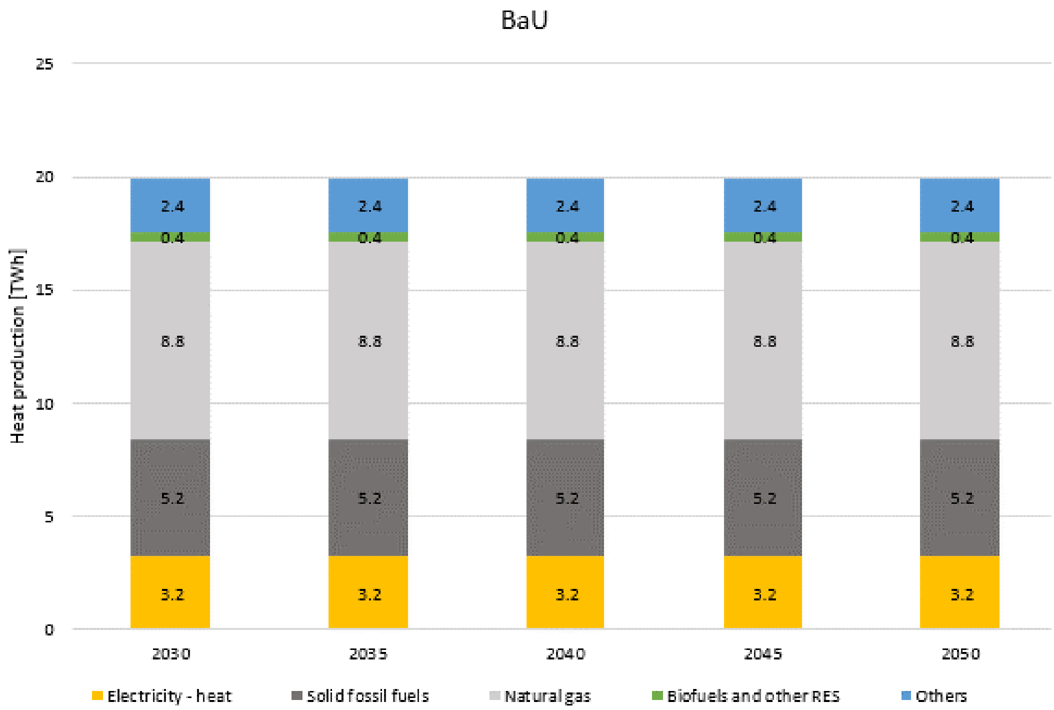

Figure 24. Heat production in food and beverage sector in Poland, BaU

Figure 25 shows the environmental impact in terms of CO_2 emissions with the overall direct and indirect emissions calculated for each source presented as CO_2 emissions for 1 MWh_{th} of heat production.

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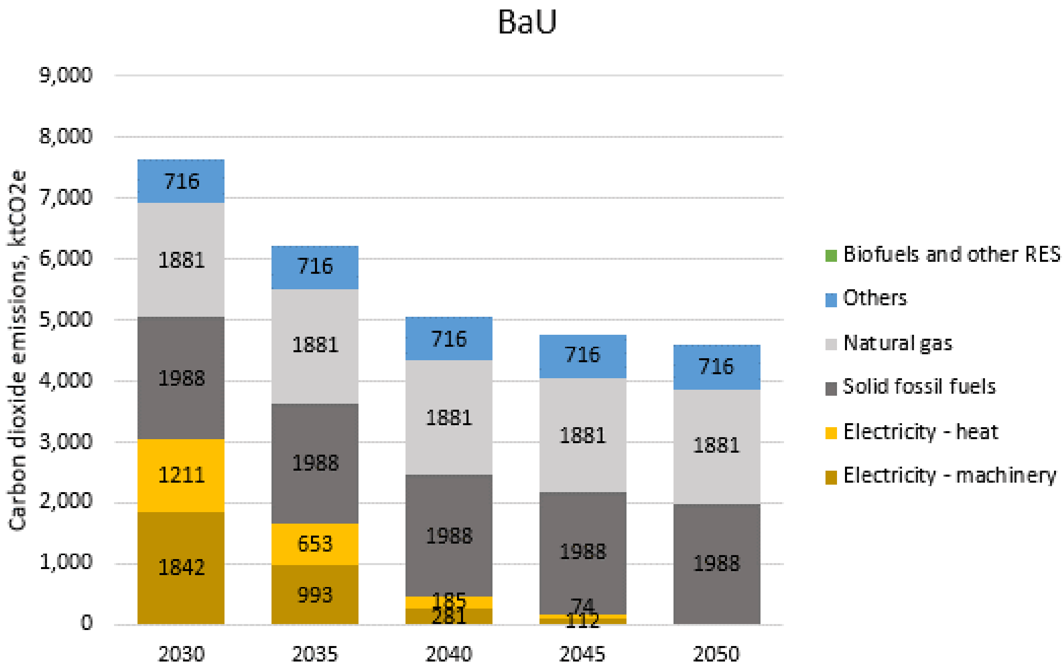

