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DOI
10.1016/j.resconrec.2022.106605

Publication date
2023

Document Version
Final published version

Published in
Resources, Conservation and Recycling

Citation (APA)
Dumont, M., Wang, R., Wenzke, D., Blok, K., & Heijungs, R. (2023). The techno-economic integrability of high-temperature heat pumps for decarbonizing process heat in the food and beverages industry. *Resources, Conservation and Recycling*, *188*, Article 106605. https://doi.org/10.1016/j.resconrec.2022.106605

Resources, Conservation & Recycling 188 (2023) 106605

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

The techno-economic integrability of high-temperature heat pumps for decarbonizing process heat in the food and beverages industry

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ARTICLE INFO

Keywords:
High-temperature heat pumps
Techno-economic assessment
GHG emissions abatement
Industrial decarbonisation

ABSTRACT

High-temperature heat pumps (HTHPs) are an emerging technology to improve overall process efficiency and reduce energy demand while enabling a switch from fossil fuels to renewable electricity. New industrial HTHP technologies aim to achieve an output heat temperature of 250 °C, suitable for decarbonising the food and beverages industry considering its temperature requirements of <250 °C. Here, we employ a bottom-up approach to investigate the techno-economic feasibility of integrating new HTHP technologies into heat processes of the German food and beverages industry and estimate emissions reduction potentials under waste heat scenarios. Our results indicate that the new HTHP technologies could meet 12 TWh of process heat demand in the German food and beverages industry and cut emissions by 9% considering Germany's current electricity fuel mix. A modest carbon tax of 38 €/t CO2 eq. or higher makes the HTHPs cost-competitive with an optimised fossil fuel-based alternative.

1. Introduction

To meet the 1.5 °C goal of the Paris Climate Agreement, Germany has enhanced its carbon dioxide (CO_2) emission reduction targets to −65% by 2030 from the 1990 level and to reach carbon neutrality by 2045 (Agora Energiewende 2021). As the second-largest final energy user and greenhouse gas (GHG) emitter in the German economy, the industrial sector stagnated in emission reductions over the last decades (KEI 2021) (Agora Energiewende and Wuppertal Institut 2019). It must reduce its CO_2 emissions by over 35% in this decade, from 186 million tons (Mt) in 2020 to 118 Mt by 2030, to reach the 2030 industrial target (KEI 2021; BMWi 2021). Natural gas is the primary energy carrier for German industries, with fossil fuels supplying 61% of industrial energy demand (Destatis 2021), mainly for process heating at various temperatures (dena 2019). In Europe, process heating accounts for 66% of the total industrial energy demand (de Boer et al., 2020). Therefore, decarbonising process heat is a central component of industrial decarbonisation in Germany and many other countries.

Heat pumps (HPs) are crucial for realising the needed emission reductions in industrial heat processes. HPs reduce industrial energy demand by improving the overall process efficiency. As a critical electrification technology, they also enable the transition from fossil fuels to low-carbon electricity as an energy source (de Boer et al., 2020). In the Net-Zero-Emissions (NZE) scenario developed by the International Energy Agency (IEA), HPs will supply 30% of the heat demand at low to medium temperature levels (up to 400 °C) in light industries, especially the "food, beverages, and tobacco" industry, by 2050 (IEA 2021). Such heat supply capacity entails 500 MW of heat pump installations globally in the light industries every month over the next 30 years (IEA 2021).

However, there is a limited understanding of the technical and economic integrability of HPs in various industrial processes, which is a prerequisite for large-scale implementations. The knowledge gap is especially critical for emerging high-temperature heat pumps (HTHPs) that supply heat above 100 °C. Current heat pump technologies are mostly limited to heat supplies of 70–80 °C, while heat demand temperature in many industrial processes is significantly higher. Wolf and Blesl (Wolf and Blesl, 2016) estimated that heat pumps supplying temperature levels of <100 °C can lead to a final energy consumption reduction of 477 TWh in EU industries (Wolf and Blesl, 2016). Kosmakadis (Kosmadakis, 2019) matched the estimated heating demand and the waste heat flow in EU industries, showing that 1.5% of the total

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https://doi.org/10.1016/j.resconrec.2022.106605
Received 16 March 2022; Received in revised form 25 July 2022; Accepted 11 August 2022

industrial heating demand can be produced by exploiting 7% of the waste heat potential with commercially available heat pumps. Moreover, heat recovery options are most promising in the food and beverages industry, among others (Kosmadakis, 2019). Focusing on the technical potentials of HTHPs, Marina et al. (Marina et al., 2021) estimated that HTHPs delivering temperatures of up to 150 °C could offer 201 TWh of heat per year to European industries (Marina et al., 2021). Zühlsdorf et al. (Zühlsdorf et al., 2019) presented one of the first techno-economic feasibility analyses of HTHPs supplying process heat up to 280 °C for two specific process cases, spray drying and alumina production (Zühlsdorf et al., 2019). They highlighted the effects of economies of scale on HTHPs' investment costs: 959 €/kW$_{th}$ for larger HTHPs (50 MW) on average compared to an average investment cost of 1933 €/kW$_{th}$ for smaller HTHPs (8.2 MW) (Zühlsdorf et al., 2019). Without a carbon tax, the HTHPs can only compete against natural gas boilers (natural gas price: 31 €/MWh) when electricity rates are low (35–50 €/MWh) (Zühlsdorf et al., 2019).

