The decarbonisation of process heat in the German food and beverages industry

A study quantifying the techno-economic potential of High-Temperature Heat Pumps in the German food and beverages industry, GHG emission abatement potential, and evaluating the economic and political framework conditions for industrial decarbonisation.

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« Pour ce qui est de l’avenir, il ne s’agit pas de le prévoir, mais de le rendre possible. »

« As for the future, it is not a question of predicting it, but of making it possible. »

Antoine de Saint Exupéry, Citadelle, 1948

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Summary

Industrial decarbonisation has largely stagnated over the last years in Germany. A large share of Greenhouse Gas (GHG) emissions stem from the combustion of natural gas for producing higher temperature process heat. High-Temperature Heat Pumps (HTHPs) are an emerging technology that can upgrade waste heat with electrical input to high temperatures needed for the processes and thus can contribute to the electrification of industries. Hence, HTHP can significantly reduce GHG emissions stemming from the production of process heat. While residential heat pumps are widely commercially available due to lower temperature requirements, no HTHPs were installed in German industries in 2018 due to multiple technical, market, and knowledge barriers. HTHPs are expected to reach temperatures up to 250°C soon, making the food and beverages industry a suitable sector due to process temperature requirements at the lower industrial spectrum (<250°C). The International Energy Agency (IEA) outlines that HTHPs are a core emerging technology to replace fossil-fuel boilers in industry over the next decades. Thus, there is a large market ahead for manufacturers.

This study evaluates the techno-economic potential of HTHPs in the Germany food and beverages industry. Further, it evaluates the GHG emissions abatement potential in relation to total GHG emissions of the industrial sector. This study has a generalized and systemic scope, thus does neither consider specific case studies, nor performs process optimization. It follows a bottom-up approach to include process- and technology-specific information and scales it up to national level. This study uses two waste heat scenarios, first considering an average 45°C industrial waste heat availability as worst-case, and second considering direct exhaust temperatures as best-case scenario. The generic bottom-up approach results in limited, but more detailed, coverage which makes the results conservative estimates for the application potential of HTHPs in German industries.

The most energy-intensive sub-sectors of the German food and beverages industry are sugar production, meat processing, dairy processing, bakery products production and beer production, which together accounted for approximately 9333 kt-CO_2-equivalents in 2020. The processes dominating the thermal energy demand are mainly pasteurisation, cooking, baking, evaporation, and drying processes, which require higher temperatures for the evaporation of liquids and boiling off bacteria. The thermodynamic efficiency, the COPs, of applying HTHPs to the processes lay between 1,7 – 4,8 for the worst-case scenario and 2,4 – 22,7 for the best-case scenario. The technical potential for 2018 results in 12 TWh. Between 3 - 5,5 TWh of electricity are required to cover the technical potential. The GHG emissions abatement potential lays between 52 - 855 kt-CO_2-eq. This could mean a reduction of up to 9% of total GHG emissions of the five sub-branches. Due to very high electricity costs and an absent carbon tax in industry in 2018, the most cost-effective scenario (50 MW HTHP in the best-case) is not cost-competitive with the optimized fossil-fuel benchmark. The levelized cost of heat (LCOH) for this scenario is 37 €/MWh, of which approximately 67% are stemming from electricity costs. With a carbon tax of min. 48 €/t-CO_2-eq. the switch to an HTHP becomes cost-competitive (incl. maintenance and investment costs). With an expected increase in carbon taxation, less efficient scenarios become cost competitive. By reducing the electricity price by 50%, the best-case scenario with the large HTHP is cost-competitive without a carbon tax. Hence, there is a strong correlation between electricity price and cost-competitiveness of HTHPs. It is expected that the emission factor of the German electricity mix will decrease further in the future and strive towards zero in the long-term, which will lead to substantial increase of GHG emissions abatement potential. When the emission factor for electricity is reduced by 38%, the GHG emissions abatement potential lays at 16% of total GHG emissions of the five sub-branches. The timely investment into HTHPs drastically reduces the risk of sunken costs and makes industrial decarbonisation efforts in this decade attractive from an industrial perspective. Subsidies, carbon taxation, and the reduction of electricity prices by for example removing the German renewable energy levy (EEG) can contribute to making low-carbon technologies such as HTHPs more competitive to fossil-fuel infrastructure that run on fossil fuels with low prices in the industrial sector. Industrial decarbonisation is highly relevant in Germany due to the recent tightening of industrial decarbonisation targets and the systemic demonstration of HTHPs potentials crucial to achieving the latter.

Keywords

Industrial decarbonisation, process heat, high temperature heat pumps, techno-economic potential, GHG emissions abatement potential, carbon tax, German food and beverages industry, bottom-up approach.

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Nomenclature

Abbreviations

BAT	Best-available technology
CHP	Combined Heat and Power
CO_2-eq.	CO_2-equivalents
DI	DLR Institut für CO_2-arme Industrieprozesse
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DM	Dry matter
ECR	Effective Carbon Rate
EU ETS	European Emission Trading System
GHG	Greenhouse gases
HTD	High-temperature drum
HP	Heat pump
HTHP	High-temperature heat pump
IEA	International Energy Agency
MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network
NACE	The Statistical Classification of Economic Activities in the European Community
OECD	Organisation for Economic Co-operation and Development
PBL	Planbureau voor de Leefomgeving
R&D	Research & Development
SMEs	Small- and Medium Enterprises
UBA	Umweltbundesamt
UHT	Ultra-High Temperature Treatment
VAT	Value-added tax
VHTHP	Very-high temperature heat pump

Variables

APV	Annual Production Volume, in unit of product
c_{el}	Specific cost of electricity, in €/MWh
CF	Annual Cash Flow, in €/a
c_{gas}	Specific cost of natural gas, in €/MWh
CRF	Capital Recovery Factor/a, -
COP	Coefficient of Performance, -
COP_{Carnot}	COP Carnot Efficiency, -
COP_{Real}	Real COP, -
E_{el}	Electrical Input, in GJ
EF_{el}	Emission Factor Electricity, in g-CO_2-eq./kWh
EF_{gas}	Emission Factor Natural Gas, in kg-CO_2-eq./GJ
i	Interest Rate, in %
LCOE	Levelized Cost of Electricity, in €/MWh_{el}
LCOH	Levelized Cost of Heat, in €/MWh_{th}
N	Lifetime, in years
OH	Annual Operating hours, in h/a
P	Pinch Value, in °C
Q_{Sink}	Heat rate supplied to sink, in kW
Q_D	Thermal energy demand, in GJ
Q_S	Extracted heat from Source (Waste Heat), in GJ
SEC_{th}	Thermal specific energy consumption, in GJ/unit of product
TCI	Total Capital Investment (incl. maintenance), in €
T_P	Sink temperature, in °C
T_{P*}	Low temperature of refrigerant, plus P, in °C
T_W	Source temperature °C
T_{W*}	High Temperature of refrigerant, plus P, in °C

1 Introduction

1.1 Problem Context

Germany's national greenhouse gas (GHG) emission target for 2020 was a reduction of -40% (based on 1990) and was reached with -42,3%. A recent study shows that Germany reached this target due to the Corona pandemic (less energy consumption, less industrial production, less transport, etc.) (Agora Energiewende, 2021). Without the pandemic, the GHG emission reductions would have laid at -37,8%. Thus Germany would have missed its 2020 climate target (Agora Energiewende, 2021). Germany's newly formulated ambition of GHG emission reductions aims at -45% by 2030 compared to 1990 and reaching carbon neutrality by 2045 (The Guardian, 2021). To meet those targets, four sectors (industry, transport, agriculture, buildings) must be decarbonised more rapidly and more drastically than intended initially (Agora Energiewende, 2021).

The industrial sector plays a vital role for Germany, as it is at the heart of its economy and a driver for high-quality employment (Agora Energiewende & Wuppertal Institut, 2019). It is the second-largest primary energy user in Germany (UBA, 2021), and fossil fuel energy carriers still provide 70% of this final energy (Destatis, 2021). Approximately two-thirds of industrial energy consumption is used for the provision of mainly process heat in the industrial sector itself (dena, 2019). Simultaneously, the industry records the second-largest sectoral GHG emissions with 187 million tons CO_2-equivalents (t-CO_2-eq.) in 2018, shortly after the energy industry with 250 million t-CO_2-eq. Since 2005, industrial GHG emissions have largely stagnated (KEI, 2021). Reasons are that rapid energy efficiency improvements have largely reached their technical limits, while production has increased drastically (KEI, 2021). The rapid uptake of renewable energy sources has compensated for the growth-related emissions in the whole of Germany, but the low degree of electrification for industrial heat applications (8% in 2020) has hindered the integration for renewable electricity in industry and hence shows in stagnating industrial emissions reductions (Schlosser et al., 2020). Nonetheless, the industrial sector must reduce its GHG emissions by 69 million t-CO_2-eq. in 12 years to meet the tightened climate targets of maximum industrial GHG emissions of 118 million t-CO_2-eq. in 2030 (Agora Energiewende, 2021). Therefore, the decarbonisation of industrial processes must start at reducing process heat-related GHG emissions.

The International Energy Agency (IEA) has demonstrated that the uptake of heat pumps (HP) plays a dominating role in replacing fossil-based heaters for process heat production in industry by 2050 and hence in reducing process heat-related GHG emissions. According to the IEA, 500 MW of HPs must be installed in industry every month over the next 30 years if a global net-zero scenario is to be reached by 2050 (IEA, 2021). Current state-of-the-art HPs are mostly applicable to residential heating demand due to lower temperature achievements, but with ongoing technological developments, HPs reaching higher temperatures, so called high-temperature heat pumps (HTHPs), become a promising technology for industrial applications with higher temperature requirements (IEA, 2021). The largest share of industrial heating demand at the lower end of industrial temperatures (<250°C) occurs in the food, beverages, and tobacco industry, which is said to increase until 2050 (IEA, 2021). Hence, the food, beverages, and tobacco industry is a promising sector to evaluate the feasibility of HTHPs to reduce process heat-related GHG emissions (IEA, 2021).

1.2 Problem statement

By 2018, no HTHPs were installed in German industries (EHPA Stats, 2021). The reasons are that HTHPs for industrial application have not yet reached market maturity (Arpagaus, Bless, Uhlmann, Schiffmann, & Bertsch, 2018). Large-scale, long-lived, and capital-intensive industrial technologies have long investment cycles (IEA, 2021). Competitive global markets lead to low margins, making it difficult for industrial players to absorb costs from expensive emerging low-carbon technology (IEA, 2021). Further, low fossil-fuel prices, high electricity prices, and low emission taxation have not yet created economic incentives for industrial players (Arpagaus et al., 2018). And lastly, a lack of knowledge amongst industrial players, research, manufacturers, and governments have hindered the large-scale uptake of HTHPs in industries (Arpagaus et al., 2018; Wolf, Lambauer, Blesl, Fahl, & Voß, 2012). Therefore it is not only a question of technological developments but at the same time of economic profitability and the political and systemic framework conditions. These barriers make the integration of HTHPs into industry an interdisciplinary and systemic problem.

1.3 Relevance

The IEA outlined that relative to current baseline trends, approximately half the emission savings required to achieve net-zero emission rely on technologies that are not yet commercially available (IEA, 2021). The report further demonstrates that between 2020 and 2030, rapid technological innovation progress through research and development (R&D), demonstration, and initial development are crucial to bringing new technologies like HPs for industries to market. By 2035, all heavy industry capacity additions must follow innovative low-emissions routes, and by 2040, around 90% of existing fossil fuel capacity in industry must reach the end of investment cycles (IEA, 2021). Consequently, this decade is crucial to advance research on the contribution potential of HTHPs to demonstrate the yet largely untapped opportunity to decarbonise industrial process heat in German industries (Marina, Spoelstra, Zonday, & Wemmers, 2021; TNO, 2020).

The interdisciplinary field of Industrial Ecology aims at bridging this gap and takes the interdisciplinary perspective to integrate industrial, technological, environmental, and economic aspects. The systemic perspective on industrial decarbonisation is highly relevant for industrial ecology, because industrial decarbonization is embedded in a complex system tightly connected to the energy transition and other systemic transitions. Industrial decarbonisation is highly relevant for Germany due to the recent tightening of the GHG emission reduction targets and the demonstration of heat pumps potentials crucial to achieving the latter.

1.4 Research objective

The objectives of this research are to 1) investigate the techno-economic feasibility of integrating HTHPs on process-level into the German food and beverages industry, 2) to estimate the GHG emissions reduction potentials in relation to the industrial branch emissions with two different waste heat scenarios, 3) and to discuss political and economic framework conditions and their impacts on the profitability of HTHPs. This research is explorative and utilises a bottom-up approach to consider necessary technical process information. Since HTHPs are an emerging technology and not yet commercially available in higher temperature ranges, a generalised approach allows for a first estimation of the techno-economic potential from multiple perspectives. Therefore, the aim is to inform a wide array of stakeholders through the interdisciplinary approach, from research, to HTHP manufacturers, to industrial players, and governments. This study aims to bridge this gap and can build the foundations for future research. This study answers the following main research question:

"*What is the techno-economic potential of high-temperature heat pumps to decarbonise process heat in the German food and beverages industry, what is the GHG abatement potential, and what are the economic and political framework conditions?*"

1.5 Scope of research

This study focuses on the German manufacturing industry of food and beverages due to its significant heating demand in the low/medium industrial temperature range that is attractive for emerging HTHPs (IEA, 2021). This industrial sector is defined by a heterogeneity of products, processes, and temperature ranges. Therefore, the five most energy-intensive industrial sub-branches (Sugar, dairy, bakery, meat, beer) and their most thermal energy-intensive processes build the scope of this research. The data used is from the year 2018 and hence the analysis reconstructs this year. This study utilises estimates, generalisations, and simplifications to inform on the potentials of HTHPs and draw a systemic picture. This research is not aiming at process optimisation or plant-specific energy efficiency improvements.

1.6 Outline

This study will continue in Chapter Two by providing background information on the definition of potentials, the thermodynamic principles and state-of-the-art research of HPs and HTHPs, carbon taxing in Germany, and reviews existing literature. Chapter Two will conclude by identifying a literature gap that this study aims to fill. Chapter three provides the necessary background information of the industry, its most energy-intense sub-branches and explains the main processing steps. Chapter four outlines the methodological approach, the sub-research questions relating to each step, and reviews the availability of data and its uncertainties. Chapter Five presents the results of this study. In Chapter Six, the results are being discussed and evaluated in the systemic context. Chapter Seven follows by outlining limitations and opportunities for further research. Chapter Eight closes the study with a conclusion.

2 Background

2.1 Definition of Potentials

The definition of 'potential' is to quantify what can be done or what is possible. This highly depends on the constraints that are being set, and therefore different types of potentials exist (Blok & Nieuwlaar, 2020, p. 233). Figure 1 shows an overview of the different kinds of potential: 1) the theoretical/physical potential, 2) the technical potential, and 3) the economic/feasible potential (also called market potential) (Brückner, Liu, Miró, Michael, & Cabeza, 2015).

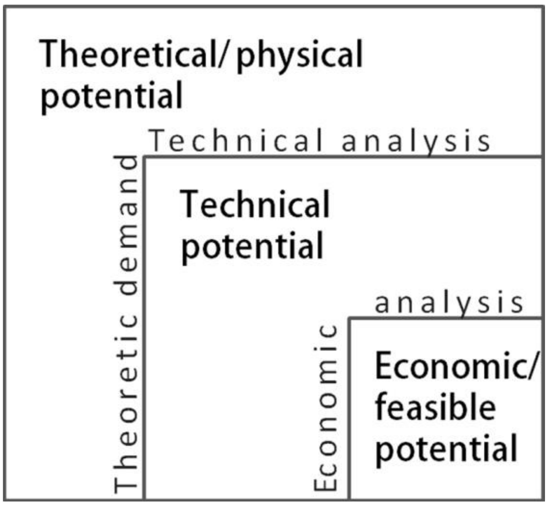

Figure 1. Types of Potentials. Brückner et al. (2015)

Physical limitations mark the boundary of the theoretical/physical conditions (Blok & Nieuwlaar, 2020, p. 223). The technical potential describes the contribution that could be made by emerging technologies available in the future (Blok & Nieuwlaar, 2020, p. 233). It allows estimating which part of the physical potential is technically feasible, focusing on one particular technology, including its constraints. It will most likely increase over time due to technological developments (Blok & Nieuwlaar, 2020, p. 23). The economic/feasible potential allows for assigning the share of technical potential that is economically feasible or profitable from an economic perspective (Brückner et al., 2015). The economic potential can be scaled up to estimate the market potential for specific technologies. For emerging technologies, it is often difficult to evaluate the economic potential due to a lack of specific financial data from manufacturers. Nonetheless, it can be estimated for emerging technologies by calculating investments costs based on component costs and dimensions, and operating costs, which then represent a preliminary estimate (Zühlsdorf, Bühlera, Bantlec, & Elmegaarda, 2019).

Since the installation of HTHPs corresponds to additional investment costs compared to the existing fossil-fuel optimised infrastructure, their economic potential depends on the investment costs itself, and the cost-ratio of energy carriers such as natural gas and electricity (Arpagaus et al., 2018; Hita, Djemaa, Seck, & Guerassimoff, 2011). As investment costs of emerging technologies tend to decrease over time, the operational costs (including taxation on GHG emission) are playing more important roles for the cost-competitiveness of HTHPs (IEA, 2021).

2.2 Heat Pumps

A HP is thermodynamic equipment that contains two heat exchangers, a condenser and an evaporator, a compressor and a valve. The pump extracts heat from the outside air or other sources via the evaporator, upgrades the heat with the help of the compressor, and transfers it via the condenser to the inside (Arpagaus et al., 2018). HPs can be applied in a stand-alone manner or combined with other renewable or hybrid energy mixes (European Copper Institute , 2018).

There is currently a lot of debate about the exact definitions of HTHPs that can higher temperature ranges. Arpagaus et al. (2018) defined HPs as being able to achieve temperatures up to 80°C, while HTHPs are defined as achieving temperatures up to 100°C. Apargaus et al. (2018) use definitions of very high temperature heat pumps (VHTHP) for temperature achievements of 200°C, which is however not common in other research. Therefore, this study refers to HPs achieving higher temperatures (up to 250°C) as HTHPs.

The technology used in HP systems is diverse, in terms of heat pump cycles and refrigerants. The working medium (air, liquids, or gases) and the HP cycle determine the application area and temperature lift achievable (Spoelstra, 2014). There are mechanically driven HPs, where electricity is the work that is used to drive the system, which are the most common (Blok & Nieuwlaar, 2020, p. 50). Further, there are thermally driven HPs, where heat drives the system, or hybrid systems of the two (Spoelstra, 2014). Most common mechanically driven systems work on condensing / evaporating working mediums, like in the Vapor Compression or Vapor Recompression systems (Spoelstra, 2014). Gaseous working mediums are also common in mechanically driven systems like in the Sterling, the Thermoacoustic, or the Brayton system. Liquid working mediums occur in the mechanical Malone system (Spoelstra, 2014). Solid state mechanical heat pumps are the Thermo-electric, the Magnetocaloric, or the Elektrochemical system (Spoelstra, 2014). For the thermally driven HP systems, liquid or solid sorption HPs are the most common. Thermal Vapor Compression Steam Ejectors are also common thermally driven systems. For gaseous working mediums, the same cycles as for the mechanical HPs can be executed, namely the Stirling, the Thermoacoustic, and the Brayton cycles, and additionally also the Vuilleumier cycle (Spoelstra, 2014). This study is not evaluating the different technologies of HP technologies and their ideal application due to the systemic nature of this study. For an up-to-date comparison of different HP cycles, refer to Apargaus et al. (2018). The next section elaborates on the thermodynamic background that is relevant for the analysis.