Figure 25. Carbon dioxide emissions in 2050 perspective in food and beverage sector in Poland, BaU

Further study included scenario analysis. In the assumed scenario, biofuels and other RES will play a crucial role in final energy consumption by 2050 and substitute the role of coal in final energy consumption by 2050 thus its visibility in total energy demand increases. The remaining heat demand will be electrified with mainly low-temperature technologies such as heat pumps. In this variant, after 2040 coal-based sources are no longer present in the energy mix for the sector. Nevertheless, geothermal sources are not visible in this scheme, therefore further analysis involved increased penetration of geothermal sources up to 30% of low-temperature heat supply in 2050 substituting the fossil fuels initially and then replacing some of the electrification technologies. The results are presented in Figure 26 and Figure 27.

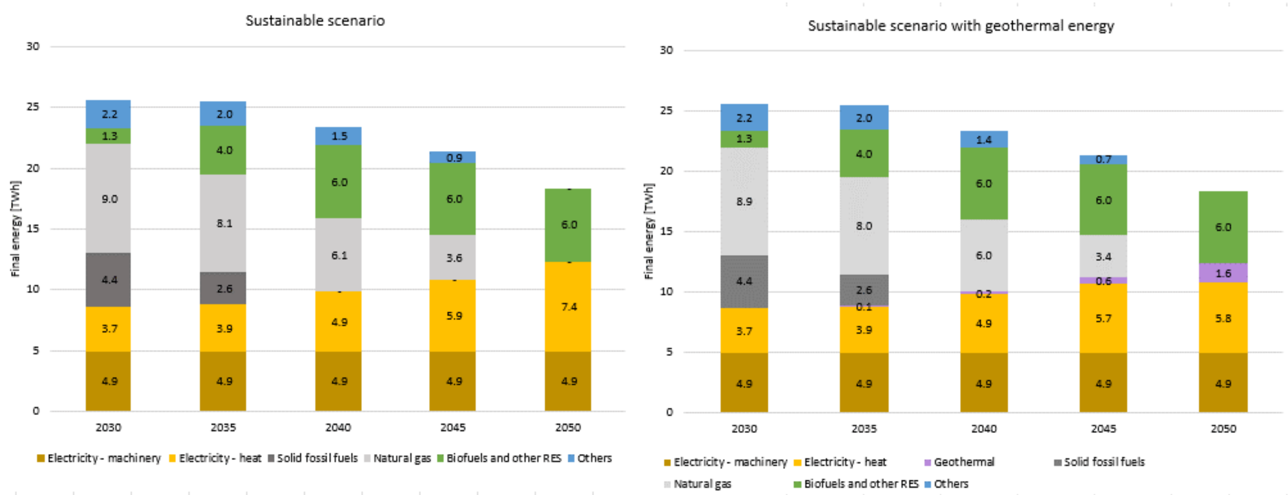

Figure 26. Final energy breakdown for assessed scenarios in food and beverage sector in Poland