2.2.1 Thermodynamic theory

The technical analysis of HPs is mainly ruled by the laws of thermodynamics. The first law of thermodynamics, the law of energy conservation, states that energy can neither be created nor destroyed; it can only be converted (Blok & Nieuwlaar, 2020, p. 18). The second law of thermodynamics has to do with the conversion of energy. It states that heat from a heat source cannot be fully converted into work by a thermodynamic cycle and will therefore end up in a heat sink. If an ideal process uses heat at high temperatures (T_P), heat is released to a heat source at lower temperatures (T_W) (Blok & Nieuwlaar, 2020, p. 124). Relating to these principles, the amount of heat (Q_D) that a HP can deliver at higher temperatures as process heat is related to how much heat is extracted (Q_S) at lower temperatures from the source plus the added electrical input (E_{el}) (Equation 1) (Hita et al., 2011):

Equation 1. Thermodynamic Principle, Hita et al (2011)

$$Q_D = Q_S + E_{el}$$

A waste heat source from a process is the input into the system at T_W. By adding electrical input, the air (or other mediums) is being compressed and relaxed, increasing and decreasing the temperature levels at the respective stage of the cycle. With the help of heat exchangers, process heat at T_P at the heat sink can be produced, while at the same time cooling can be provided (DLR, 2021a). The coefficient of performance (COP) defines the performance of a HP, which is the ratio of Q_D to E_{el} (Equation 2) (Marina et al., 2021):

Equation 2. COP ratio of heat pump output and electricity input, Marina et al. (2021)

$$COP = Q_D / E_{el}$$

The COP is an important parameter indicating the efficiency of HPs and depends on the temperature lift between T_W and T_P (TNO, 2020). The larger the temperature lift, the smaller the COP. Schlosser et al. (2020) provide an overview of the correlation of COP and temperature life based on 88 case studies, which supports the latter statement (see Figure 2). Schlosser et al. (2020) found an average COP of 4,46 for an average temperature lift of 46,6 K.

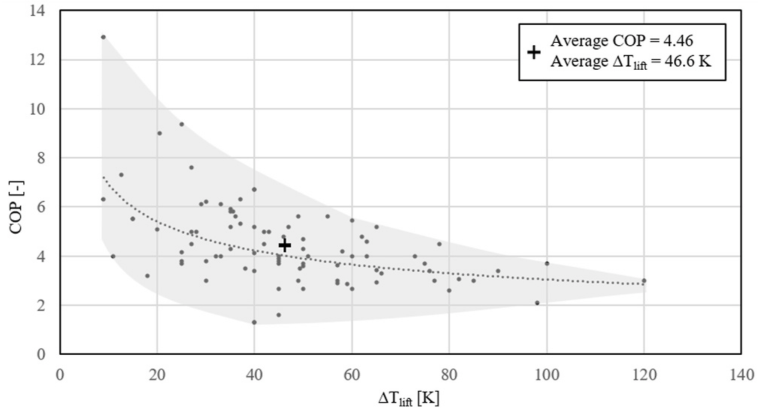

Figure 2. Correlation between COP and temperature lift, Schlosser et al. (2020)

The Carnot Efficiency describes the theoretical maximum that can be achieved by a HP (Equation 3):

Equation 3. Carnot COP, Marina et al. (2021)

$$COP_{Carnot} = T_P / (T_P - T_W)$$

Since the Carnot Efficiency describes the theoretical maximum in ideal conditions, the real COP usually lies within an efficiency range of 50%-70% (Hita et al., 2011; Marina et al., 2021). Therefor this study assumes an average efficiency of 60% (Equation 4):

Equation 4. Real COP

$$COP_{real} = 0{,}60 * COP_{Carnot}$$

The residential HP COP value usually is in the range between 3 to 5 (Blok & Nieuwlaar, 2020, p. 50). By using waste heat and upgrading the temperature with electric energy input, the delivered heat exceeds electric input. Therefore the COP can be greater than 1 (>100%) (Blok & Nieuwlaar, 2020, p. 51). HTHPs usually show lower COPs than residential HPs due to larger temperature lifts.

A pinch analysis can determine the most efficient thermodynamic conditions of a process and a HP but exceeds the scope of this study. If the simultaneous provision of heating and cooling is to be assessed, an allocation method for the electricity demand is needed between the two forms of useful energy, heating and cooling (Schlosser et al., 2020). This allocation methodology is currently not described in literature for HPs and therefore is excluded from this study (Schlosser et al., 2020). The standard cooling technologies in Germany already use electricity (cooling compression technology); thus, only optimised heat pump integration could increase the efficiency.

Two major technical boundary considerations determine the technical potential of HP applications. First, the HP can only upgrade waste heat to certain temperature levels, depending on the technology. The maximum achievable temperature forms the boundary condition one. Second, a waste heat source is a necessary input to the HP system, which should be in close proximity, ideally have the same volume as the process heat demand, and should exhibit the smallest temperature lift possible, compared to the process heat temperature level, to increase the efficiency. These factors are assumed to be available in the analysis.

2.2.2 State of the art of HTHPs

Commercially available large scale HP systems can achieve temperatures up to 100°C, like the mechanical vapor recompression pump (Spoelstra, 2014). The application of these HPs mostly occurs in the residential sectors and in industrial applications with very low heating demands (below 100°C). In 2018, European industries had 3823 units of HTHPs installed, none of them located in Germany (EHPA Stats, 2021). There are numerous reasons why HTHPs have not yet achieved a larger share in supplying industrial heat. One main reason is that there have not been many manufacturers of HTHP equipment in the last years that can reach higher sink temperatures above 100°C (Marina et al., 2021). Other market barriers are the lack of knowledge and understanding among users, investors, plant designers, producers and installers (Arpagaus et al., 2018; Wolf et al., 2012). Further, the long investment cycles of capital-intensive infrastructure make it difficult for industrial players to absorb additional costs (IEA, 2021; Wolf et al., 2012).

In recent years, research relating to HTHPs with higher heat sink temperatures increased. In 2018, Arpagaus et al. (2018) compiled the most comprehensive overview of 22 commercial state-of-the-art heat pump models from large companies that can supply heat sink temperatures above 110°C (See Table 1). Temperature levels below this temperature have already been widely commercially available (Zühlsdorf et al., 2019). In 2018, three HTHP technologies could supply 130°C-165°C of heat (Arpagaus et al., 2018). The other 19 heat pumps could supply temperatures between 90°C and 120°C (Arpagaus et al., 2018). In 2019, laboratory-level research showed that supplying higher temperatures between 150°C and 180°C is technically feasible (Zühlsdorf et al., 2019). Further, two case studies demonstrated the technical and economic application potential of specific HP cycles (steam compression system and reversed Brayton cycle) to supply process heat up to 280° (Zühlsdorf et al., 2019). Another research pilot project has demonstrated sink temperatures up to 200°C (Marina et al., 2021). These pioneering research projects only exist in theoretical research and are not yet commercially available (Marina et al., 2021; Zühlsdorf et al., 2019).

Manufacturer	Product	Refrigerant	Max. heat sink temperature	Heating capacity	Compressor type
Kobe Steel (Kobelco steam grow heat pump)	SGH 165 SGH 120 HEM-HR90, -90A	R134a/R245fa R245fa R134a/R245fa	165°C 120°C 90°C	70 to 660 kW 70 to 370 kW 70 to 230 kW	Twin screw
Vicking Heating Engines AS	HeatBooster S4	R1336mzz(Z) R245fa	150°C	28 to 188 kW	Piston
Ochsner Energie Technik GmbH	IWWDSS R2R3b IWWDS ER3b IWWHS ER3b	R134a/ÖKO1 ÖKO (R245fa) ÖKO (R245fa)	130°C 130°C 95°C	170 to 750 kW 170 to 750 kW 60 to 850 kW	Screw
Hybrid Energy	Hybrid Heat Pump	R717/R718 (NH_3/H_2O)	120°C	0.25 to 2.5 MW	Piston
Mayekawa	Eco Sirocco Eco Cute Unimo	R744 (CO_2) R744 (CO_2)	120°C 90°C	65 to 90 kW 45 to 110 kW	Screw
Combitherm	HWW 245fa HWW R1234ze	R245fa R1234ze(E)	120°C 95°C	62 to 252 kW 85 to 1'301 kW	Piston
Dürr thermea GmbH	thermeco$_2$	R744 (CO_2)	110°C	51 to 2'200 kW	Piston (up to 6 in parallel)
Friotherm	Unitop 22 Unitop 50	R1234ze(E) R134a	95°C 90°C	0.6 to 3.6 MW 9 to 20 MW	Turbo (two-stage)
Star Refrigeration	Neatpump	R717 (NH_3)	90°C	0.35 to 15 MW	Screw (Vilter VSSH 76 bar)
GEA Refrigeration	GEA Grasso FX P 63 bar	R717 (NH_3)	90°C	2 to 4.5 MW	Twin screw (63 bar)
Johnson Controls	HeatPAC HPX HeatPAC Screw Titan OM	R717 (NH_3) R717 (NH_3) R134a	90°C 90°C 90°C	326 to 1'324 kW 230 to 1'315 kW 5 to 20 MW	Piston (60 bar) Screw Turbo
Mitsubishi	ETW-L	R134a	90°C	340 to 600 kW	Turbo (two-stage)
Viessmann	Vitocal 350-HT Pro	R1234ze(E)	90°C	148 to 390 kW	Piston (2 to 3 in parallel)

Table 1. Overview of state-of-the-art HTHPs, Arpagaus et al. (2018)

In 2019, the DLR (Deutsches Zentrum für Luft-und Raumfahrt) opened a new research institute, the Institute for Low-carbon Industrial Processes (DI). Three different departments conduct research relating to the field of industrial decarbonisation. The three departments are: (1) High-temperature heat pumps, (2) Simulation and virtual design, and (3) Low-carbon reducing agents (DLR, 2021b).

Currently, the departments are developing two prototypes of HTHPs. One pilot project is a HTHP Rankine cycle with water, and the second is a HTHP Brayton cycle running on air (Stathopoulos, 2021). The technical scope of these two pilot HTHPs is to achieve a heat delivery by at least 500°C (Stathopoulos, 2021). Due to the early stage of the research, the lower temperature ranges up to 250°C are being researched first, with the goal to venture into higher temperatures at a later stage (Oehler, Gollasch, Tran, & Nicke, 2021). Especially the Rankine cycle HTHP is suitable for many processes of the food and beverages industry, due to the temperature requirements at the lower end of the industrial spectrum, and due to the main sources of heat being liquids and steam in the food and beverages industry. This pioneering HTHPs researched by the DLR exhibits a promising technology to be applied in industrial processes to deliver process heat in a temperature range that is not yet commercially available (up to 250°C) and is thus used as a reference to investigate the potentials of HTHPs for this study.

2.2.3 Systemic relevance of HTHPs

In general, HTHPs can enhance the energetic efficiency of industrial processes significantly. They can upgrade the temperature of waste heat sources and reuse the upgraded heat within a process with electric power (Arpagaus et al., 2018; TNO, 2020). Consequently, they can contribute to lower GHG emissions in two ways: first, they lead to energy savings due to increased energy efficiency by upgrading waste heat, which reduces the energy demand and thus results in lower GHG emissions. And second, HTHPs contribute to the electrification of industries, and thus offer a switch from fossil fuels to (renewable) electricity as an energy source (Arpagaus et al., 2018; Marina et al., 2021; TNO, 2020). Depending on how the electricity is generated, electrification with renewable energy can lead to drastic GHG emission reductions. These aspects make HTHPs a promising emerging technology to advance industrial decarbonisation not only in Germany. Breaking the temperature ceiling of conventional HP technology is important to not only target industrial branches at the lower temperature spectrum, such as the food and beverages industry, but also venture into higher temperatures to heavy industries such as steel and aluminium, which are not only highly energy-intensive, but also require very high temperatures (>1000°C) that are currently produced by fossil fuels (TNO, 2020). All industries will have to decarbonise their process heat and cut GHG emissions drastically in the near future due to tightening climate targets all around the globe. Hence, there is a pressing need for not only technical advancements investigating new concepts of HTHPs to achieve higher temperatures, but also systemic studies to investigate the potentials of applying HTHPs in various industrial sectors and with that inform multiple players.

2.3 Carbon Pricing in Germany

Carbon prices are argued to be the most cost-effective tool to reduce emissions (OECD, 2021a). The effective carbon rate (ECR) is the total price of CO_2 emissions from energy use, which is steered by market-based policy instruments. It consists of three components: 1) carbon taxes, 2) excise taxes per unit of energy, and 3) the price of tradeable emission permits, like the European Emission Trading scheme (EU ETS) (OECD, 2021a). If too few emissions are priced, or the ECR is too low, countries either pay too much for abatements today or delay abatement. The Organisation for Economic Co-operation and Development (OECD) states that 'delaying abatement until it is unavoidable severely risks increasing the costs since carbon-intensive capital can suddenly become obsolete' (OECD, 2021a).

In 2018, Germany did not have an explicit carbon tax in industry. The ECR in German industries consists of fuel excise taxes and a small extent of permit prices for the EU ETS. The EU ETS affected 918 industrial plants in Germany in 2019 (UBA, 2020). Most of those plants (96%) belong to heavy industries: refineries, iron and steel, non-metal irons, mineral processing industry, paper and pulp, and chemical industry. The other 4% concern ‘other combustion plants’. Energy-intense sugar plants are part of this, but most of the other sub-branches examined are not (UBA, 2020).

Germany’s energy taxation is levied within the Energy Tax Directive of the EU. In 2018, the main taxes were the energy tax for the use of liquid, gaseous and solid fossil fuels, and biofuels; and the electricity tax for specified forms of electricity consumption (OECD, 2019). The energy tax is a fuel excise tax that concerns the combustion of fuels for heat production (in CHP) in industry. This tax can be as low as 0,4 €/GJ in 2018, when specific provisions for industries apply (1,43 €/MWh & 7,15 €/t-CO_2-eq.) (OECD, 2019). In reality, 90% of Germany’s industrial emissions were taxed between 0-5 €/t-CO_2, 87% were taxed between 5 €- 30€/t-CO_2-eq. and only 1% above 30 €/t-CO_2-eq. in 2015 (excluding the combustion of biomass) (OECD, 2021a). In Germany, the largest share of unpriced emissions falls upon the industrial sector (OECD, 2021b).

2.4 Literature Review

Previous literature has shown the most promising application potential of HTHPs to be in the food, paper, chemical and refining industry (Marina et al., 2021). Due to the nature of HTHPs, it is crucial to follow a bottom-up methodology to include process-specific information, opposed to a top-down approach assigning shares of total energy demand (Marina et al., 2021; Zühlsdorf et al.; 2019). The estimated specific investment costs of HTHPs vary greatly between existing literature, ranging from 300 €-1500 €/kW_P (Hita et al., 2011; Marina et al., 2021), while the specific levelized cost of heat (LCOH) strongly depends on the local preconditions such as electricity prices, fossil fuel prices, and other political boundary conditions such as carbon pricing and other taxes (Zühlsdorf et al., 2019). Most authors investigate the whole European industrial landscape, which makes it difficult to compare and apply the results of specific geographical settings. In summary, HTHPs show strong GHG emissions reduction potential when the energy system is decarbonised and can significantly contribute to the electrification of industris (Wolf & Blesl, 2016).

Marina et al. (2021) provide the most current bottom-up estimation and overview of the market potential for HTHPs in European industries. The authors estimate the magnitude, sizing and number of HTHPs units needed to decarbonise process heat up to 150°C with pioneering technology and 200°C in the coming years. The results are a cumulative heating capacity of 23 GW, consisting of 4174 heat pumps, covering 641 PJ/a of process heat in EU28 (Marina et al., 2021). The authors summarise that on European level, the application potential for HTHPs is the most promising in the food, paper, chemical and refining sector (Marina et al., 2021). Marina et al. (2021) have combined individual process data with average plant capacities, coupled with production statistics, and then upscaled it to European level for the relevant processes. It is the first of its kind to estimate the market potential in a bottom-up way, including cumulative heating capacity, numbers of units, process information on typical sizing, and temperature levels (Marina et al., 2021). Marina et al. (2021) summarise that the specific investment price for HTHPs >100 kW_P varies greatly: from 300 € - 1000 €/kW_P, whereas the reported industry average in China lies at 400 €/kW_P. It must be considered that a capacity of ~100 kW_P is not closely comparable to current gas-based capacity generation of large industrial plants. The authors calculate that to realise the market potential identified, an investment between 4,6 billion € - 11,50 billion € is needed (Marina et al., 2021). This supports the statement of the IEA (2021) that a significant opportunity for HTHPS manufacturers exists.

Zühlsdorf et al. (2019) assess the techno-economic feasibility of supplying process heat up to 280°C with HTHPs. The authors estimated the environmental and economic potential by considering different energy supply scenarios for three different countries in two case studies (alumina production and spray drying) (Zühlsdorf et al., 2019). Zühlsdorf et al. (2019) present the most detailed and technologically up-to-date estimate of the investment costs, including maintenance and subsystems, for two different potential HTHPs up to 280°C (Total Cascade Multi-Stage System and Reversed Brayton System) with two capacities (8,2 MW, 50 MW). For the spray drying case, the investment costs of the two HTHPs systems of 8,2 MW capacity lie between 15,35 million - 16,42 million €. The investment costs for HTHPs with a significantly larger capacity of 50 MW for alumina production lie between 47,34 million € -48,32 million € (Zühlsdorf et al., 2019). The authors found that the specific investment costs are lower for the HTHPs with larger capacity due to economies of scale and decreasing investment costs from upscaling (Zühlsdorf et al., 2019). Arpagaus et al.'s (2018) overview of state-of-the-art HTHPS technology shows no commercially available HTHPS with a capacity of 50 MW. Hence, Zühlsdorf et al. (2019) provide the first detailed estimate of specific investment costs for HTHPs with larger capacity. For the alumina production case, the LCOH from the HTHPs vary between 45 €/MWh in Denmark and 31 €/MWh in Norway, not considering the costs of CO_2 emissions (Zühlsdorf et al., 2019). The LCOH is between 9 €/MWh and 12 €/MWh more expensive for the spray drying case due to the higher specific investment costs mentioned above. The HTHPs can only compete without a CO_2-tax with natural gas boilers when the electricity costs are low (35 €/MWh-50 €/MWh). When the two different HTHPs operate on self-produced renewable electricity (incl. investment costs), the LCOH from HTHPs was competitive with natural gas boilers when a CO_2-tax between 46 €-35 €/t-CO_2-eq. was imposed (Zühlsdorf et al., 2019).

Kosmadakis (2019) investigates the potential of HTHPs in the EU for application in the temperature range of 100°C-200°C. The author has estimated two flows separately: the waste heat and its temperature level, and the industrial heat consumption with its temperature requirements. By matching the aggregated flows, the study results in the potential of HTHPs of 28,37 TWh/a, which corresponds to 1,5% of the EU's total heat consumption (Kosmadakis, 2019). The study quantifies that 21TWh/a of waste heat is needed to cover the potential, equivalent to 7% of total waste heat potential in the EU industries (Kosmadakis, 2019).

Wolf and Blesl (2016) quantified the contribution of HTHPs to the European climate change mitigation strategy. The authors follow a combined top-down and bottom-up methodology to calculate waste heat, process heat amounts, and temperature levels (Wolf & Blesl, 2016). The authors found that with state-of-the-art HTHPs of 2016, 15% of final energy consumption and 17% of energy-related CO_2 emissions can be reduced. When considering economic conditions, these reduction potentials decreased to 2,3% and 4,2%, respectively (Wolf & Blesl, 2016). A sensitivity analysis demonstrated a strong positive correlation of decreasing electricity costs from renewables and decreasing investment costs on the profitability of HTHPs (Wolf & Blesl, 2016). Wolf and Blesl (2016) further found that the decarbonisation of the energy system strongly impacts the environmental benefits.

Wolf et al. (2012) investigate the potential, technological development and market barriers for HTHPs in nine different industries in Germany. Compared to the previous studies, this is the only one exploring the technical potential for HTHP integration exclusively into German industries. Due to the state-of-the-art HTHPs in 2012, the authors consider a maximum future sink temperature of 140°C (Wolf et al., 2012; 2014). Further, a top-down approach assigning the share of the energy demand for specific end-uses of heat rather than process-specific data has been used (Wolf et al., 2012; 2014). Wolf et al. (2012) found a technical potential of HTHPs of 75 TWh for all German industries and another 91 TWh by future HTHPs that can deliver up to 140°C in German industries.

Hita et al. (2011) investigate heat recovery potential in the French food and beverages industry using the TIMES model. The authors consider economic and technical conditions for recovering waste heat with HTHPs and estimate the market accessibility mainly based on economic competitiveness (Hita et al., 2011). The authors use the TIMES energy model for modelling and include the disaggregated industrial branches, end-uses, and temperature ranges per energy use (Hita et al., 2011). The authors argue that the average waste heat temperature range in this industrial branch is between 30°C-60°C. Therefore they use a constant waste heat availability of 45°C on average (Hita et al., 2011). Hita et al. (2011) find a technical substitutable heat of 11 TWh/a up to 140°C, which corresponds to 15% of total consumed energy in the industry. When considering energy prices in France 2005, 30% of this potential is deemed economically attractive. The authors calculate the profitability by assuming a specific investment cost of HTHPs (<140°C) of 1500 €/kW (Hita et al., 2011). Hita et al. (2011) conclude that 2 Mt of CO_2-eq./a is avoidable.

In the literature, it becomes clear that the methodological approaches (top-down, bottom-up, mixed), the geographical and industrial scopes, and the technical boundary conditions of HTHPs vary greatly. Further, the technical and economic assumptions utilised play a vital role in determining the results. Therefore, it is not recommended to compare the results of the latter studies directly. Marina et al. (2021) argue that top-down approaches do not allow for heat pumps potential quantifications due to the lack of process-specific and technical information, considering the inherent process-specific nature of HTHPs. Bottom-up approaches, however, start with individual process information and aggregate these up to the desired higher level, allowing for more differentiated results than top-down approaches (Marina et al., 2021; Rehfeldt, Fleiter, & Toro, 2018).

2.5 Research Gap

There is coherent consensus in the literature that the food and beverages industry is a promising industrial sector for HTHPs due to its low/medium temperature requirements (Arpagaus et al., 2018; Marina et al., 2021). The more up-to-date systemic evaluations of the technical and economic feasibility of HTHPs focus on the whole European industrial sector (Kosmadakis, 2019; Marina et al., 2021; Wolf & Blesl, 2016), which prohibits the possibility to investigate the German industrial landscape in particular. Further, there is generally a lack of bottom-up methodologies such as Marina et al. (2021) and Rehfeldt et al. (2018), including process-specific information, making the studies more applicable for industrial players. For German industries in particular, up-to-date quantifications of the technical and the economic potentials for industrial heat pump integration, with current energy-related and technology-related data, are largely absent.

Hence, there are two issues concerning existing literature. First, the literature concerning the integration of HTHPs into German industries is scarce and outdated regarding technological developments and the data concerning energy use and emissions (Marina et al., 2021; Wolf et al., 2014). The studies that do exist for Germany either focus on the whole German industrial sector and do not go into detail for specific industrial branches (Wolf et al., 2012). Or they aim at comparing various decarbonisation options, which does not allow for specific techno-economic potential analysis (Fleiter, Schlomann, & Eichhammer, 2013; Maaß, Sandrock, & Fuß, 2018). Second, the studies on the European level are either too generic or follow top-down approaches that are insufficient to provide a detailed analysis and inform industrial players (Zühlsdorf et al., 2019).

This study aims to fill the identified gap. It can build the foundations for future research and provide insights into the realizability of process-heat decarbonisation to multiple stakeholders, such as industrial players, manufacturers, research, but also to policy makers. Further, it can specifically provide insights for the decarbonisation of the processes in the food and beverages industry in other European countries, if production processes and technical standards are comparable. This study is considering the German status quo of final energy consumption, the emission factor of the electricity mix, and the pricing of fuels in 2018. Hence, the applicability of the economic and systemic results, such as the GHG emissions abatement potential and the LCOH, is hardly comparable due to widely varying economic framework conditions in other European countries, and thus might vary depending on the other country's framework conditions.

3 Manufacturing industry of food and beverages

3.1 Industry description

The heterogeneity of production processes characterises the manufacturing of food and beverages industry, with roughly 170.000 different products produced (Gühl, Schwarz, & Schimmel, 2020) (BVE, 2020b). It is economically the fourth largest industrial sector in Germany, with 618.721 employees in 6.123 enterprises in 2019; hence, it plays a crucial economic role (BVE, 2020a). Especially in regions dependent on coal (Rheinisches Revier, Mitteldeutsches Review, Lausitz), the food and beverages industry plays a crucial role in securing employment after the coal exit and creating a more just energy transition in Germany (Agora Energiewende , 2017). The industry is dominated by small-to-medium-sized enterprises (SMEs), which are at the same time opposed by large-scale industrial players (BVE, 2020b).

The Statistical Classification of Economic Activities in the European Community (NACE) classifies the manufacturing industry of food products with the codes from C10 (Manufacture of food products) to C11 (Manufacture of beverages). It includes manufacturing food products, animal feed products, and beverages but purposively excludes the tobacco industry. Ten sub-sectors make up the manufacturing industry of food and beverages. In 2019, the industry accounted for 185,3 bn.€ turnover, of which 123,1 bn.€ occurred in Germany and 62,2 bn. € occurred abroad through exports (BVE, 2020b). In 2019, the economically most contributing sub-sectors to the industry's turnover are the manufacturing of 1) meat and meat products, 2) milk and dairy products (excl. ice cream), 3) bakery products, 4) confectionery, long-life bakery products and ice cream, and 5) alcoholic beverages (BVE, 2020b) (see Figure 3).

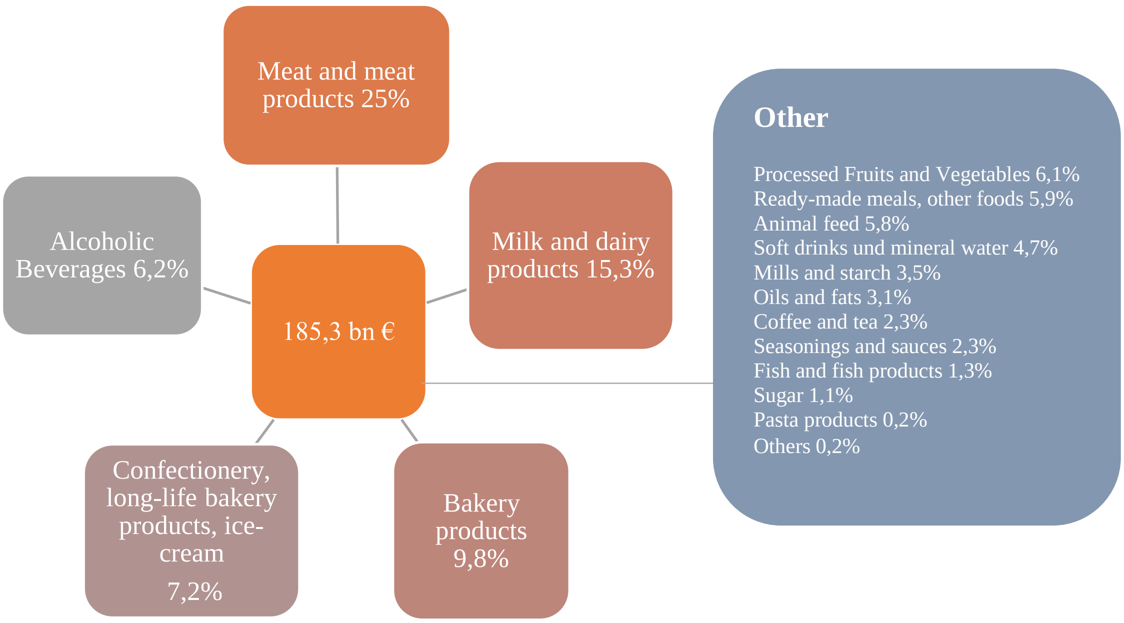

Figure 3. Contribution of branches to total turnover of industry in 2019, BVE (2020b)

The industry belongs to Germany's six most energy-intensive industrial sectors (Fleiter, Schlomann, & Eichhammer, 2013). In 2019, this industry accounted for 5,6% of the total energy consumption of German industries (Destatis, 2021). In 2018, the final energy consumption accounted for 64,87 TWh. The energy carriers with the most significant contributions are natural gas with over 60%, followed by 28,9% electricity and district heat with 5,14% (Destatis, 2018). Hence, fossil fuels are the most dominant energy carrier.

The main use of energy in the industry can be attributed to process heating, process cooling, cooling, power for electric motors and for other processes (Gühl, Schwarz, & Schimmel, 2020). Even though the industry is marked by numerous and largely differing processes, it can be generalised that:

1) Fuel is mainly used to produce process heating (warm and hot water, scalding, sanitising, drying, smoking, thermal treatments etc) while
2) electric energy is used to cover the power requirements (for cooling, compressed air generation, vacuum generation, transport) and lighting (Fleiter, Schlomann, & Eichhammer, 2013).

3.2 Industrial Sub-branches

The five most energy-intensive branches with the most significant heating demand are: 1) Production of sugar, 2) Processing of dairy, 3) Production of bakery products, 4) Processing of meat, 5) Production of beer (Fleiter et al., 2013; Gühl et al., 2020). The energy-intensity and heating demand of these five branches has not changed drastically since 2013 (BMEL Statistik, 2018; Gühl et al., 2020). In 2018, these five most energy-intense branches required 49,7% of the final energy consumption of food and beverages manufacturing industry (see Figure 4).

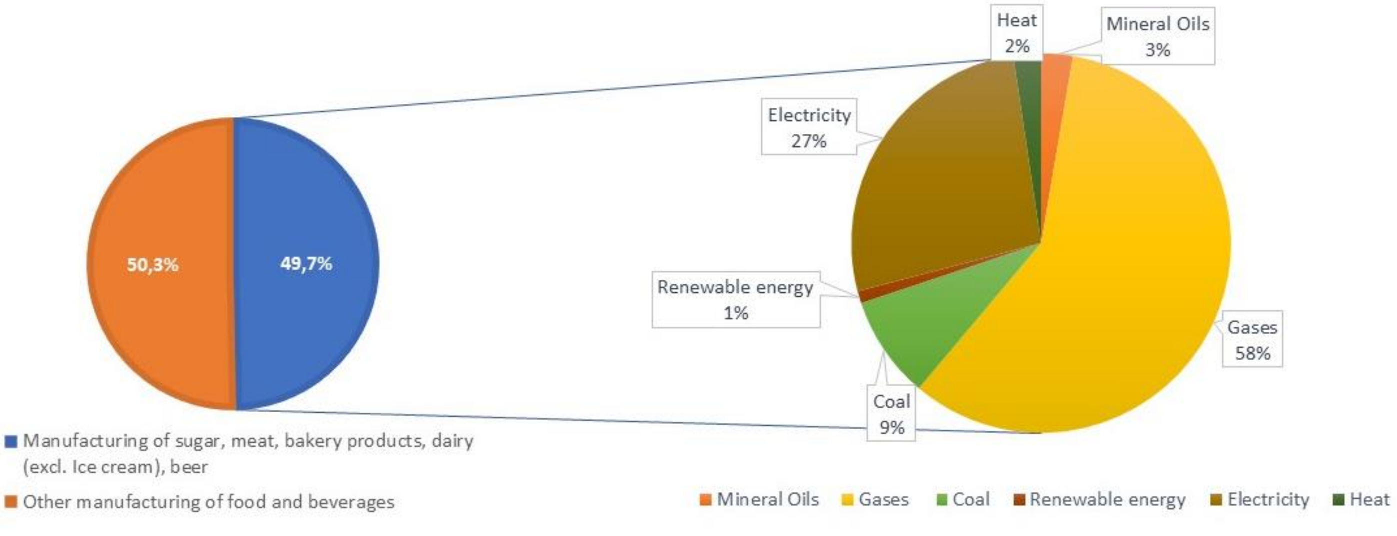

Figure 4. Left: Final Energy Consumption of whole industry in 2018. Right: Final Energy Consumption by energy carrier of five sub-branches in 2018, BMEL Statistik (2018)

The largest contributing energy carrier is gas with 58%, electricity with 27%, coal with 9%, mineral oils with 3%, and district heat with 2% (see Figure 4). The share of renewable energy in these five branches is negligibly small (1,03%), whereas the share of fossil fuels is approximately 70% in 2018 (BMEL Statistik, 2018). There is an absence of GHG emission disclosure for the food and beverages manufacturing industry. Hence, Fleiter et al. (2013) have estimated the GHG emissions for the five sub-branches in multiple scenarios for 2020 (frozen efficiency, market barriers, economic diffusion, and technical diffusion). The average GHG emissions for the five sub-branches amount to 9333 kt-CO_2-eq. in 2020, based on the GHG emissions from 2008 (Fleiter et al., 2013).

3.3 Industrial Processes

Some processes dominate the energy and heating demand for the sub-branches outlined above. In the food and beverages industry, the most energy-intensive processes usually also have the greatest heating demand. The following section explains the general production processes and identifies the most thermal-energy intensive processes.

3.3.1 Sugar Production

The production of sugar is a seasonal business, with the main ingredient being sugar beets. They are harvested in so-called 'campaigns' between September and January. In Germany, 20 sugar plants are processing around 26 million tons of sugar beets every year. Figure 5 exhibits a simplified overview of the main processing steps. Two main production steps can be differentiated: 1) the processing of sugar beets itself, and 2) the refining of raw juice extract to white sugar (Fleiter et al., 2013).

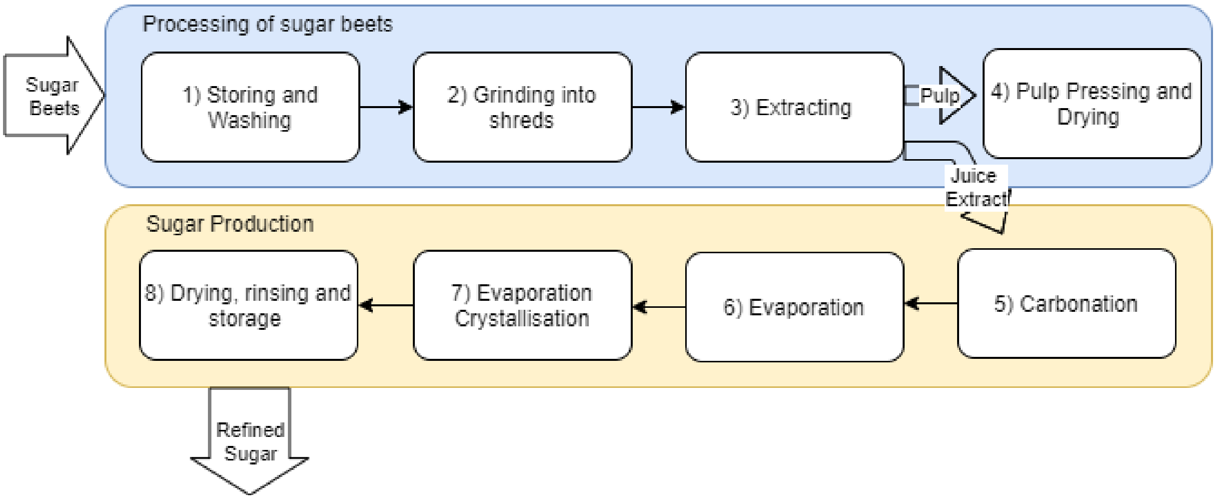

Figure 5. Simplified overview of sugar production processes. Own figure.

First, the sugar beets are stored and washed, then ground into shreds, and third scalded over with hot water (70°C) to extract the sugar stored in the sugar beet cells. Two products result from this step: 1) the main raw juice extract and 2) sugar beet pulp. The sugar beet pulp is a by-product and is pressed, thermally dried, and sold as animal feed. Usually, a high-temperature drum (HTD) dryer is used to dry the pressed pulp, which requires high temperatures and runs on natural gas (Rademaker & Marsidi, 2019). Then, the raw juice extract is mixed with milk of lime and CO_2 – the carbonation process. After the purification process, the cleaned juice extract is being evaporated to thicken to 70% dry matter (DM). The evaporators are usually set up in a cascading system so that the steam from one stage heats the next stage (Gühl et al., 2020). After the first evaporation, the thickened extract goes into a crystallisation process. In this step, small sugar crystals are being added to the substance so that in a vacuum condition, more water evaporates while the crystals grow. The sugar crystals are centrifuged and rinsed to separate the crystals from the syrup. The end product is white refined sugar (Fleiter et al., 2013)- The pulp pressing and drying, the evaporation, and the crystallisation steps are the most thermal energy-intensive process steps in sugar production (Fleiter et al., 2013; Gühl et al., 2020).

3.3.2 Dairy Processing

In 2019, 31,7 million tons of raw milk were delivered to 155 dairy processing facilities in Germany, and with 39.131 employees, it plays a vital role in the overall economy (MIV, 2020a). Dairy processing facilities are characterised by the heterogeneity of products they produce. Many products must remove large quantities of water, e.g. to produce milk powders and condensed milk. For that, concentration and drying processes require large amounts of heat (Ramírez, Patel, & Blok, 2006). This heat is typically produced by combusting natural gas, either in boilers or combined heat and power (CHP) plants (Pierrot & Schure, 2020). Figure 6 provides a simplified overview of general processes and different products in average dairy processing plants.

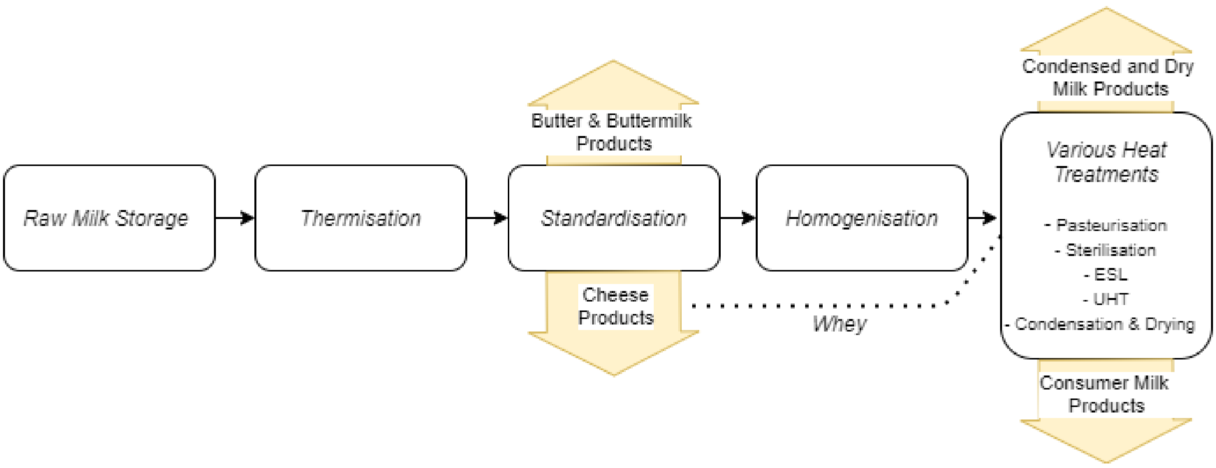

Figure 6. Simplified overview of dairy processing. Own figure.

After storage, the raw milk generally goes through a thermisation process to prevent the growth of bacteria (Pierrot & Schure, 2020). Standardisation separates the fat content from the skimmed milk content in a centrifuge. Part of the fat content is used to make butter and buttermilk. The resulting milk streams go through homogenisation processes (fat globules get reduced in size), inhibiting the separation of water- and fat-soluble components of the milk. Depending on the product made, different forms of heat treatments can be applied. Heat treatments for milk are pasteurisation, sterilisation, or ultra-high temperature treatment (UHT) (Pierrot & Schure, 2020). Other standard production processes include the evaporation of milk to produce condensed milk and further spray drying or roller drying of the condensed milk to produce different milk powders (Gühl et al., 2020). For cheese production, the standardised milk is sterilised and then pasteurised by either bactofugation or microfiltration. Leftover liquid, so-called whey, is removed. The cheese curls are heated and pressed to produce cheese. The whey goes through a similar condensing and drying process as present in milk powder production, with the final product being whey powder (Pierrot & Schure, 2020).