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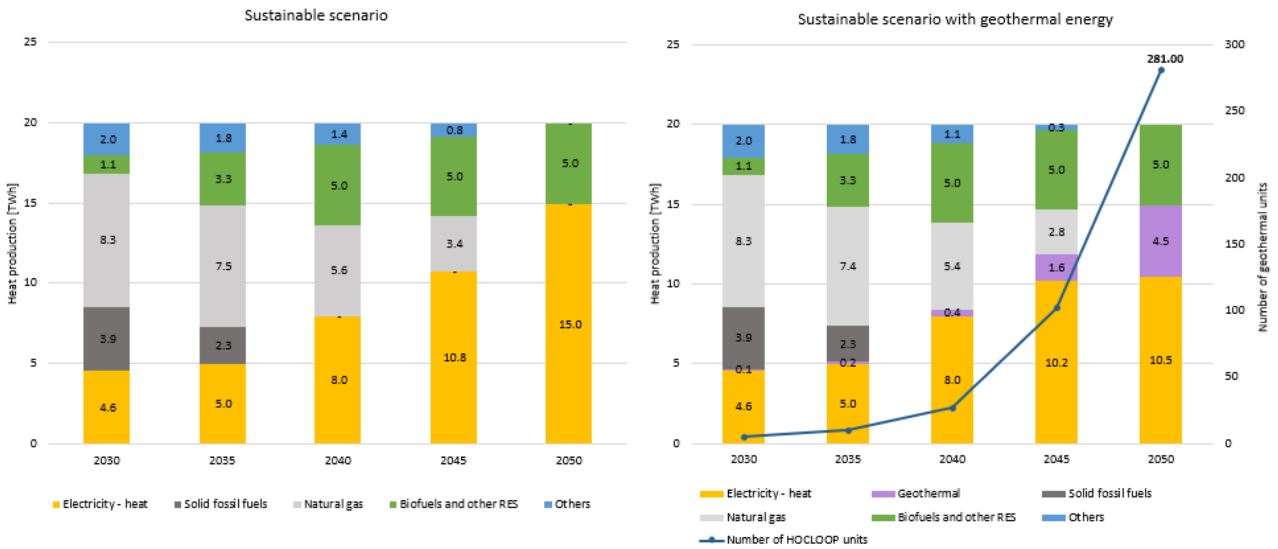

Figure 27. Heat production breakdown for assessed scenarios in food and beverage sector in Poland

Based on that, the geothermal potential to serve as a heat source for industrial application was assessed. In 2050 it can achieve values on a similar level to bio-based sources. Assuming the average power of HOCLOOP unit as 2 MW_{th}, the number of installations was calculated. It increases exponentially starting from 5 units in 2030 to 281 units in 2050. The values correspond to optimistic scenario showing the maximum market penetration within food and beverage sector in Poland. Moreover, the emissions reduction was also assessed (Figure 28). Introducing geothermal energy lowers the carbon dioxide emissions from fossil-based sources.

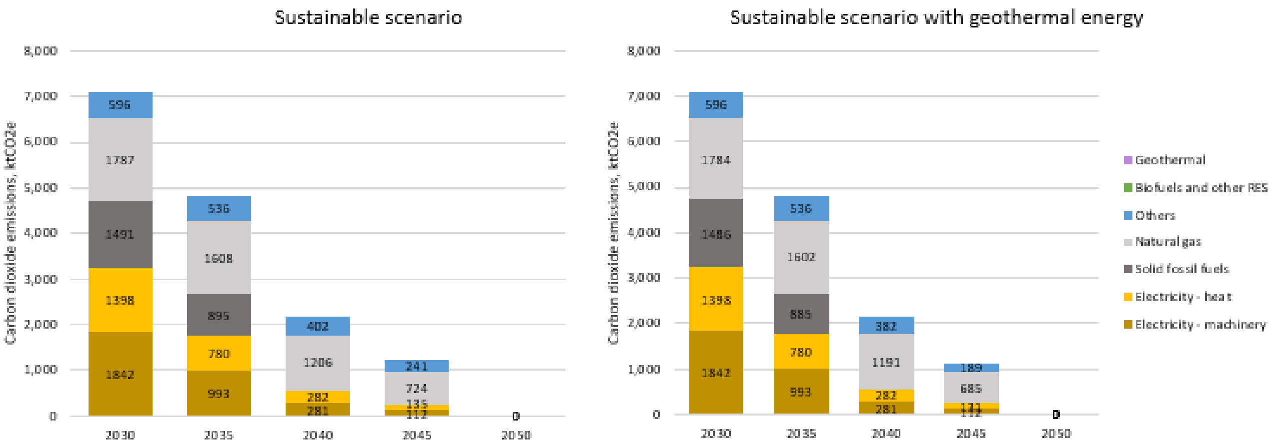

Figure 28. Carbon dioxide emissions breakdown for assessed scenarios in food and beverage sector in Poland

6. SWOT Analysis

This SWOT analysis aims to evaluate the technical, operational, economic, regulatory, and market-related factors influencing the deployment of the HOCLOOP concept in industrial applications.