The production steps with the highest thermal energy demand are concentration and spray drying, pasteurisation, and UHT (Gühl et al., 2020; Ramírez, Patel, & Blok, 2006). Due to advanced regenerative heating technologies, pasteurisation nowadays usually consumes 95% less energy (Pierrot & Schure, 2020; Ramírez et al., 2006). Concentration is generally done by evaporation or membrane concentration, and for evaporation, multistage evaporators are the standard (Ramírez et al., 2006). Drying can be done with multiple technologies: roller drying, spray drying, or foam drying. In Germany, the technology that dominates the drying are spray dryers (in 2000, 99,5% of all skim milk powders were spray dried) (Ramírez et al., 2006). UHT-milk forms accounted for 92,3% of all milk products in 2018 in Germany and therefore have a high significance (MIV, 2020b). Hence, the processes of focus for this study are spray drying and UHT treatment.

3.3.3 Production of bakery products

The production of bakery products is marked by the heterogeneity of products produced, with a large variety of processes. Figure 7 presents a simplified overview of the general processes. The industrial branch is marked by a dual structure, where large-scale industrial bakeries oppose small-scale manufacturing business. In 2019, there were 10.491 production facilities in Germany (Statista, 2020a).

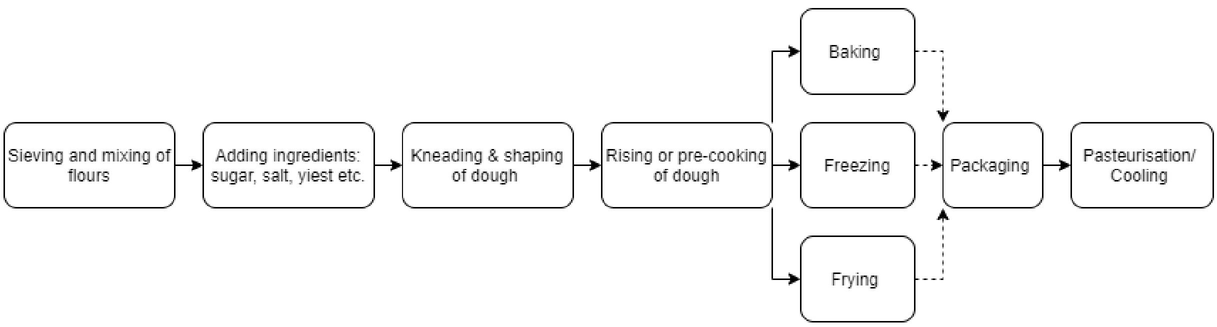

Figure 7. Simplified overview of bakery product processes. Own figure.

The production process generally starts with sieving and mixing flours. Other ingredients get added and kneaded in, then divided and shaped into the desired form. The dough usually needs to rise depending on the product or further proceeds into a cooking cabinet or chamber for pre-cooking (Fleiter et al., 2013). The product can either be baked in ovens, deep-frozen or deep-fried in pans. The baking process takes place in ovens, mainly utilising natural gas (Fleiter et al., 2013; Gühl et al., 2020). Depending on the size of the production facility, there is a distinction between continuous and discontinuous baking processes. Continuous baking processes in tunnel ovens are used in large-scale industrial bakeries, while small-scale bakeries usually use deck-baking ovens or oven cabinets. Additional energy is used during baking due to overheating or lack of controlling (Gühl et al., 2020). The latter factors and the high temperatures required make the ovens the largest thermal energy consumer in the production of bakery products (Fleiter et al., 2013).

If the product is easily perishable (like toast), some products also get pasteurised. The pasteuriser is also highly energy-intensive and usually runs on natural gas (ZREU, 2000). Lastly, the products are packed and sometimes cooled until shipping (Fleiter et al., 2013; Gühl et al., 2020). The cooling and freezing process is also highly energy-intense, but the technological standard in Germany are conventional compression refrigeration machines, which run on electricity (Fleiter et al., 2013).

3.3.4 Processing of meat

The meat industry has the largest contribution to total turnover (25%) of Germany's whole food and beverages industry, accounting for 46,3 bn. € (BVE, 2020b). Meat processing has had a share of 23 bn.€ and thus plays a crucial economic role. In 2019, meat was processed in more than 1400 processing facilities, with domination of large-scale industrial players, such as Tönnies (turnover of 6,9 bn. €) (Statista, 2020c). In 2018, 8511,03 thousand tons of meat had been produced (gross self-production) (BMEL Statistik, 2020). The two main product groups are meat products and sausage products (BVDF, 2020). The processing of meat consists mainly of the following steps: slaughtering, cutting, further processing and packaging (Gühl et al., 2020). A simplified overview can be found in Figure 8.

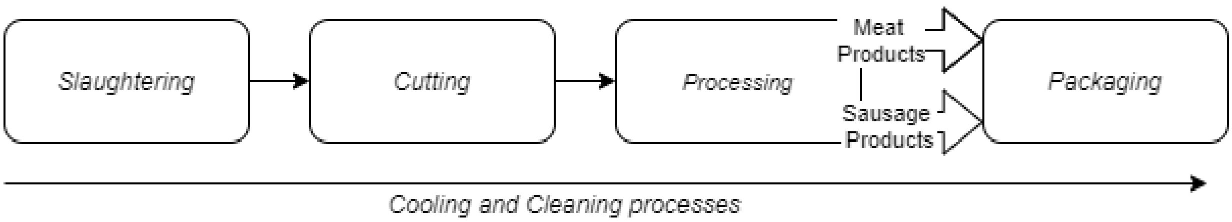

Figure 8. Simplified overview of meat processing. Own figure.

The most energy-intensive processing steps are cooling and vacuum packaging, while the most thermal energy-intensive processes are cooking, scalding, simmering and smoking processes (Fleiter et al., 2013; Gühl et al., 2020). The product group with the greater heat demand are sausage products due to preservation (cooking, scaling, simmering, smoking etc.). In contrast, meat products usually are sold raw or with little heat treatment (Heinz & Hautzinger, 2007). The already slaughtered meat is usually cured with an injector and tumbler to produce meat products and further packed into forms. Sometimes, a short thermal treatment is carried out in the smokehouse (Fleiter et al., 2013). For sausage products, the different meats get weighted, refined with spices and other ingredients, processed to become sausage meat or filled into forms and natural or synthetic bowels (Fleiter et al., 2013). Usually, the sausages are preserved by different heating, maturation and ripening processes. For finishing, the sausage products get cut, sliced, and packed for consumers or transported as a whole to retail, gastronomy, or further industrially processed. A part of the products is preserved in glass jars or cans (Gühl et al., 2020).

In the product chain of meat products, constant cooling is crucial. Cooling includes room cooling, deep-cooling, process-cooling and ice preparation. The standard technology to produce the cooling demand is usually compression cooling machines running on electricity (Gühl et al., 2020). The process heat for the reddening, cooking, scaling, smoking and cleaning processes is usually produced based on natural gas (Gühl et al., 2020). In general, only limited specific process information is available about the energy use in meat processing. For generalizability, the thermal treatments of sausage products have been aggregated and best-available-technology (BAT) information for sausage products has been utilised (AEE Intec, 2013).

3.3.5 Production of beer

In 2019, the industrial branch of alcoholic beverages had the fifth-largest turnover in the German industry, with a total turnover of 11,5 bn € (BVE, 2020b). The largest share of turnover falls upon beer products, which had a turnover of 8,4 bn € in 2019. In 2019, 1548 breweries produced a total volume of 91610 thousand hectolitres of beer (Brauer Bund, 2019). In Germany, approximately 6000 different sorts of beer exist. The main processes in beer brewing are the production of beer wort in the brewhouse, the fermentation and storage in cellars, and the filling and preservation in the filling hall (Lauterbach, Schmitt, & Vajen, 2011). Figure 9 shows a simplified overview of general processes.

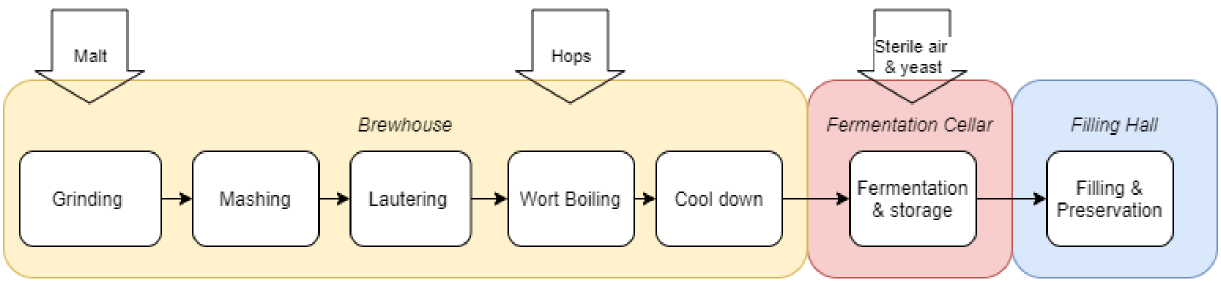

Figure 9. Simplified overview of beer production processes. Own figure.

The most thermal energy-intensive processes are the mashing and the wort boiling in the brewhouse and the cooling (Fleiter et al., 2013). In larger breweries, the technical standard for cooling is compression refrigeration systems that run on ammonia (Kalinowski, 2005).

First, the purchased malt (barley, wheat, rye or others) is milled in a grinding process. Then the ground malt is mixed with warm water (~35-70°C) and subsequently slowly heated to release the malt ingredients (Fleiter et al., 2013). The third step is the lautering process, in which the spent malt grains are separated from the dissolved components, the wort (Fleiter et al., 2013). Later, the separated wort is boiled with added hops for 40 to 100 minutes, depending on the boiling technology (Lauterbach et al., 2011). The bitter and aromatic components of the added hops are transferred to the wort while the protein is excreted. Here, a large quantity of water must be evaporated to obtain the desired concentration of the wort, depending on the type of beer. The average amount of evaporated water is 8-10% of the preceding wort volume (Lauterbach et al., 2011). This wort boiling process also serves the purpose of sterilisation. Once the desired wort concentration is reached, the boiling process ends, and the hot trub gets removed. Subsequently, the hot wort is cooled down with single- or two-stage plate heat exchangers (Lauterbach et al., 2011). Sterile air and yeast are added and pumped into fermentation tanks. In the fermentation process, the sugar in the wort is converted to alcohol and CO_2. It can take up to ten days, depending on the type of beer. Lastly, the beer can be filtered again, is then bottled (if not yet done), sometimes pasteurised in the respective filling container and finally labelled (Fleiter et al., 2013).

4 Methodology

As outlined in the literature review, Marina et al. (2021) criticise the top-down methodological approaches. Therefore, this study follows a similar bottom-up methodological approach as Marina et al. (2021). The bottom-up approach allows the inclusion of process- and technology-specific characteristics, scaling it up to the national level to paint a systemic picture. Further, this study utilises the economic costing estimates from Zühlsdorf et al. (2019) to evaluate the economic profitability. Hence this study combines the two studies methodological approach, including their assumptions, and applies it to the case of Germany. Due to the explorative nature, this paper is based on estimates to calculate the techno-economic potential. All data sources and estimates are disclosed in Appendix A.

This study neither focuses on any specific case studies nor compares different decarbonisation technologies due to the complexity of industrial decarbonisation. In short, first the total thermal energy demand of specific processes is calculated, second the COPs are calculated for a worst- and best-case scenario, third the electricity demand and GHG emissions abatement potential is calculated, and lastly the cost-competitiveness of the applied HTHPs is evaluated. The calculated technical potential only applies to the selected processes and hence serves the purpose of giving a first insight and general overview. An increasing potential is expected when including more processes, and more industrial sectors, which lies outside the scope of this study.

4.1 Research questions

This study is answering the following main research question with the help of five sub-questions:

Main RQ:

"*What is the techno-economic potential of high-temperature heat pumps to decarbonise process heat in the German food and beverages industry, what is the GHG abatement potential, and what are the economic and political framework conditions?*"

Sub RQ 1:

"What is the status quo in the food and beverages industry? What are relevant and suitable processes, and what are their technical requirements?"

Sub RQ 2:

"What is the total thermal energy demand, and resulting GHG emissions in the relevant processes?"

Sub RQ 3:

"What is the thermodynamic efficiency of applying HTHPs to the suitable processes, and what is the resulting technical potential of HTHPs?"

Sub RQ 4:

"What is the electricity demand and what is the resulting GHG emissions abatement potential in the industrial sub-branches?"

Sub RQ 5:

"What is the specific levelized cost of heat, and when is it competitive to the existing infrastructure?"

4.2 Methodological steps

This study is answering the sub-questions by performing the corresponding five methodological steps with the following equations:

Step 1. Industry data

In Step 1, the most energy-intensive sub-branches and their most thermal energy-intensive processes are identified with the help of industrial reports and literature. Process-related data is collected, including thermal specific energy consumption (SEC_{th}) per unit of product, process temperature requirements, exhaust temperature, average operating hours and number of largest facilities. Further, the technical requirements for HTHPS are collected through the DLR and literature sources. Lastly, technically suitable processes are identify based on temperature requirements.

Step 2. Total thermal energy demand & GHG emissions

In Step 2, the thermal energy demand (Q_D) that the HTHPs need to deliver is calculated by multiplying the SEC_{th} with the annual production volume (APV) for the associated product (Equation 5). Further, Q_D is multiplied with the emission factor of natural gas (EF_{gas}) to calculate the GHG emissions stemming from the combustion of natural gas (Equation 6). After the process-level calculations, Q_D and the GHG emissions$_{gas}$ are summed up to generate the total thermal energy demand ($\sum Q_D$) and total GHG emissions stemming from gas ($\sum$GHG emissions$_{gas}$) in the year 2018.

Equation 5. Thermal Energy Demand

$$SECth * APV = Q_D$$

Equation 6. GHG emissions from natural gas

$$Q_D * EF_{gas} = \text{GHG emissions}_{gas}$$

Step 3. Thermodynamic Calculation of COPs of HTHPs and technical potential

In Step 3, the process-specific COPs, based on the temperature ranges, are calculated for the processes that have been found suitable (Equation 7 & 8). For the COP calculations, a pinch value of 5°C is added and subtracted to the high (T_{P*}) and low (T_{W*}) temperature, respectively, to represent the temperature of the refrigerant in the HTHPs (Hita et al., 2011). The COPs are calculated for two different waste heat scenarios: The Worst-Case Scenario assumes waste heat available at 45°C industrial average (Hita et al., 2011), and the Best-Case Scenario assumes waste heat available at exhaust temperatures. By having two scenarios, uncertainties regarding the temperature level of waste heat availability in industrial plants is minimised. Lastly, the technical potential is calculated by taking the fraction of $\sum Q_D$ of the processes demonstrating a suitable temperature (Equation 9).

Equation 7. Carnot COP

$$COP_{carnot} = T_{P*} / (T_{P*}-T_{W*})$$

Equation 8. Real COP

$$COP_{real} = 0{,}60*COP_{carnot}$$

Equation 9. Technical Potential

$$\text{Technical potential} = \sum Q_D \text{ if } T_W<250°C$$

Step 4. Electricity use and GHG emissions abatement potential

In Step 4, the electricity demand (E_{el}) for powering the HTHPs for the relevant processes is calculated by dividing Q_D by the COP_{real} per process (Equation 10). Further, the GHG emissions stemming from the electricity demand (GHG emissions_{el}) are calculated by multiplying E_{el} with the emission factor for electricity (EF_{el}) in Germany in 2018 (Equation 11). The GHG emissions abatement potential (EAP) is calculated by subtracting the GHG emissions_{el} from the GHG emissions_{gas} (Equation 12). Equation 10-12 are first performed on process level, and then summed up to scale up to national level. Lastly, the sum of GHG EAP ($\sum$EAP) is divided by the total estimated GHG emissions from the five sub-branches, based on Fleiter et al. (2013) (Equation 13).

Equation 10. Electricity Demand, Marina et al. (2021)

$$E_{el} = Q_D/COP_{real}$$

Equation 11. GHG emissions from electricity.

$$E_{el} * EF_{el} = \text{GHG emissions}_{el}$$

Equation 12. GHG emissions abatement potential

$$\text{GHG emissions}_{gas} - \text{GHG emissions}_{el} = EAP$$

Equation 13. Contribution to total GHG emissions of sub-branches.

$$\sum EAP \, / \, \text{total GHG emissions} = \% \text{ contribution}$$

Step 5. Specific levelized cost of heat of HTHPs

In Step 5, the LCOH for HTHPs is calculated (Equation 14). This is done for the two waste heat scenarios and two different capacities of HTHPs (8,2 MW and 50 MW) (Zühlsdorf et al., 2019). The calculation is firstly performed on process level, and subsequently on aggregated level for all processes to receive a generalized LCOH (See Appendix B). Equation 14 shows the formula applied to calculate both the process-specific and the aggregated LCOH. On process-level, Q_D is divided by the number of large facilities and annual operating hours (OH) in the respective sub-branch to get the average heat rate per facility (Q_{sink}). Based on Q_{sink}, the capacity and number of HTHPs per facility is determined. For the aggregated LCOH, an average OH is used and from thereon generalized, how many HTHPs of both capacities are needed to cover the summed heat rate supplied to sink ($\sum Q_{sink}$). For the aggregated LCOH calculations, Equation 14 is performed with sums.

In both calculations, the total capital investment (TCI) of the number of HTHPs needed to cover Q_D is multiplied with the capital recovery factor (CRF). The CRF is calculated with the interest rate (i) of 5% over the lifetime (N) of 20 years (Equation 15) (Zühlsdorf et al., 2019). This product is subsequently divided by the product of OH and Q_{sink}. The quotient is then added to the quotient of the cash flow (CF) and the product of OH and Q_{sink}. The CF is calculated by multiplying the specific cost of electricity (c_{el}) with OH and E_{el} (Equation 16). The resulting LCOH represents how much one MWh output from the different HTHPS systems and waste heat scenarios costs, including investment and maintenance, costs in €. The results are then compared to the specific costs of natural gas (c_{gas}) and the fuel excise tax for the natural gas benchmark scenario (excl. investments & maintenance). Lastly, the necessary carbon tax to levelize the costs between the scenarios is calculated. Even though the benchmark scenario excludes investments and maintenance costs of the existing natural gas scenario, the results provide a first indication on how much the transition to a low-carbon heat supply will costs from the industrial perspective.

Equation 14. Specific Levelized Cost of Heat, in €/MWh, Zühlsdorf et al. (2019)

$$LCOH = ((TCI * CRF) / (OH * Q_{sink})) + ((CF / (OH * Q_{sink}))$$

Equation 15. Capital Recovery Factor, Zühlsdorf et al. (2019)

$$CRF = (i(1+i)^N) / ((1+i)^N - 1)$$

Equation 16. Annual Cash Flow, Zühlsdorf et al. (2019)

$$CF = c_{el} * OH * E_{el}$$

4.3 Data Assumptions and Uncertainties

This study and the calculations are based on numerous assumptions. A complete overview of all industrial, technical, and economic data assumptions, and their respective sources, are listed in Appendix A. This section elaborates the data availability and hence, justifies the respective data choices.

4.3.1 Industry Data

Literature concerning the whole general industrial sector is vastly available. The data availability (temperature levels, specific heat consumption, standard technologies, operating hours, etc.) however is significantly more limited on process level per sub-branch. Especially grey literature reports from industry associations (meat-, dairy-, beer-, bread-, and sugar industry association) build the basis for industry-specific literature. Since these reports are usually annual reports for the public, they disclose more the industrial branch's economic- and trade-related information than energy-, emissions- or process-specific technical details. Unfortunately, there is no generic database for German industries to gather process-related technical information for decarbonisation research. Therefore, the Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN), founded by the Netherlands Environmental Assessment Agency (PBL) and TNO, has been used for the technical process information regarding the sugar and dairy industry (MIDDEN , 2021). It proved to be more difficult to find up-to-date data for the German meat and bakery industry. In these two branches, one particular product does not necessarily correlate with a specific production process, as in sugar, dairy and beer. It is unclear which product line undergoes which step of processing due to the heterogeneity of products and the importance of plant-specific recipes and traditions. Therefore process-specific information is rarely publicly disclosed. These industrial branches are further not yet included in the MIDDEN database. Hence, assumptions are used for the meat and bakery branches in particular. Industry reports show that sausage products have higher importance for thermal treatment than meat products (Heinz & Hautzinger, 2007). Therefore, a best-available-technology (BAT) document regarding the specific heat of salami products and sausage production statistics have been used to estimate the average heat consumption for sausage products (AEE Intec, 2013). Other grey literature provides the information that only highly perishable bakery products get pasteurised, which is argued to be mainly toast (ZREU, 2000). Therefore only the production volume of toast is assumed to be pasteurised, while for the baking process, a fraction of the total production volume was used.

Process temperature requirements are more easily accessible (Arpagaus et al., 2018) than specific exhaust temperatures. The reason is that the temperature requirements are usually in the same ranges, while the exhaust temperatures depend on particular process technologies and plant-specific energy management. Two different waste heat scenarios are used to minimise the uncertainty of the waste heat temperatures: 1) Worst-Case represents an average waste heat temperature of 45°C (representative for the food industry), as in Hita et al. (2011), and 2) Best-Case is the direct process exhaust temperature (from various grey literature sources).

The operating hours for the sub-branches are estimated due to the lack of generic data. The sugar industry is the only sub-branch that works in campaigns and therefore has significantly lower OH (2900h/a) than the other branches. Based on the spray drying case study (dairy processing) of Zühlsdorf et al. (2019), an average OH of 7000 h/a are estimated for the other branches. For the capacities, only the largest facilities are considered due to the assumption that larger facilities dominate the process-heat demand. Hence, only facilities with an annual turnover of >10 million €/a are considered, based on an overview of the Hans-Böckler Stiftung on the company size structure of various sub-branches of the food and beverages industry measured by turnover (Vorderwülbecke, Korflür, & Löckener, 2018).

4.3.2 Energy and Emission Data

The energy balances regarding the final energy consumption per energy carrier of the food and beverages industry, and the five sub-branches, are taken from the German federal ministry of food and agriculture (BMEL Statistik, 2018). The energy balances are only available for the year 2018. No reliable, up-to-date data concerning the number of facilities per sub-branch and the energy-usage distribution in production facilities could be found (see above). Further, no up-to-date data regarding specific GHG emissions of the sub-branches could be found. Therefore, the specific GHG emissions stemming from the combustion of natural gas are estimated based on the emission factor of natural gas (UBA, 2018a). Due to the absence of GHG emission data for the whole food and beverages industry, the GHG abatement potential has been put in relation to the average estimated GHG emissions of the five sub-branches from the 2020 scenarios from Fleiter et al. (2013).

4.3.3 Technical Data

Technical information regarding HPs and their thermodynamic workings is vastly available in academic sources. Even though most current research concerns HPs for lower temperature ranges, recent years show increasing attention on HTHPs and thus an increase in their technical information (Arpagaus et al., 2018; Hita et al., 2011; Marina et al., 2021; Zühlsdorf et al., 2019). The specific technical assumptions for the HTHPs <250°C are provided by experts of the HTP and SVD department at the DLR Institute for low-carbon industrial processes (DLR, 2021a; Stathopoulos, 2021).

4.3.4 Economic Data

The economic data regarding the industrial electricity and natural gas prices stem from the international comparison fuel price data set from the German federal ministry of economic affairs and energy (BMWi, 2018). The c_{el} and c_{gas} exclude value-added tax (VAT), and refundable taxes and duties since these are traversing costs, not at the expense of the industrial player. The c_{el} represent average values calculated annually and affect energy-intensive industrial players with a yearly consumption between 20000 MWh

< 70000 MWh (BMWi, 2018). Energy-intensive industrial players had a significantly lower electricity price than smaller industrial players in 2018 due to multiple tax concessions and exemptions of levies (BMWi, 2018). The reduced industrial electricity price is based on the average estimated plant size and annual capacity in the economic analysis. Zühlsdorf et al. (2019) work with a German electricity price scenario estimate for 2020 of 52,10 €/MWh, 40% lower than the BMWi (2018) price statistics used in this analysis. In reality, the German c_{el} did not decline as expected in the scenario, and therefore the price statistics of BMWi (2018) are taken as the most representative.

The fuel excise tax and the EU ETS permit prices that apply to industries are difficult to generalise. No data sets are available that list exact tax rates for specific industrial players or plants. Therefore, it is assumed that the industrial branches examined are mostly excluded from the EU ETS trading scheme, since mostly heavy industry falls into the EU ETS. Further, the lowest industrial fuel excise of 0,4 €/GJ (7,15 €/t-CO_2-eq.) in 2018 has been assumed, considering the fact that 90% of emissions were taxed between 0 €-5 €/t-CO_2-eq. and the largest share of untaxed emissions fell upon the industrial sector in 2015 (OECD, 2021b).

There are not yet many academic sources that provide a sophisticated costing estimate for HTHPs in high-temperature ranges due to the novelty of the emerging technology. The economic potential of emerging technologies is determined by various parameters, including the initial investments, operation costs, and capacities (Comello, Glenk, & Reichelstein, 2017). Due to manufacturers' lack of concrete investment costs, main component costs need to be estimated, for which capital costs can be extracted using correlation (Zühlsdorf et al., 2019). The capital costs can be compared to the operating costs, considering the lifetime and the interest rate (Zühlsdorf et al., 2019). With the investment cost estimates and the operational costs from electricity, the LCOH can be estimated. It allows relating the investment cost of one year to the annual operating costs to the heat flow supplied (Zühlsdorf et al., 2019). Levelized Cost is a common metric used to compare the cost-competitiveness of alternative energy-generating technologies, with the Levelized Cost of Electricity (LCOE) being the most famous (Comello, Glenk, & Reichelstein, 2017). Therefore, LCOH allows the comparison of the profitability of different heat-generating systems over time. To stay within the scope of this study, the most sophisticated investment cost estimates by Zühlsdorf et al. (2019) for two HTHPs of different capacities (8,2 MW & 50 MW) are utilised. Zühlsdorf et al.'s (2019) economic estimates result in specific investment costs between 1000 €/kW – 2000 €/kW, for the larger and smaller HTHP case studies respectively, which occurs to be in a similar range than the specific investment costs presented in the literature review. The HTHP department at DLR expects their HTHP designs to revolve around the same price scale of 1000 €/kW, but are expected to reach a smaller capacities than the estimates at the early stage (Oehler et al., 2021), which makes higher specific prices as in Zühlsdorf et al. (2019) more likely.

4.3.5 Data Uncertainties

As explained in the section above, the study is based numerous data assumptions. Other parameters values could be chosen and yet it is not known what the variation of values would do to the results of this study. This is called data uncertainties, which investigates the effects of uncertain parameter values and uncertain data inputs on the results of the study (Hofer, 2018). Hence, it is crucial to investigate the uncertainties that are tied to the data inputs, by manipulating the parameters and study how it would affect the main findings. Table 2 presents an overview of the three parameters chosen for manipulation, and the upper and lower manipulation limit.

As this study is investigating technical, economic, and systemic parameters, one of each domain has been chosen for manipulation. For the technical side, the efficiency factor for the HTHPs is manipulated, first to the lower value of 50%, and further to the upper value of 70%. The lower and upper value are in line with the range of efficiencies characterised by Hita et al. (2011) and Marina et al. (2021). The purpose is to investigate which influence the technical advancements of efficiencies has on all results, due to the importance of efficiency factors in the conversion of energy and systemic comparisons.

The second parameter is from the economic side, the electricity price for industrial players. The electricity price that affects industrial players is highly flexible in Germany. Among industrial players, some companies can pay three times the price for electricity than others, due to exemptions from taxes and levies (Clean Energy Wire, 2019). Further, forecasts for industrial electricity price developments vary majorly. Industrial associations claim that the coal exit in 2038 will push electricity prices considerably higher, whereas research institutes state that the coal phase-out and the swath to renewables will only have a small impact, if not even beneficial impacts on industrial electricity prices (Clean Energy Wire, 2019). Due to the price uncertainties, the electricity price input is manipulated with a lower value of -50% (44 €/MWh) and upper value of +50% (131 €/MWh) to investigate which impacts the variations have on the economic profitability.

The third systemic parameter that is manipulated is the emission factor of electricity, which is currently based on the year 2018 in Germany. It plays a crucial role how the electricity is produced, e.g. if it is produced largely by coal with a high emission factor, largely by natural gas with a slightly lower emission factor, or if it is dominated by renewables and thus has a low emission factor. Coupled with the efficiency factor, it is essential to consider that the direct combustion of natural gas to produce heat would always be more efficient than an electricity mix largely based on natural gas, converting it to electricity, and then powering the HTHPs. Therefore, the emission factor for electricity will be manipulated in two ways: the upper value is based on the assumption that natural gas is suddenly becoming drastically more expensive or unavailable due to economic-political influences, and hence the share of natural gas is to the same share fully replaced by lignite and hard coal, due to the current merit order in Germany. With help of a basic calculation of assigning shares to energy carriers, their emission factors, and conversion efficiency factors, the upper value results in an emission factor for electricity of 516 g/kWh (See Appendix B). The lower value represents a full elimination of lignite assuming a rapid lignite coal exit, considering the real share of hard coal stays the same as in 2018. In this case it can be expected that the share of the lignite is fully replaced with natural gas, which leads to lower emission factor of 302 g/kWh. It is also interesting to investigate what would happen, if the emission factor for electricity goes towards 0 g/kWh, which could happen in case of own renewable electricity production or an electricity mix based fully on renewables and nuclear.

Table 2. Data Manipulation Parameters. Own table.

Domain	***Parameter***	***Initial Value***	***Lower Value***	***Upper Value***
Technical	Efficiency of HTHP	60%	50%	70%
Economic	Electricity Price	87 €/MWh	44 €/MWh	131 €/MWh
Systemic	Emission Factor Electricity	468g CO_2-eq/kWh	302 g/kWh (long run: 0 g/kWh)	516 g/kWh

5 Results

5.1 Identification of suitable processes and technical information

Nine thermal energy-intensive processes can be identified which dominate the process-heat demand for the five sub-branches. Table 3 summarises the relevant processes and outlines the maximum process temperatures, the average exhaust temperatures and the specific thermal energy demand. For specific sources, see Appendix A.

Table 3. Overview of relevant processes and technical details. Own table.

	Max. Process Temperature	Average Exhaust Temperature	SEC_{th}	Unit	Suitable Temperature for HTHP
Sugar					
Pulp pressing & drying	550°C	111,5°C	6,08	GJ/ton dried pulp	NO
Evaporation & Crystallisation	135°C	50°C	2,94	GJ/ton white sugar	YES
Dairy					
Evaporation & Spray drying	180°C	75°C	7,85	GJ/ton dry milk product	YES
UHT Treatment	142°C	80°C	0,4	GJ/ton milk	YES
Bakery					
Baking	180°C	150°C	0,0061	GJ/kg baked product	YES
Pasteurisation	202°C	190°C	0,0003	GJ/kg perishable product	YES
Meat					
Sausage products thermal treatment	80°C	45°C	3,23	GJ/t sausage product	YES
Beer					
Mashing	100°C	76°C	0,007	GJ/hectolitre	YES
Wort Boiling	100°C	100°C	0,034	GJ/hectolitre	YES

Eight of these nine processes fulfil the technical boundary condition of requiring temperatures below 250°C. Only one process, the pulp pressing and drying in the sugar industry, requires significantly higher temperatures of up to 550°C. Therefore, this process is unsuitable for the considered HTHPS and is further not considered in the techno-economic analysis. The other eight processes that are technically suitable consist mainly of pasteurisation, cooking, evaporation, and drying processes, which often require removing large quantities of water. In the German industrial landscape, most of these processes still receive their heat from the on-site combustion of natural gas: CHPs such as in large sugar plants and gas-fired boilers for smaller production facilities. The food and beverages industry generally has a medium upper limit for temperature requirements since the food products are damaged with too high temperatures. The temperature ranges for food products rarely exceed 200°C, sometimes 250°C for short exposure times. By-products (e.g. the beet pulp) or material inputs (e.g. lime for the calcination) in rare cases require temperatures up to 1000°C, which is not yet achievable with an HTHPS. Nonetheless, the food and beverages industry is a promising sector for the application of emerging HTHPs.

5.2 Thermal energy demand & GHG emissions

The total thermal energy demand of the eight processes results in 12 TWh in 2018. The three processes with the largest contribution to the total thermal energy demand in 2018 are the evaporation and crystallisation of white sugar with 4,2 TWh, followed by the thermal energy demand for baking of bakery products with 3,2 TWh, and the thermal treatment of sausage products in the meat processing industry with 1,4 TWh. These three processes contribute 73% to the thermal energy demand of the processes in focus in 2018. Firstly, they have a high specific thermal energy demand, but at the same time also show a large production volume and therefore contribute significantly.

The associated GHG emissions stemming from the analysed processes are 2419 kt-CO_2-eq. in 2018, roughly 26% of the assumed total GHG emissions of the five sub-branches. The largest contributing processes correlate to those with the largest thermal energy demand: the evaporation and crystallisation of white sugar with 854 kt-CO_2-eq., followed by baking bakery products with 652 kt-CO_2-eq., and the thermal treatment of sausage products in the meat processing industry with 280 kt-CO_2-eq. Appendix B provides an overview of all specific calculations per step.

5.3 Technical evaluation: COPs & technical potential

In the worst-case scenario (waste heat temperatures of 45°C), the calculated COPs range between 1,7 and 4,8. The lowest COP occurs in pasteurisation due to the highest temperature requirements and thus the largest temperature lift. The highest COP in this scenario occurs in the thermal treatment of sausage products due to the lowest temperature requirements and therefore exhibits the smallest temperature lift when the waste heat temperature is fixed.

In the best-case scenario (direct exhaust temperatures), the resulting COPs range between 2,4 and 23. The lowest COP occurs in evaporation since the temperature lift between sink and source temperatures is largest in this process. Therefore the thermodynamic efficiency is smaller. The highest COP occurs in the wort boiling of beer. Literature has shown that this process is thermodynamically ideal for waste heat recovery. The exhaust temperature is argued to be the same as the process temperatures, which, coupled with a high efficiency factor, results in a very high thermodynamic performance. A COP this high is theoretically possible, as shown in the calculations, but in practice, is not the case due to temperature losses occurring when reusing waste heat and HTHP component limitations. The technical potential to apply HTHPs <250°C in the eight most thermal energy-intensive processes in the German food and beverages industry results in 12 TWh in 2018.

5.4 Systemic contribution: Electricity use & GHG emissions abatement potential

In the worst-case scenario, the electricity demand needed to power the HTHPs in 2018 results in 5 TWh. In the best-case scenario, the electricity demand required is 3,3 TWh. The large range of required electricity for the two scenarios stems from the significant deviation of COPs between worst-case and best-case discussed above; the higher a COP, the less electric input needed. Consequently, the GHG emissions stemming from the electricity in Germany in 2018 are 2367 kt-CO_2-eq. for the worst-case, and 1534 kt-CO_2-eq. for the best-case scenario. Therefore, the worst-case GHG emissions abatement potential results in 52 kt-CO_2-eq. The best-case GHG emissions abatement potential is 885 kt-CO_2-eq. Figure 10 compares the aggregated electricity demand, the resulting GHG emissions, and the GHG emissions abatement potential of both scenarios. The GHG emissions abatement potential is substantially more significant in the best-case scenario, which shows the environmental benefit of reusing direct process waste heat from exhaust to enhance the energy efficiency of HTHPs.

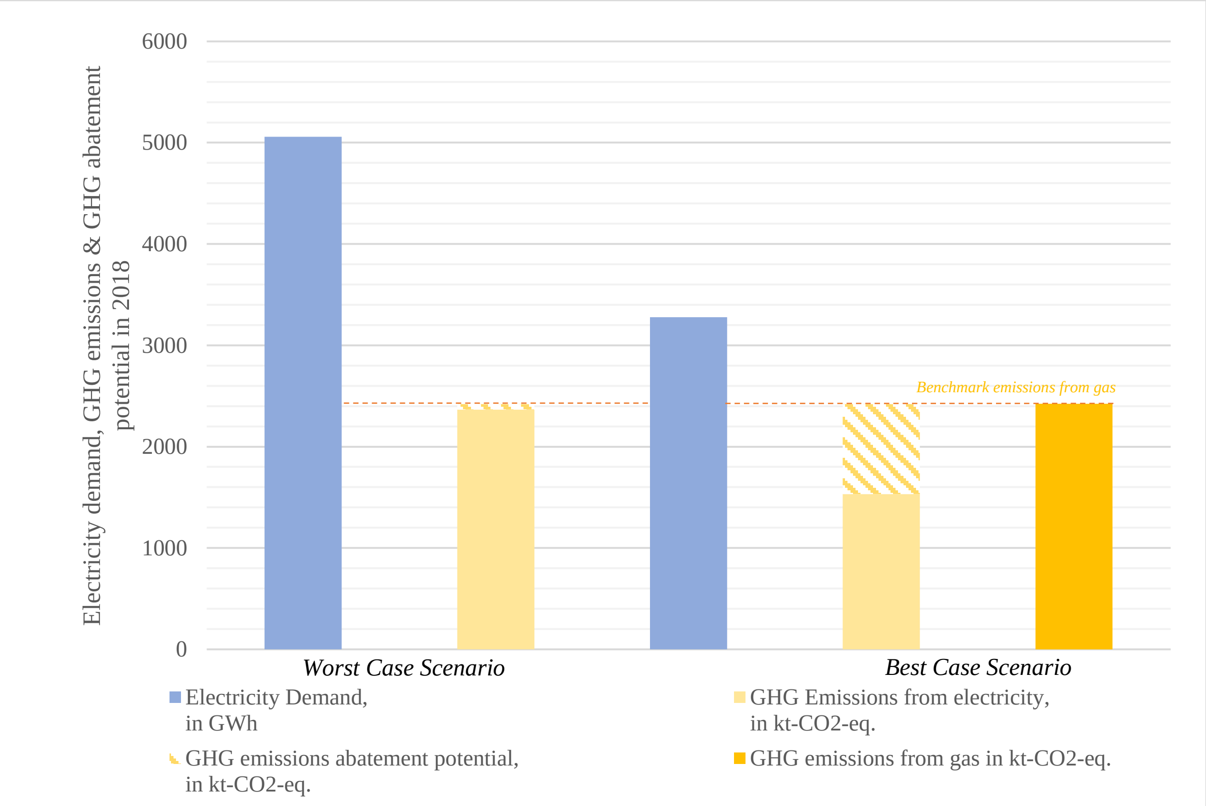

Figure 10. Comparison of aggregated electricity demand, GHG emissions from electricity, GHG emissions abatement potential for both scenarios in 2018. Own figure

In the worst-case scenario, the processes evaporation and spray drying, baking, and pasteurisation have more GHG emissions stemming from the electricity required than the status quo of gas combustion. The reason is the low COP resulting from the high temperature lift and the comparably high electricity emissions factor in Germany in 2018. It must be considered here that the emission factor is a yearly average and does not necessarily reflect the actual emissions of the electricity used in industry at that time. The largest absolute GHG abatement potential occurs in the processes of the thermal treatment of sausage products with 144 kt-CO_2-eq and in wort boiling with 60 kt-CO_2-eq abatable.

In the best-case scenario, all processes show lower GHG emissions from the electricity required than from the combustion of natural gas. The largest absolute GHG emissions abatement potential occurs in the baking process with 432 kt-CO_2-eq., followed wort boiling with 160 kt-CO_2-eq. abatement potential, and lastly in the thermal treatment of sausage products with 144 kt-CO_2-eq. abatable. These three processes contribute 83% to the total GHG emission abatement.

When comparing the level of COPs and the systemic abatement potential of GHG by replacing the on-site combustion of natural gas with German electricity from 2018, a COP of 2,3 marks the threshold for lower emissions from electricity than from gas. This comes from the fact that the GHG emissions for producing 1 kWh for electricity in 2018 in Germany is 2,3 times higher than the GHG emissions from 1 kWh of natural gas. Hence, as long as the electricity has an emission factor this high, a COP of 2,3 is required to produce less GHG emissions when applying HTHPs.

Consequently, applying HTHPs to the chosen processes in the worst- and best-case scenario could lead to a GHG emissions reduction of 0,6%-9%, respectively, of total GHG emissions stemming from the five sub-branches investigated, based on Fleiter et al. (2013).