a) Technical

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Strengths	Weaknesses
• Stable ground temperatures enable reliable base-load heating/cooling • Promising concept for low-enthalpy geothermal heat utilization • Compatible with high-efficiency heat pumps and ORC systems	• Limited temperature lift in direct use (<100°C) • Geology-dependent performance • Location-based system
Opportunities	**Threats**
• Hybridization with waste heat systems • Development of thermal storage solutions to balance output • Possible integration with high-temperature heat pumps to reach temperatures >120°C • Scalable for different industrial loads	• Performance highly sensitive to subsurface conditions • Technological competition from biomass or electrification sources

b) Operational

Strengths	Weaknesses
• System with low maintenance • Potential integration into existing heat recovery setups or different industrial configuration for process heat applications • No on-site combustion or fuel handling	• Limited flexibility • Dependent on consistency of ground conditions for stable performance
Opportunities	**Threats**
• Can support baseload heat supply for continuous industrial processes • Integration with smart control systems for load balancing	• Operational performance may decline depending on thermal recharge

c) Economic

Strengths	Weaknesses
• Low operating cost • Reduced dependency on fuel price volatility • Long system lifespan reduces long-term cost per unit of heat	• High investment costs • May not be cost-effective for small or intermittent loads
Opportunities	**Threats**
• Potential access to green financing, subsidies, or carbon credits • Eligible for public funding and tax incentives	• Competing technologies (e.g. electrification, biomass, hydrogen) may receive stronger incentives or policy attention

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under energy transition frameworks • Integration with carbon pricing schemes (such as EU ETS) can enhance ROI	• High upfront cost may threaten adoption in cost-sensitive industries

d) Regulatory and market

Strengths	Weaknesses
• Aligns with EU Green Deal, decarbonization targets • Eligible for green subsidies, carbon credit programs • Ideal for sectors with constant thermal demand • Potential to serve for district heating • Strengthens corporate sustainability/ESG reporting in energy-intensive industries	• Permitting process for drilling • Lack of standardized frameworks in industrial contexts • Limited market visibility compared to more established technologies
Opportunities	**Threats**
• New policy incentives due to decarbonization programmes supporting low-carbon heat sources • Potential to benefit from carbon pricing mechanisms • Positioning as a renewable heat solution in decarbonization supply chain	• Alternative solutions such as electric heating or biomass-based systems may constitute market competitiveness • Delays in permitting or policy fragmentation can slow adoption • Market uptake may be slowed by low awareness or lack of demonstration projects

7. Conclusions Summary

This deliverable presents a preliminary technical evaluation of integrating the HOCLOOP closed-loop geothermal concept into current and future industrial systems. A structured, indicator-based methodology was employed to assess integration feasibility across multiple European industrial sectors, using key criteria such as process temperature range compatibility, sectoral heat demand profiles, continuous vs. seasonal operation patterns, and potential CO_2 emissions reduction. The analysis targets low- to medium-temperature process heat applications (typically <400 °C) as viable for HOCLOOP deployment, while high-temperature processes (>400 °C in industries like steel, cement, or glass) are excluded as incompatible. Integration pathways considered include direct use of HOCLOOP-supplied thermal energy for processes requiring hot water or steam within the system's output temperature, and indirect or hybrid configurations (e.g. incorporating industrial heat pumps or heat recovery) for higher temperature needs. The study focuses on selected sectors that dominate Europe's industrial heat consumption in the target temperature range - namely the food and beverage, pulp and paper, textile, and chemical processing industries - along with an emerging application (direct air capture). Across these

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sectors, the findings indicate strong integration feasibility and decarbonization potential: HOCLOOP technology could supply a significant share of process heat demand (particularly in the ~60–180 °C range) directly or via augmentation, enabling substantial reductions in fossil fuel use and CO_2 emissions. The EU-wide assessment highlights considerable market uptake potential for HOCLOOP-driven geothermal industrial heat supply, given that roughly half of industrial heat demand lies within manageable temperature ranges and that these sectors are actively seeking low-carbon heat solutions. The preliminary results show that the potential CO_2 emissivity reduction may reach up to 30% (70 $kgCO_2$/MWh) at the European level, assuming that CO_2-intensive sources are replaced by near-zero geothermal solutions providing 30% of the total process heat demand. Furthermore, sector-specific analysis, such as for the food and beverage industry in Poland, indicates that the contribution of geothermal heat becomes more pronounced after 2040. By gradually replacing conventional low- and medium-temperature heat sources, this transition leads to a sectoral emissivity decrease of up to 8% by 2045, highlighting the long-term decarbonization impact of HOCLOOP integration.

The results presented and discussed in this Deliverable will feed into the next one, which will investigate the findings of processes modelling and simulations for the integrated industrial HOPCLOOP systems within the preselected industrial system and adequate subsurface energy systems. This will allow us to verify the proposed methodology, as well as compare the results from the energy KPIs point of view.

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