5.5 Economic evaluation: Specific levelized cost of heat from HTHPs

The specific LCOH with the application of HTHPs is used to compare the investment costs for changing the heat supply to the operating costs. It can be compared to the current operating costs of the benchmark scenario and hence allows a conclusion of which carbon tax would be required to make a switch profitable. Figure 11 compares the LCOH for the two waste heat scenarios, two HTHPs with varying capacities, and the benchmark scenario of combusting natural gas, incl. lowest and highest required carbon tax to levelize the costs. Figure 11 is based on the cost assumptions as displayed in Appendix A.

In the worst-case scenario, the specific LCOH results in 50 €/MWh for the larger HTHP (50 MW). The investment costs contribute by approximately 13€ /MWh and the costs of electricity contributed by 37 €/MWh. The smaller HTHP (8,2 MW) shows an increased LCOH in the same scenario, with 61 €/MWh. The investment costs are higher with the smaller HTHP than with the large HTHP and contribute 24 €/MWh (~45%).

In the best-case scenario**,** the specific LCOH results in 37 €/MWh for the HTHPs with the larger capacity (50 MW). The costs when using the large HTHP with less electricity requirements due to higher COPs results in a cost reduction of 13 €/MWh compared to the HTHP with the same capacity in the worst-case. While the specific investment costs stay the same as in the worst-case, the electricity costs are reduced to 24 €/MWh and make up ~67% of the LCOH. The smaller HTHP (8,2 MW) shows a similar trend. The LCOH results to 48 €/MWh, which exhibits the same reduction in price compared as recorded for the larger HTHP. Now that the electricity costs are reduced, the investment costs contribute 24 €/MWh. The best-case scenario with the smaller HTHPs is the only case in which the investment costs contribute half to the LCOH. In the other cases, the costs stemming from electricity always dominate the LCOH.

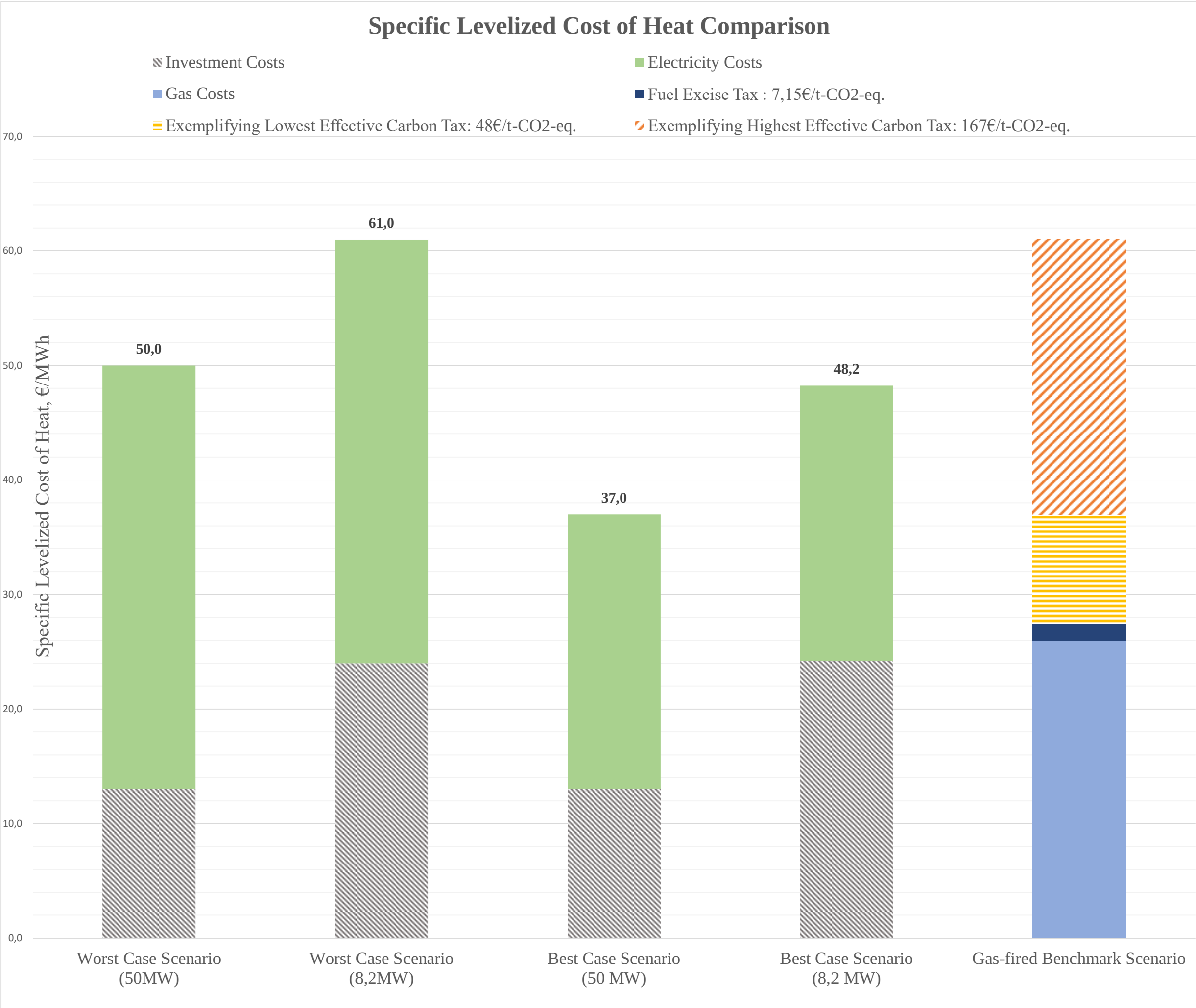

Figure 11. Comparison of specific Levelized Cost of Heat in €/MWh. Own figure.

In both scenarios, 38.904 units of the large HTHPs (50 MW) would be needed to cover the heating demand. In comparison, 237.215 units of the smaller HTHPs would be needed to cover the heating demand. For HTHPs manufacturers, this would translate to a significant and promising market potential ahead.

It can be seen that the HTHPs with the smaller capacity have an investment cost per MWh that is almost double as high as the larger capacity HTHPS. Zühlsdorf et al. (2019) found the same results in their case studies. The authors attribute this trend of decreasing investment costs to the theory of economy of scale, which is strongly visible in this case. The most cost-efficient alternative occurs when a large HTHP (50 MW) is used with high temperatures from direct process heat reuse. The LCOH then results to 37 €/MWh.

The specific cost of gas and the assumed average fuel excise tax for industrial players in Germany resulted in a LCOH of 27,43 €/MWh. Comparing this to the lowest LCOH achieved by the large HTHP in the best-case scenario, it becomes clear that it is not yet cost-competitive. It must be considered that the investment costs of the HTHP include capital investment and maintenance of the systems – the investment costs and maintenance costs of the gas-fired infrastructure is not considered. This allows to analyse how much the change to a *new* system from *existing* infrastructure costs for the industrial player. It could be found that to make the HTHPs system economically competitive, a carbon tax of minimum 48 €/t-CO_2-eq. is required to levelized the cost with the most cost-effective HTHPs. Further, a maximum carbon tax of 167 €/t-CO_2-eq. would be required to levelize the costs with the least cost-effective HTHP system.

In Zühlsdorf et al. (2019), the HTHPs were only competitive to natural gas boilers without a CO_2-tax when the electricity costs are as low as 35 €-50 €/MWh. In this analysis, the electricity costs are 85 €/MWh (BMWi, 2018). The HTHPs scenarios in this study are also not competitive with the benchmark scenario without adding a carbon tax.

Adding the existing average fuel excise tax means that Germany would need to have an industrial ECR of minimum 56 €/t-CO2-eq. (maximum 175 €/t-CO2-eq.) to make the switch to low-carbon heat production with HTHPs economical from the industrial perspective. This minimum required carbon tax is in the middle range of the recommendation of the High-level Commission on Carbon pricing of at least 33 €-66 €/t-CO_2-eq. in 2020, and 41 €-83 €/t-CO2-eq. in 2030, to reach the goals of the Paris Agreement (OECD, 2021a). In 2015, only 19% of German GHG emissions were taxed above 30 €/t-CO_2-eq., most of them not in industry (OECD, 2021a). In 2018, the German Environment Agency (UBA) calculated that each t-CO_2-eq. causes damage to the amount of 180 € (UBA, 2018b). Germany did not have any specific carbon tax for the industrial sector in 2018, except for the fuel excise costs, showing that the political incentive for industrial decarbonisation is not sufficient to produce large-scale change. The GHG emissions are not sufficiently priced to produce neither an economic incentive for decarbonisation efforts from the industrial perspective nor to cover the costs resulting from the environmental impacts of each t-CO_2-eq. exhausted.

5.6 Parameter manipulation

When manipulating the technical parameter of the efficiency of HTHPs from 60% to either 50% or 70%, the COP results change by the same percentage (see Table 4). Hence when altering the efficiency for HTHPs, the thermodynamic efficiency in form of COPs change predictably and linear. However, the COPs are not only affecting the technical evaluation, but also how much electricity is needed and hence how many GHG emissions can be abated. In comparison, the lower efficiency of 50% results in an increase of GHG emissions by 20% in the worst- and best-case scenario, while a higher efficiency of 70% leads to a decrease of GHG emissions by 14% for both scenarios. The results indicate the importance of HTHP efficiencies and a proportionally larger effect when the COPs decrease.

Table 4. Technical Parameter Manipulation: COP. Own table.

COP	**Initial Results (60% Efficiency)**	**Lower Value Results (50% Efficiency)**	**Upper Value Results (70% Efficiency)**
Worst Case	1,7 – 4,8	1,4 - 4	2 -5,6
Best Case	2,4 - 22,7	2 -19	2,8 – 26,4

When reducing the electricity price input by 50%, the results in the lower value change between 25% to 37%, depending on the share of investment costs that stays the same to the initial results (see Table 5). The cost-competitiveness of both types of HTHPs are significantly enhanced when the electricity priced is reduced. The large HTHP in the best-case scenario with a reduced electricity price is cost-competitive to the benchmark scenario, which indicates the importance of the electricity price for low-carbon technologies such as HTHPs. This also goes in line with Zühlsdorf et al. (2019) results that HTHPs were only competitive to when the electricity costs are as low as 35 €-50 €/MWh. The upper value results increase in the same range as the lower value results decrease, which is logical since the share of electricity to LCOH stays the same within both modifications. The upper value results are not cost-competitive to the benchmark scenario. Nonetheless, the best-case HTHP with the increased electricity price still stay within the same price range as the worst-case results of the initial results, which further indicates the importance of reusing direct process heat and hence enhance energy efficiency.

Table 5. Economic Parameter Manipulation: Electricity Price. Own table.

LCOH	**Initial Results (87 €/MWh)**	**Lower Value Results (44 €/MWh)**	**Upper Value Results (131 €/MWh)**
Worst Case			
50 MW	49 €/MWh	31 €/MWh	68 €/MWh
8,2 MW	61 €/MWh	43 €/MWh	79 €/MWh
Best Case			
50 MW	36 €/MWh	25 €/MWh	48 €/MWh
8,2 MW	48 €/MWh	36 €/MWh	60€/MWh

The emission factor for electricity plays a more crucial role for the variation of results (see Table 6). With a 35% lower emission factor for electricity, the worst-case GHG emissions abatement potential increases 16-fold, while the best-case results almost double. When the emission factor is increased by 10%, then the worst case exhibits almost four times more emissions than the initial scenario, and exhibit significantly more emissions from electricity than from the benchmark scenario of combusting natural gas on site. The best-case scenario nonetheless still results in a significant GHG abatement potential, 18% reduced compared to the initial results. Hence, the emission factor for electricity plays an important role for the systemic contributions of HTHPs, and with a lower emission factor of 302 g/kWh and direct process heat reuse, could abate up to 16% of total GHG emissions emitted by the five sub-branches in focus.

Table 6. Systemic Parameter Manipulation: Emission Factor Electricity. Own table.

EAP (% of total emissions of five branches)	**Initial Results (468 g/kWh)**	**Lower Value Results (302 g/kWh)**	**Upper Value Results (516 g/kWh)**
Worst Case	52 kt-CO_2-eq. (-0,6%)	892 kt-CO_2-eq. (-10%)	-191 kt-CO_2-eq. (+2%)
Best Case	885 kt-CO_2-eq. (-9%)	1492 kt-CO_2-eq. (-16%)	728 kt-CO_2-eq. (-7,8%)

6 Discussion

The technical assumptions for the processes and the HTHPs influence the results. The temperature ranges assumed, especially the direct exhaust temperatures, result in very high COPs, which do not necessarily mirror reality and are subject to change with different temperature levels. No technical details such as pressure drops, heat losses, and others are incorporated. It would require a more detailed engineering approach or a case study on plant-level. The amount and temperature of waste heat available influence how much electricity is needed. Due to the lack of data, the specific volumes have not been considered, assuming that large waste heat flows are available (Hita et al., 2011).

The generalized approach coupled with the reconstruction of the year 2018 entails some uncertainties. Energy efficiency improvements take place continuously in German industries, which means that the thermal energy demand of processes is likely decreasing over time. It is expected that the production volume of food and beverage products is stable or slightly increasing due to a strengthening of the industrial sector. Therefore, the energy efficiency improvements and the enhanced production volumes can be assumed to levelize themselves. Further, the German industrial landscape and its industrial players are relatively stable in the long run, and therefore the data for 2018 is considered representative until today. Economic inputs such as the electricity and the gas price fluctuate constantly, hence the parameter manipulation. By including the upper and lower variations of the electricity price and the emission factor for electricity, not only the technical results, but also the economic and systemic results could potentially be applied to other European food and beverages industries. The framework conditions vary significantly over temporal and geographic scopes, so the parameter ranges can help make the results more applicable to other contexts where technical standards are comparable.

The investment costs calculated by Zühlsdorf et al. (2019) are preliminary estimates. However, experts of the DLR confirmed the assumption that the HTHPs will range around 1000 €/kW, probably slightly above, due to a smaller size in the early research and the identified economies of scale, which then falls in line with the economic estimates used. The actual costing of an HTHPS always depends on the way it is integrated into existing processes and how systems needed to be modified to perform most optimally. This analysis cannot consider the individual integration and hence is using generalised investment estimates.

Gas-based heat is often produced in industrial CHP plants that cogenerate electricity and heat. They are more efficient than other electricity generation plants because heat is produced as a by-product. Efficient CHPs are further subject to fuel excise tax exemptions if the electricity is fed into the grid or district heat is produced (OECD, 2019). They also require less fuel than other power generation and hence the modern CHP plants are currently unbeatable when it comes to energy efficiency or economic competitiveness (BMWi, 2020b). Further, industrial CHPs can have very high capacities, which enhances their cost-effectiveness. Additionally, they are expected to replace non-CHP fossil-fuel-powered plants such as gas boilers (BMWi, 2020b). However, the BMWi (2020b) argues that after 2030, fossil-fuel-powered CHPs will see their role gradually decrease. Therefore, CHPs only have a long-term future if they run on renewable fuels. Renewable fuels, however, are expected to have limited availability or very high costs (BMWi, 2020b). This is important to consider in the industrial sector, where investment cycles are long, to reduce the danger of sunken costs or stranded assets.

Nonetheless, enhancing energetic efficiency is not the only priority. The decarbonisation of the energy system and the heat supply is also of high priority and urgency, especially considering the expected rapid increase of CO_2-taxation. Therefore there is a trade-off between an energy system with the highest energy efficiency still based on fossil fuels and decarbonisation of the energy system. The results of the best-case scenario show that a combination of the two priorities is possible. Reusing high-temperature waste heat flows efficiently and enhancing energy circularity is an essential part of making HTHPs more attractive, enhancing the environmental benefits, and increasing the cost-competitiveness against optimised fossil fuel systems. The analysis showed the importance of higher COPs in generating higher GHG emissions abatement potentials and thus enhancing the cost-competitiveness. Hence, not only electrification of the heat supply is needed, but a simultaneous increase in energetic efficiency by reusing waste heat streams.

The current and future energy system plays a crucial role in determining the environmental benefits of heat pumps, as demonstrated in the parameter manipulation of the emission factor. Suppose the German electricity generation is still largely based on fossil fuels, then the direct combustion of fuels for heat in, for example, CHPs shows fewer losses and hence is more efficient. The analysis showed that a process with a COP below 2,4 recorded higher GHG emissions from the electricity mix than from the combustion of natural gas due to the ratio of the emission factor of electricity and natural gas. Germany's coal exit, planned for the latest 2038, might lead to an increasing role of natural gas in the short run, which could hinder the developments of renewables, but would still lead to a decreasing emission factor. In the long run, the emission factor of electricity is expected to go towards zero due to renewable energy generation, which could then lead to the abatement potential of 2419 kt-CO_2-eq., which is 26% of the total GHG emissions of the five sub-branches. The increasing efficiency of gas-optimized infrastructure does not outweigh the limited development capabilities of this energy carrier, and is not able to compete with the zero-emission trajectory that electricity promises. Therefore, a renewable electricity-based future energy system is significantly more promising in the long-run, which must be considered for industrial players.

It is expected that the price of renewable electricity generation technologies will further decrease over the coming decade. The own generation of renewable electricity can have substantial economic benefits for industrial players: regarding emissions, efficiency of electricity transmissions, and price of electricity, especially when considering the dominance of the cost of electricity in the LCOH analysis. Even though own generation of electricity means more up-front investment costs, additional to HTHPs, in the long run it would make HTHPs significantly more cost-competitive.

The cost of natural gas in 2018 is used as a benchmark scenario in this study. Even though it is significantly cheaper than electricity, the cost of natural gas is expected to increase over time (Zühlsdorf et al., 2019). The reason is that fossil fuels are limited resources, and their prices are very susceptible to fluctuations in global trade. Further, with the elimination of accepting the combusting coal and oil due to GHG emissions, the demand for gas is expected to increase (Zühlsdorf et al., 2019). Increasing demand, especially for industrial use, can lead to scarcity and hence a price increase. Additionally, other political measures such as national and international carbon taxes on heating fuels can substantially affect the cost of gas in the future. Generally, the expected trend is that the market will become more and more beneficial for electricity-based solutions, such as HTHPs (Zühlsdorf et al., 2019).

In Germany, the renewable energy law (EEG) is a levy added to the electricity price for private consumers and industrial consumers (except the largest) to finance renewable energy generation. The current problem with the EEG levy is that it puts extra costs on electricity usage, resulting in Germany's household electricity prices being the most expensive in Europe 2020 (Eurostat, 2021). In 2018, the EEG levy laid at 6,8 ct/kWh for private consumers. For industrial consumers who are not exempt, the electricity price consists to 48% of non-refundable taxes (part of which can be the renewables levy) (BMWi, 2020a). The economic analysis showed that electricity costs play a dominating role in three of four scenarios. Recently, a debate about the EEG levy and its effects is gaining more momentum in Germany. It is argued that this financing model of renewable energy does not fulfil its original intend anymore. Instead, the pressure for finding market-based solutions is rising. One idea is to implement a carbon tax instead of the EEG levy, supporting and financing the transition to low-carbon technologies and sustainable solutions (Neumann, 2021). The result would be to relieve electricity consumers by lower electricity prices, make sector coupling easier and promote electrification in industry (Neumann, 2021). The parameter manipulation of the electricity price has shown that a lower electricity price can make the larger HTHP with direct process heat reuse cost-competitive, even without a carbon tax or considering the maintenance costs of gas infrastructure.

The investment costs of HTHPs and other emerging low-carbon technologies require large up-front investments compared to the existing gas-optimised infrastructure. The IEA (2020) argues that with increasing installed cumulative capacity and component-specific learning rates, the cost of HTHPs will decrease over time. Apart from market developments, a carbon tax is not the only mechanism to support low-carbon transitions. Further political interventions, such as subsidies for low-carbon technologies such as HTHPs, could significantly help to level out the fluctuating electricity prices and help industrial players overcome the initial investment hurdle.

This study is not comparing any other alternative heating systems to the cost-effectiveness of HTHPs due to the sheer complexity of the issue. There might be more economical or more efficient alternatives in particular cases, such as the combustion of biogas, biofuels, hydrogen, and others. A direct comparison of different alternatives requires an in-depth analysis of case studies with energy modelling, which is not the intend of this study.

When it comes to integrated systemic sustainability, it is important to consider the whole picture. The largest GHG emissions in the food and beverages industry do not occur in the processing stage of the products itself. They often occur upstream at the farm level, especially in the meat and dairy industry. Other environmental impacts, such as land-use change due to fodder production, energy use for large-scale farms, water usage, transport, and more, can also lead to indirect GHG emissions and other environmental impacts associated with the final product. The processing in the industrial facility often only has a small contribution to the final environmental footprint of the product. It is important to understand the share of environmental impacts along the whole value chain when discussing systemic sustainability. Nonetheless, it is also important to improve the energetic efficiency, circularity and reduce GHG emissions all along the value chain, thus also in processing where the reduction of GHG emissions requires complex and expensive infrastructural and technological changes Further, sectoral GHG emission reduction targets (such as industry-, agriculture-, transport-specific targets) are associated to sectors, and not to the value chain of specific products. Another aspect in the transition to a low-carbon energy system and the decarbonisation of the industrial sector is the material-intensiveness of technologies. Materials and their value chains also play important roles in discussing systemic sustainability, and can potentially create trade-offs between low-carbon, material- and energy-efficient industries.

7 Limitations and future research

7.1 Limitations

The systemic nature of this study exhibits several limitations. First, the existing heat recovery practices that are already implemented, strongly depend on the case of each industrial plant. Second, no generic studies are outlining existing common heat recovery practices and volumes on process-level, including temperature levels, in the German industrial landscape. Generalizing those could have led to an overestimation of the results. Hence, the two waste heat scenarios with different available temperatures are used to represent the average but do not fully represent reality.

This study does not perform calculations for the thermodynamic optimum (Pinch analysis) or energy efficiency improvements through process optimisation. Therefore, only the status-quo and the alternative heating through HTHPs are evaluated without considering possible changes to the system. Further, no heat losses through energy conversion are considered due to the heterogeneity of the technologies used. This leads to a potential underestimation of the natural gas usage and hence of resulting GHG emissions of the benchmark. Further, the simultaneous cooling capacity of HTHPs is not considered, which could show significant improvements in the techno-economic potential and the GHG abatement potential. For the simultaneous provision of process heating and cooling, an integrated energy modelling is necessary, which cannot be performed on a generic and systemic level.

The bottom-up approach leads to more in-depth analysis but simultaneously results in limited coverage of processes. The techno-economic potential is expected to increase by increasing the number of processes for the analysis, which was outside the scope of this study.

7.2 Future Research

Several possibilities for future research can be outlined. First, the techno-economic potential and the systemic contributions must be evaluated for more processes and more industrial branches to increase the limited coverage.

Further, specific case studies of industrial plants enable a more detailed analysis of existing practices. This allows for more detailed modelling of the energy and waste flows and allows for more specific results.

Lastly, more systemic and case studies can be performed for other technologies that enable industrial decarbonisation. This would also allow for a comparison of different alternative heating systems, such as biomass, hydrogen, and more, to the HTHP integration. Other systemic studies could further include future trend projections and include scenarios with a more future-oriented approach.

8 Conclusion

This study investigated the techno-economic potential of integrating HTHPs on process-level <250°C into the German food and beverages industry. It assessed the environmental benefits in GHG emissions abatement potential for two waste heat, the worst-case with an average of 45°C waste heat, and the best-case with direct process exhaust heat. Further, it discussed the political and economic framework conditions present in Germany and their impacts on the profitability of HTHPs.

The five most energy-intense sub-branches are sugar production, dairy processing, bakery products, meat processing, and beer production. The most thermal energy-intensive processes consist mainly of pasteurisation, cooking, evaporation, and drying processes, which often require removing large quantities of water. The technical potential for applying HTHPs to the processes is 12 TWh in 2018. The electricity demand to cover the technical potential lies between 3,3-5 TWh. By applying HTHPs to the processes, up to 9% of current GHG emissions stemming from the five sub-branches can be abated. With a reduced emission factor for electricity by 35%, the GHG emission abatement potential increases to 16%.

The LCOH lies between 37 €/MWh-61 €/MWh. The contribution of the electricity costs dominates the LCOH in all scenarios. The current high electricity price of 87 €/MWh makes the transition to the electrification of industries not yet cost-competitive. The lowest LCOH achieved by the 50 MW HTHP in the best-case scenario was not cost-competitive with the operating costs of the benchmark scenario. For the lowest LCOH to become cost-competitive, a carbon tax of min. 48 €/t-CO_2-eq. is required. However, when the electricity price is reduced by 50%, then this scenario becomes cost-competitive without a CO_2 tax. The results show that the GHG emissions in the German industry are not sufficiently priced to produce neither an economic incentive for decarbonisation efforts nor to cover the costs resulting from the environmental impacts of each t-CO_2-eq. exhausted. Further, the results feed into a discussion recently gaining momentum in Germany that the EEG levy used to finance the generation of renewable electricity should be restructured to a) implement a carbon taxation instead to finance a low-carbon transition, and b) thus make electricity cheaper and foster electrification in industry.

HTHPs can offer a substantial contribution to industrial decarbonisation and support reaching the tightened industrial climate targets. To avoid a trade-off between enhancing energetic efficiency of the existing energy system or the decarbonisation of the latter, not only the electrification through HTHPs is crucial, but simultaneously reusing high temperature waste heat streams to increase the process efficiency. It further enhances the costs-competitiveness and GHG abatement potential of HTHPs drastically. The HTHP market is entering a promising decade for manufacturers, research, and industrial players. The timely investment into low-carbon technologies such as HTHPs can drastically reduce the risk of sunken costs and make industrial decarbonisation cost-effective from the industrial perspective. Furthermore, the expected increase in carbon prices will make the transition towards low-carbon technologies such as HTHPs even more cost-competitive. Consequently, now is a crucial and decisive period for industrial players to evaluate alternative technologies for the generation of low-carbon process heat. More research is needed to demonstrate the dormant potential of HTHPs and its significant impacts on systemic transformation towards a low-carbon industry in Germany, in Europe, and beyond.

Bibliography

AEE Intec. (2013). *Efficiency Finder: Salami and sausages*. Retrieved May 2021, from http://wiki.zero-emissions.at/index.php?title=Salami_and_sausages

Agora Energiewende . (2017). *Eine Zukunft für die Lausitz: Elemente eines Strukturwandelkonzepts für das Lausitzer Braunkohlerevier.* Berlin: Agora Energiewende.

Agora Energiewende & Wuppertal Institut. (2019). *Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen.* Berlin : Agora Energiewende.

Agora Energiewende. (2021). *Die Energiewende im Corona Jahr: Stand der Dinge 2020. Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2021.* Berlin: Agora Energiewende.

Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., & Bertsch, S. (2018). High Temperature Heat Pumps: Market Overview, State of the Art, Research Status, Refrigerants, and Application Potential. *International Refrigeration and Air Conditioning Conference. Paper 1876.* Purdue University Purdue e-Pubs.

Biogasrat. (2017). *Zuckerfabrik Anklam beendet die Ruebenkampagne 2016/17*. Retrieved June 2021, from https://www.biogasrat.de/2017/01/13/zuckerfabrik-anklam-beendet-die-ruebenkampagne-201617/

BLE. (2018). *Bericht zur Markt- und Versorgungslage Zucker 2018.* Bonn: Bundesanstalt für Landwirtschaft und Ernährung.

Blok, K., & Nieuwlaar, E. (2020). *Introduction to Energy Analysis* (3rd Edition ed.). Routledge.

BMEL Statistik. (2018). *Bundesministerium für Ernährung und Landwirtschaft, Ernährung & Fischerei, Lebensmittelindustrie: Energieverbrauch des Produzierenden Ernährungsgewerbes [SJT-4101700-2018]*. Retrieved May 2021, from https://www.bmel-statistik.de/index.php?id=1030&L=0.

BMEL Statistik. (2020). *Bundesministerium für Ernährung und Landwirtschaft, Versorgungsbilanz Fleisch ab 1991 [DFT-0200502-0000]*. Retrieved May 2021, from https://www.bmel-statistik.de/ernaehrung-fischerei/versorgungsbilanzen/fleisch/

BMWi. (2018). *Internationaler Energiepreisvergleich für Industrie, Erdgas, und Elektrizität (Industrie); Tabellen 29 & 29a der Gesamtausgabe Energiedaten*. Retrieved May 2021, from https://www.bmwi.de/Redaktion/DE/Infografiken/Energie/Energiedaten/Energiepreise-und-Energiekosten/energiedaten-energiepreise-39.html

BMWi. (2020a). *EEG-Umlage 2021: Fakten & Hintergründe.* Berlin: BMWi.

BMWi. (2020b, July). *Electricity Market of the Future: Combined heat and power.* Retrieved June 2021, from https://www.bmwi.de/Redaktion/EN/Artikel/Energy/modern-power-plant-technologies.html

Brauer Bund. (2019). *Statistik Brauwirtschaft in Zahlen Deutschland 2011-2019*. Retrieved May 2021, from https://brauer-bund.de/wp-content/uploads/2020/07/200508-Statistik-Brauwirtschaft-in-Zahlen-Deutschland-2011-2019-1.jpg

Brückner, S., Liu, S., Miró, L., M. R., & Cabeza, L. F. (2015). Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. *Applied Energy 151* , pp. 157-167.

BVDF. (2020). *Geschäftsbericht 2019/2020* . Bundesverband der Deutschen Fleischwarenindustrie e.V.

BVE. (2020a). ERNÄHRUNGSINDUSTRIE 2020. Berlin: Bundesvereinigung der Deutschen Ernährungsindustrie.

BVE. (2020b). *Jahresbericht 2019/20.* Berlin: Bundesvereinigung der Deutschen Ernährungsindustrie.

Chowdhury, J. I., Asfand, F., Y. H., Balta-Ozkan, N., Varga, L., & Patchigolla, K. (2019). Waste heat recovery potential from industrial bakery ovens using thermodynamic power cycles. Poland: PROCEEDINGS OF ECOS 2019 - THE 32ND INTERNATIONAL CONFERENCE ON EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS.

Clean Energy Wire. (2019, July). *Industrial Power Prices and Energiewende*. Retrieved from https://www.cleanenergywire.org/industrial-power-prices-and-energiewende

Climate Change News. (2021, May). *To meet net zero by 2050 we need a long-term vision for carbon pricing*. Retrieved from Climate Home News: https://www.climatechangenews.com/2021/05/26/meet-net-zero-2050-need-long-term-vision-carbon-pricing/

Comello, S., Glenk, G., & Reichelstein, S. (2017). Levelized Cost of Electricity Calculator. Stanford: Stanford Graduate School of Business . Retrieved June 2021, from http://stanford.edu/dept/gsb_circle/sustainable-energy/lcoe

dena. (2019). *Process heat in industry and commerce: Technology solutions for waste heat utilisation and renewable provision.* Berlin: Deutsche Energie-Agentur GmbH (dena).

Destatis. (2018). *Statistisches Bundesamt (Destatis), Genesis-Online: Jahreserhebung über die Energieverwendung der Betriebe im Verarbeitenden Gewerbe, im Bergbau und in der Gewinnung von Erden und Steinen [43531-0001]*. Retrieved May 2021, from https://www-genesis.destatis.de/genesis/online?operation=statistic&levelindex=&levelid=&code=43531&option=table&info=on#abreadcrumb

Destatis. (2021, June 2). *Statistisches Bundesamt Destatis, Energy Use Data*. Retrieved May 2021, from Destatis: Stastisches Bundesamt: https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Energy/Use/_node.html

DLR. (2021a). *DLR Department of the High-Temperature Heat Pump (HTP)*. Retrieved June 3, 2021, from https://www.dlr.de/di/en/desktopdefault.aspx/tabid-15753/

DLR. (2021b). *DLR Institut für CO2-arme Industrieprozesse*. Retrieved June 3, 2021, from https://www.dlr.de/di/desktopdefault.aspx/tabid-13342/23331_read-54008/

EHPA Stats. (2021, June 2). *Heat Pumps Sales Overview*. Retrieved from European Heat Pump Association: http://stats.ehpa.org/hp_sales/story_sales/

European Copper Institute . (2018). *Heat Pumps: Integrating technologies to decarbonise heating and cooling* . European Copper Institute: Copper Alliance .

Eurostat. (2021). *Electricity price statistics: Electricity prices (including taxes) for household consumers, second half 2020*. Retrieved June 2021, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics

Fleiter, T., Schlomann, B., & Eichhammer, W. (2013). *Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien – Einsparpotenziale, Hemmnisse und Instrumente.* Stuttgart : Fraunhofer Verlag.

Gühl, S., Schwarz, M., & Schimmel, M. (2020). *Energiewende in der Industrie: Potenziale und Wechselwirkungen mit dem Energiesektor; Branchensteckbrief der Nahrungsmittelindustrie.* Navigant Energy Germany .

Heinz, G., & Hautzinger, P. (2007). *Meat Processing Technology - For Small- To Medium-Scale Producers.* Bangkok: FAO.

Hita, A., Djemaa, A., Seck, G., & Guerassimoff, G. (2011). Assessment of the potential of heat recovery in food and drink industry by the use of the TIMES model. *ECEEE 2011 SUMMER STUDY; Energy efficiency first: The foundation of a low-carbon society*.

Hofer, E. (2018). *The Uncertainty Analysis of Model Results: A Practical Guide.* Dorfen, Germany: Springer International Publishing AG.

IEA. (2020). *Energy Technology Perspectives 2020.* Paris: IEA.

IEA. (2021). *Net Zero by 2050: A roadmap for the global energy sector* . Paris: IEA.

Kalinowski, R. (2005). *Kehrwert der Thermischen Energie - Absorptionskälteanlagen, Wärmepumpen, Strahlpumpen als alternative Technik?* Brauindustrie.

KEI. (2021, June). *Klimaschutz in der Industrie*. Retrieved from Kompetenzzentrum Klimaschutz in energieintensiven Industrien : https://www.klimaschutz-industrie.de/themen/klimaschutz-in-der-industrie/

Kosmadakis, G. (2019). Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. *Applied Thermal Engineering 156* , pp. 287-298.

Lauterbach, C., Schmitt, B., & Vajen, K. (2011). *Das Potential solarer Prozesswärme in Deutschland.* Kassel: Institut für Thermische Energietechnik Universität Kassel.

Maaß, C., Sandrock, M., & Fuß, G. (2018). Strategische Optionen zur Dekarbonisierung und effizienteren Nutzung der Prozesswärme und -kälte. Hamburg Institut.

Marina, A., Spoelstra, S., Zondag, H., & Wemmers, A. (2021, January 31). An estimation of the European industrial heat pump market potential. *Renewable and Sustainable Energy Reviews 139: 110545*.

MIDDEN . (2021). *The database - Manufacturing Industry Decarbonisation Data Exchange Network*. Retrieved May 2021, from https://www.pbl.nl/en/middenweb/the-database

MIV. (2020a). *Fakten Milch Informationsbroschüre des Milchindustrie-Verbandes e.V.: Milch und mehr –die deutsche Milchwirtschaft auf einen Blick.* Berlin: Milchindustrie-Verband e.V.

MIV. (2020b). Milchindustrie-Verband e.V. Beilage zum Geschäftsbericht 2019/2020: Zahlen -Daten - Fakten. Berlin: Milchindustrie-Verband e.V.

Müller-Lindenlauf, M., Cornelius, C., Gärtner, S., Reinhardt, G., Rettenmaier, N., & Schmidt, T. (2014). *Umweltbilanz von Milch und Milcherzeugnissen: Status Quo und Ableitung von Optimierungspotenzialen* . Heidelberg: ifeu.

Neumann, P. D. (2021, April 1). *Debate Energy: EEG-Umlage Nach der Novellierung ist vor der Revision.* Retrieved June 2021, from https://debate.energy/a/eeg-umlage-nach-der-novellierung-ist-vor-der-revision/

OECD. (2019). Supplement to taxing energy use: Taxing energy use 2019: Country Note - Germany. Paris: OECD Publishing.

OECD. (2021a). *Effective Carbon Rates 2021: Pricing Carbon Emissions through Taxes and Emissions Trading.* Paris: OECD Publishing.

OECD. (2021b). Supplement to Effective Carbon Rates 2021: Germany. *Effective Carbon Rates 2021*. Paris: OECD Publishing.

Oehler, J., Gollasch, J., Tran, A. P., & Nicke, E. (2021). Part Load Capability of a High Temperature Heat Pump with Reversed Brayton Cycle. *13th IEA Heat Pump Conference* (pp. 000-000). Jeju, Korea: IEA HPT.

Pierrot, J., & Schure, K. (2020). *Decarbonisation Options For The Dutch Dairy Processing Industry.* Netherlands: MIDDEN, PBL, TNO.

Rademaker, K., & Marsidi, M. (2019). *Decarbonisation options for the Dutch sugar industry*. Netherlands: TNO MIDDEN.

Ramírez, C., Patel, M., & Blok, K. (2006). From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry. *Energy 31* , pp. 1984–2004.

Rehfeldt, M., Fleiter, T., & Toro, F. (2018, October 5). A bottom-up estimation of the heating and cooling demand in European industry. *Energy Efficiency 11*, pp. 1057-1082.

Scheer, F. M. (2014). Thermal Process Engineering for Brewers: Basics in Theory and Practice. Krones Inc.

Schlosser, F., Jesper, M., Vogelsang, J., Walmsley, T., Arpagaus, C., & Hesselbach, J. (2020). Large-scale heat pumps: Applications, performance, economic feasibility and industrial integration. *Renewable and Sustainable Energy Reviews 133* .

Spoelstra, S. (2014, November). Industrial Heat Pumps Presentation . Netherlands: ECN - Energy Research Centre of the Netherlands.

Stathopoulos, P. (2021, May). The design process of the DLR Brayton cycle High Temperature Heat Pump (HTHP). *Deep dive - IEA Annex 58*. DLR.

Statista. (2020a). *Anzahl der Betriebe, Filialen und Verkaufsstellen im Bäckerhandwerk in Deutschland in den Jahren 1990 bis 2019*. Retrieved May 2021, from https://de.statista.com/statistik/daten/studie/29282/umfrage/anzahl-der-baeckereien-in-deutschland-zeitreihe/

Statista. (2020b). *Backwaren*. Retrieved May 2021, from https://de.statista.com/themen/2684/backwaren/

Statista. (2020c). *Fleischverarbeitung in Deutschland*. Retrieved May 2021, from https://de.statista.com/themen/4069/fleischverarbeitung-in-deutschland/

Statista. (2021). *Entwicklung des CO2-Emissionsfaktors für den Strommix in Deutschland in den Jahren 1990 bis 2019*. Retrieved May 2021, from https://de.statista.com/statistik/daten/studie/38897/umfrage/co2-emissionsfaktor-fuer-den-strommix-in-deutschland-seit-1990/

The Guardian. (2021, April 30). *'Historic' German ruling says climate goals not tough enough*. Retrieved from The Guardian: https://www.theguardian.com/world/2021/apr/29/historic-german-ruling-says-climate-goals-not-tough-enough

TNO. (2020). *Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat.* Netherlands: TNO.

UBA. (2018a). *Climate Change: CO2 Emission Factors for Fossil Fuels.* Berlin: Umweltbundesamt.

UBA. (2018b, November). *Hohe Kosten durch unterlassenen Umweltschutz: Eine Tonne CO2 verursacht Schäden von 180 Euro – Umweltbundesamt legt aktualisierte Kostensätze vor.* Retrieved from Umweltbundesamt: https://www.umweltbundesamt.de/presse/pressemitteilungen/hohe-kosten-durch-unterlassenen-umweltschutz

UBA. (2020, November). *Der Europäische Emissionshandel.* Retrieved from Umweltbundesamt : https://www.umweltbundesamt.de/daten/klima/der-europaeische-emissionshandel#treibhausgas-emissionen-deutscher-energie-und-industrieanlagen-im-jahr-2019

UBA. (2021, May 4). *Umweltbundesamt Indikator: Emission von Treibhausgasen*. Retrieved May 2021, from Umweltbundesamt: https://www.umweltbundesamt.de/daten/umweltindikatoren/indikator-emission-von-treibhausgasen#die-wichtigsten-fakten

Vorderwülbecke, A., Korflür, I., & Löckener, R. (2018). *Branchenanalyse Brot-und Backwarenindustrie* . Stuttgart: Hans-Böckler-Stiftung .

Wolf, S., & Blesl, M. (2016). *Model-based quantification of the contribution of industrial heat pumps to the European climate change mitigation strategy.* European Council for an Energy Efficient Economy .

Wolf, S., Fahl, U., Blesl, M., Voß, A., & Jakobs, R. (2014). *Analyse des Potenzials von Industriewärmepumpen in Deutschland* . Stuttgart: Universität Stuttgart Institut für Energiewirtschaft und Rationelle Energieanwendung.

Wolf, S., Lambauer, J., Blesl, M., Fahl, U., & Voß, A. (2012). Industrial heat pumps in Germany: Potentials, technological development and market barriers. *ECEEE 2012 SUMMER STUDY on Energy efficiency in industry.*

ZREU. (2000). *Minderung öko- und klimaschädigender Abgase aus industriellen Anlagen durch rationelle Energienutzung - Großbäckerei -.* Augsburg: Bayerisches Landesamt für Umweltschutz, Zentrum für rationelle Energieanwendung und Umwelt GmbH (ZREU).

Zühlsdorf, B., Bühlera, F., Bantlec, M., & Elmegaarda, B. (2019). Analysis of technologies and potentials for heat pump-based process heat . *Energy Conversion and Management: X 2* .

Appendices

Appendix A: Numeric assumptions and sources

Table 7. Appendix A: Overview of all numeric data assumptions and sources. Own table.

Industry-specific Assumptions	Max Sink Temp.	Average exhaust Temp.	Specific thermal energy consumption	Production Volume /2018
Sugar				
Pulp pressing & drying	550°C *Gühl et al. (2020)*	111,5°C *Rademaker & Marsidi (2019)*	6,08GJ/ton dried pulp *MIDDEN (2021)*	
Evaporation & Crystallization	135°C *Gühl et al. (2020)*	50°C *Rademaker & Marsidi (2019)*	2,94GJ/ton white sugar *MIDDEN (2021)*	5197000 tons *BLE (2018)*
Dairy				
Evaporation & Spray drying	180°C *Gühl et al. (2020)*	75°C *Pierrot & Schure (2020)*	7,85GJ/ton dried milk product *Gühl et al. (2020)*	725300 tons *MIV (2020b)*
UHT Treatment	142°C *Gühl et al. (2020)*	80°C *Pierrot & Schure (2020)*	0,4GJ/ton milk *Müller-Lindenlauf et al. (2014)*	4355600 tons *MIV (2020b)*
Bakery				
Baking	180°C *Fleiter et al. (2013)*	150°C *Chowdhury et al. (2019)*	0,061GJ/kg baked product *ZREU (2000)*	1914050000 kg *Statista (2020b)*
Pasteurisation	202°C *ZREU (2000)*	190°C *ZREU (2000)*	0,003GJ/kg perishable product *ZREU (2000)*	118540000 kg *Statista (2020b)*
Meat				
Sausage Products Thermal treatment	80°C *Heinz & Hautzinger (2007)*	45°C *Heinz & Hautzinger (2007)*	3,23GJ/sausage product *AAE Intec (2013)*	1551045 tons *BVDF (2020)*
Beer				
Mashing	100°C *Fleiter et al. (2013)*	76°C *Fleiter et al. (2013)*	0,007GJ/hectoliter *Scheer (2014)*	93652000 hectoliters
Wort Boiling	100°C *Fleiter et al. (2013)*	100°C *Fleiter et al. (2013)*	0,034GJ/hectoliter *Lauterbach et al. (2011)*	93652000 hectoliters *Brauer Bund (2019)*
Technical Assumptions				
	HTHPs Technical potential			
		Efficiency	60% Carnot *Hita et al. (2011); Marina et al. (2021)*	
		Temperature	<250°C	

			DLR (2021a)	
	Worst Case Scenario			
		Waste Heat Temp.	45°C *Hita et al. (2011)*	
	Best Case Scenario			
		Process exhaust		
			See above	
	Annual operating hours			
		Sugar	2900h/a *Biogasrat (2017)*	
		Others	7000h/a *Zühlsdorf et al. (2019)*	
	Largest production facilities			
		All branches	>10 mio. € turnover/a *Vorderwülbecke et al. (2018)*	
Economic Assumptions for HTHPs				
	Total Capital Investments Costs (TCI) HTHPs			
		Capacity 8.2 MW	15,35 mio. € *Zühlsdorf et al. (2019)*	
		Capacity 50 MW	48,32 mio. € *Zühlsdorf et al. (2019)*	
	Capital recovery factor (CRF)			
		Interest rate	5% *Zühlsdorf et al. (2019)*	
		Lifetime	20 years *Zühlsdorf et al. (2019)*	
		CRF	0,08 *Zühlsdorf et al. (2019)*	
Fuel Assumptions				
	Electricity			
		Emission factor/2018	468g CO_2-eq/kWh *Statista (2021)*	
		Specific cost of electricity, Industry Price in 2018	87€/MWh *BMWi (2018)*	
	Natural Gas			

		Emission Factor/2018	55,9kg CO_2-eq./GJ *UBA (2018a)*	
		Specific cost of natural gas, industry Price in 2018	26€/MWh *BMWi (2018)*	
		Industrial fuel excise tax/2018	1,43€/MWh & 7,15€/t-CO2-eq *OECD (2019)*	

Appendix B: Calculations

Emission Factor Electricity Calculations

Table 8. Appendix B: Emission Factor Electricity Mix. Own table.

Technology	g CO2 / kWhth	Efficiency	g CO2 / kWhel	2018	Emissions in g CO2 /kWhel2018	Upper bound	Emissions in g CO2 /kWhel up	Lower bound	Emissions in g CO2 /kWhel low
Lignite	360	30%	1200	24,10%	287	27,80%	334	0,00%	0
Hard coal	340	36%	949	14%	132,9	18%	171	14%	133
Nuclear	0			13,30%	0	13,30%	0	13,30%	0
Renewables	0			40,20%	0	40,20%	0	40,20%	0
Gas	200	40%	500	7,40%	37	0,00%	0	31,50%	158
Oil + Others	280	25%	1120	1,00%	11	1,00%	11,2	1,00%	11
Summe				**100,00%**	**468**	**100,00%**	**516**	**100,00%**	**302**

Step 2: Thermal Energy Demand & GHG Emissions

Table 9. Appendix B: Step 2 calculations. Own table.

for 2018	SEC_{th}	Unit / Unit	APV	Unit	Q_D	Unit	GHG $emissions_{gas}$	Unit	Production facilities
Sugar									20
Evaporation & Crystallization	2,94	GJ/ton white sugar	5197000	Tons	15279180	GJ	854106162	kg CO_2-eq.	
Dairy									155
Evaporation & Spray drying	7,85	GJ/ton dry milk product	725300	Tons	5693605	GJ	318272519,5	kg CO_2-eq.	
UHT Treatment	0,4	GJ/ton milk	4355600	Tons	1742240	GJ	97391216	kg CO_2-eq.	
Bakery									10491
Baking	0,0061	GJ/kg baked product	1914050000	Kg	11675705	GJ	652671909,5	kg CO_2-eq.	
Pasteurization	0,0003	GJ/kg perishable product	118540000	Kg	35562	GJ	1987915,80	kg CO_2-eq.	
Meat									1400
Sausage products thermal treatr	3,23	GJ/t sausage product	1551045	Tons	5009875,35	GJ		kg CO_2-eq.	
Beer									1548
Mashing	0,007	GJ/hectolitre	93652000	Hectolitre	655564	GJ	36646027,6	kg CO_2-eq.	
Wort Boiling	0,034	GJ/hectolitre	93652000	Hectolitre	3184168	GJ	177994991,2	kg CO_2-eq.	
Σ					**43275899,35**	**GJ**	**2139070742**	**kg CO_2-eq.**	

Step 3: Technical evaluation: COPs & Technical Potential

Table 10. Appendix B: Step 3 calculations. Worst Case. Own table.

Worst Case Scenario: (average waste heat temp: 45°C)								
COPcarnot = TP* / (TP*-TW*)	Sugar	Dairy		Bakery		Meat	Beer	
	Evaporation & Crystallisa	Evaporation 8	UHT	Baking	Pasteurisatior	Sausage productior	Mashing	Wort Boiling
Max Temperature of heat demand (sink)	135°C	180°C	142°C	180°C	202°C	80°C	100°C	100°C
TP* = TP Max + P	140°C	185°C	147°C	185°C	207°C	85°C	105°c	105°C
TP* in K	413,15	458,15	420,15	458,15	480,15	358,15	378,15	378,15
Temperature of waste heat (source)	45°C	45°C	45°C	45°C	45°C	45°C	45°C	45°C
TW* = TW Max - P	40°C	40°C	40°C	40°C	40°C	40°C	40°C	40°C
TW* in K	313,15	313,15	313,15	313,15	313,15	313,15	313,15	313,15
COPcarnot	4,13	3,16	3,93	3,16	2,88	7,96	5,82	5,82
COPreal (efficiency 60%)	**2,48**	**1,90**	**2,36**	**1,90**	**1,73**	**4,78**	**3,49**	**3,49**

Table 11. Appendix B: Step 3 calculations. Best Case. Own table.

Best Case Scenario: (direct exhaust waste heat)								
COPcarnot = TP* / (TP*-TW*)	Sugar	Dairy		Bakery		Meat	Beer	
	Evaporation & Crystallisa	Evaporation &	UHT	Baking	Pasteurisation	Sausage production	Mashing	Wort Boiling
Max Temperature of heat demand (sink)	135°C	180°C	142°C	180°C	202°C	80°C	100°C	100°C
TP* = TP Max + P	140°C	185°C	147°C	185°C	207°C	85°C	105°c	105°C
TP* in K	413,15	458,15	420,15	458,15	480,15	358,15	378,15	378,15
Temperature of waste heat (source)	50°C	75°C	80°C	150°C	190°C	45°C	76°C	100°C
TW* = TW Max - P	45°C	70°C	75°C	145°C	185°C	40°C	72°C	95°C
TW* in K	318,15	343,15	348,15	418,15	458,15	313,15	345,15	368,15
COP*Carnot*	4,35	3,98	5,84	11,45	21,83	7,96	6,30	37,82
COPreal (efficiency 60%)	**2,61**	**2,39**	**3,50**	**6,87**	**13,10**	**4,78**	**3,78**	**22,69**

Table 12. Appendix B: Step 3 calculations. Technical Potential. Own table.

Total Suitable Q_D	43275899,4	GJ
Technical potential / a (2018)	12,021	TWh

Step 4: Systemic Contributions: Electricity Use & GHG emissions abatement potential

Table 13. Appendix B: Step 4 calculations, GHG emissions abatement potential, Best Case. Own Table.

WORST CASE SCENARIO	Q_D in GJ	E_{el} in GJ	E_{el} in KWh	GHG Emissions$_{el}$	Unit	GHG emissions$_{gas}$	Unit	EAP	Unit
Sugar									
Evaporation & Crystallisation	15279180	6160959,68	1711391379	800,93	kt CO_2-eq.	854,11	kt CO_2-eq.	53,17	kt CO_2-eq.
Dairy									
Evaporation & Spray drying	5693605	2996634,21	832405051	389,57	kt CO_2-eq.	318,27	kt CO_2-eq.	-71,29	kt CO_2-eq.
UHT Treatment	1742240	738237,29	205067553,9	95,97	kt CO_2-eq.	97,39	kt CO_2-eq.	1,42	kt CO_2-eq.
Bakery									
Baking	11675705	6145107,89	1706988071	798,87	kt CO_2-eq.	652,67	kt CO_2-eq.	-146,20	kt CO_2-eq.
Pasteurisation	35562	20556,07	5710064,948	2,67	kt CO_2-eq.	1,99	kt CO_2-eq.	-0,68	kt CO_2-eq.
Meat					kt CO_2-eq.				
Sausage products thermal treatme	5009875,35	1048091,08	291138739,5	136,25	kt CO_2-eq.	280,05	kt CO_2-eq.	143,80	kt CO_2-eq.
Beer									
Mashing	655564	187840,69	52178386,22	24,42	kt CO_2-eq.	36,65	kt CO_2-eq.	12,23	kt CO_2-eq.
Wort Boiling	3184168	912369,05	253437875,9	118,61	kt CO_2-eq.	177,99	kt CO_2-eq.	59,39	kt CO_2-eq.
∑	**43275899,35**	**18209795,96**	**5058317122**	**2367,29**	**kt CO2-eq.**	**2419,12**	**kt CO2-eq.**	**51,83**	**kt CO2-eq.**

Table 14. Appendix B: Step 4 calculations, GHG emissions abatement potential, Worst Case. Own Table

BEST CASE SCENARIO	Q_D in GJ	E_{el} in GJ	E_{el} in KWh	GHG Emissions$_{el}$	Unit	GHG emissions$_{gas}$	Unit	EAP	Unit
Sugar									
Evaporation & Crystallisation	15279180	5854091,95	1626149663	761,04	kt CO_2-eq.	854,11	kt CO_2-eq.	93,07	kt CO_2-eq.
Dairy									
Evaporation & Spray drying	5693605	2382261,51	661744601,2	309,70	kt CO_2-eq.	318,27	kt CO_2-eq.	8,58	kt CO_2-eq.
UHT Treatment	1742240	497782,86	138274122,1	64,71	kt CO_2-eq.	97,39	kt CO_2-eq.	32,68	kt CO_2-eq.
Bakery									
Baking	11675705	1699520,38	472092770,7	220,94	kt CO_2-eq.	652,67	kt CO_2-eq.	431,73	kt CO_2-eq.
Pasteurisation	35562	2714,66	754077,2794	0,35	kt CO_2-eq.	1,99	kt CO_2-eq.	1,64	kt CO_2-eq.
Meat									
Sausage products thermal treatme	5009875,35	1048091,08	291138739,5	136,25	kt CO_2-eq.	280,05	kt CO_2-eq.	143,80	kt CO_2-eq.
Beer									
Mashing	655564	173429,63	48175282,52	22,55	kt CO_2-eq.	36,65	kt CO_2-eq.	14,10	kt CO_2-eq.
Wort Boiling	3184168	140333,54	38981850,46	18,24	kt CO_2-eq.	177,99	kt CO_2-eq.	159,75	kt CO_2-eq.
∑	**43275899,35**	**11798225,60**	**3277311107**	**1533,78**	**kt CO2-eq.**	**2419,12**	**kt CO2-eq.**	**885,34**	**kt CO2-eq.**

Step 5: Economic evaluation: Specific levelized cost of heat

Process-level, Worst-Case

Table 15. Appendix B: Step 5 calculations, Process Level, Worst Case. Own Table

Worst Case Scenario	Production facilities (*+largest ones*)	OH	Q_D (in GJ)	Q_D (in kWh)	Q_{sink} (in kW)	Q_{sink} (in kW)/facility	Q_{sink} (in MW)/facility	Heat pump capacity	E_{el} (in kW)/ facility	c_{el} (€/MWh)	LCOH (€/MWh)
Sugar	20	2900 h / a (can									
Evaporation & Crystallisation			15279180	4244250620	1463534,70	73176,73	73,18	2*50 MW -> 2*48,32 mio	29506,75	87	35,117
Dairy	155	7000 h /a									
Evaporation & Spray drying	*31*		5693605	1581569597	225938,51	7288,34	7,29	8.2 MW -> 15.35 mio €	3835,968	87	45,81
UHT Treatment			1742240	483959427,2	69137,06	2230,23	2,23	8.2 MW -> 15.35 mio €	945,01	87	36,94
Bakery	10491	7000 h / a									
Baking	*252*		11675705	3243277335	463325,33	1838,59	1,84	8.2 MW -> 15.35 mio €	967,68	87	45,89
Pasteurisation			35562	9878412,36	1411,20	5,60	0,005600	8.2 MW -> 15.35 mio €	3,237	87	81,71
Meat	1400	7000 h / a									
Sausage products thermal treatment	*56*		5009875,35	1391643175	198806,17	3550,11	3,55	8.2 MW -> 15.35 mio €	742,70	87	18,25
Beer	1548	7000 h / a									
Mashing	*170*		655564	182102567,9	26014,65	153,03	0,15	8.2 MW -> 15.35 mio €	35,10	87	21,10
Wort Boiling			3184168	884498187	126356,88	743,28	0,74	8.2 MW -> 15.35 mio €	212,97	87	25,17

Aggregated level, Worst-Case

Table 16. Appendix B: Step 5 calculations, Aggregated Level, Worst Case. Own Table

Aggregated Worst case calculation (50MW heat pump)	Tot. Heat flow	43275899,35	GJ	Amount of heat pumps	38903,18172	units needed
		12021083153	KWH			
		1945159,086	KW			
	Electricity total	5058317122	KWh			
		818497,9162	KW	share of electricity, in €	share of investment, in €	
Levelized Cost of heat		49	€/MWh	37	13	
Aggregated Worst Case calculation (8,2MW heat pump)	Tot. Heat flow	43275899,35	GJ	Amount of heat pumps	237214,5227	units needed
		12021083153	KWH			
		1945159,086	KW			
	Electricity total	4051838146	KWh			
		655637,2404	KW	share of electricity, in €	share of investment, in €	
Levelized Cost of heat		53,63	€/MWh	29,3	24,23	

Process-level, Best-Case

Table 17. Appendix B: Step 5 calculations, Process Level, Best Case. Own Table

Best Case Scenario	Production facilities (*+largest ones*)	OH	Q_D (in GJ)	Q_D (in kWh)	Q_{sink} (in kW)	Q_{sink} (in kW)/facility	Q_{sink} (in MW)/facility	Heat pump capacity	E_{el} (in kW)/ facility	c_{el} (€/MWh)	LCOH (€/MWh)
Sugar	20	2900 h / a (campaigns)									
Evaporation & Crystallization			15279180	4244250620	1463534,70	73176,73	73,18	2*50 MW -> 2*48,32 mio	28037,06	87	33,37
Dairy	155	7000 h /a									
Evaporation & Spray drying	*31*		5693605	1581569597	225938,51	7288,34	7,29	8.2 MW -> 15.35 mio €	3049,51	87	36,41
UHT Treatment			1742240	483959427,2	69137,06	2230,23	2,23	8.2 MW -> 15.35 mio €	637,21	87	24,90
Bakery	10491	7000 h / a									
Baking	*252*		11675705	3243277335	463325,33	1838,59	1,84	8.2 MW -> 15.35 mio €	267,63	87	12,71
Pasteurization			35562	9878412,36	1411,20	5,60	0,006	8.2 MW -> 15.35 mio €	0,43	87	23,43
Meat	1400	7000 h / a									
Sausage products thermal treatment	*56*		5009875,35	1391643175	198806,17	3550,11	3,55	8.2 MW -> 15.35 mio €	742,70	87	18,23
Beer	1548	7000 h / a									
Mashing	*170*		655564	182102567,9	26014,65	153,03	0,15	8.2 MW -> 15.35 mio €	40,48	87	23,63
Wort Boiling			3184168	884498187	126356,88	743,28	0,74	8.2 MW -> 15.35 mio €	32,76	87	3,96

Aggregated level, Best-case

Table 18. Appendix B: Step 5 calculations, Aggregated Level, Best Case. Own Table

Aggregated Best case calculation (50 MW heat pump)	Tot. Heat flow	43275899,35	GJ	Amount of heat pumps	38903,18172	units needed
		12021083153	KWH			
		1945159,086	KW			
	Electricity total	3277311107	KWh			
		530309,2406	KW	share of electricity, in €	share of investment, in €	
Levelized Cost of heat		36	€/MWh	24	13	
Aggregated Best case calculation (8,2MW heat pump)	Tot. Heat flow	43275899,35	GJ	Amount of heat pumps	237214,5227	units needed
		12021083153	KWH			
		1945159,086	KW			
	Electricity total	3277311107	KWh			
		530309,2406	KW	share of electricity, in €	share of investment, in €	
Levelized Cost of heat		48,0	€/MWh	24	24	