However, existing studies investigating the technical-economic potentials of HTHPs feature distinct geographical scopes, methodological approaches, and technological boundary conditions such as temperature limits, making it difficult to compare and synthesise the results. The available estimates of HTHP's technical potentials for industrial decarbonisation are primarily for Europe or theoretical (Wolf and Blesl, 2016; Kosmadakis, 2019; Marina et al., 2021; Zühlsdorf et al., 2019; Wolf et al., 2012; Hita et al., 2011). Further, most previous studies follow top-down approaches, while bottom-up approaches allow for integration potential in specific industrial processes. In addition, few studies investigated HTHP's economic feasibility considering particular socio-economic conditions to overcome existing market barriers. Yet, economics is particularly critical for capital-intensive technologies, such as HTHPs, given their long investment cycles. The competitive markets make it difficult for industrial players to absorb additional costs (IEA 2021; Wolf et al., 2012). Economic conditions such as electricity and fuel prices and emission taxations vary significantly between countries and likely play a critical role in determining the economic feasibility results.

The food and beverages industry generally has a medium upper limit of heating temperatures to prevent damage at higher temperatures. Thus, the heating temperatures of food products typically stay within 200 °C, sometimes 250 °C for short exposure times, and in rare cases 1000 °C for by-products (e.g., sugar beet pulp) or material inputs (e.g., lime for the calcination in sugar processing). Moreover, the food and beverages industry ranks as Germany's sixth most energy-intensive industrial sector (Fleiter et al., 2013). The five industrial sectors that are more energy-intensive belong to heavy industry and therefore have significantly higher temperature requirements not yet in the feasible range of HTHP technology. The food and beverages industry accounts for 5.6% of the German industries' total final energy consumption (Destatis 2021). The energy carriers are over 60% natural gas, followed by 29% electricity and 5% district heat (Destatis 2018). Despite the heterogeneity within the industry, fuel is primarily for process heating (warm and hot water, scalding, sanitising, drying, smoking, thermal treatments, etc.), while electricity powers cooling, compressed air generation, vacuum generation, transport, and lighting (S. Gühl et al., 2020). Therefore, HTHPs can be a promising technical solution for decarbonising the food and beverages industry.

This research investigates the techno-economic integrability of new HTHPs that can supply heat up to 250 °C in Germany's food and beverages industry. As such, it addresses an existing knowledge gap impeding large-scale implementations of HPs and industrial decarbonisation. Research on HTHPs with higher heat sink temperatures has increased in recent years (see a brief overview of the state-of-the-art technology in the SI, Table A1). The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) by the IEA is working on accelerating the implementation of heat pumps and related technologies, and bundles state-of-the-art research regarding the latest HTHP developments (IEA HPT 2022). Further, the American Council for an Energy-Efficient Economy (ACEEE) is accelerating its research focussing on HTHPs for decarbonising American industries (ACEEE 2022). The German Aerospace center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) started developing HTHP pilot systems with the goal of industrial decarbonisation (DLR 2021). The two pilot HTHPs (Rankine cycle and Brayton Cycle) are aiming at ultimately delivering process heat in a temperature range that is not yet commercially available: ultimately for at least 500 °C (Stathopoulos, 2021), with a short-term, intermediate goal of supplying 250 °C (Oehler et al., 2021). Therefore, we focus on investigating the technical potential for HTHPs up to 250 °C at the process level for meeting process heat demand in the German food and beverages industry. We then assess the HTHPs' potential to advance the industry's decarbonisation goals by considering Germany's economic and regulatory conditions, thus demonstrating the techno-economic feasibility of the HTHPs. We estimate the emission reduction potentials against sectoral emissions under two waste heat scenarios. For electrifying industries, Germany faces a high ratio of electricity to oil prices compared to other European countries (Germany: 3.3; Sweden: 1.3; France: 1.5 (Technology Collaboration Programme 2021)). Hence, our results represent a conservative feasibility estimate for HTHPs in other European countries. The contribution of this study is an approach that combines the bottom-up process-specific integration of HTHPs while providing a systemic and conservative estimate of the economic integrability of the HTHPs based on the case of Germany.

2. Methods and data

2.1. Overview of approach

Our study follows a bottom-up, four-fold methodological approach (Fig. 1). Briefly, we start by establishing a baseline quantification of the heating demand and emissions of Germany's food and beverage industry, focusing on the most energy-intensive processes. We then assess the technical and economic integrability of HTHPs in several scenarios and estimate the emission abatement potentials. Previously, a top-down methodological approach that assigns shares of heating demands top-down to industrial branches and their processes (Marina et al., 2021; Zühlsdorf et al., 2019) was employed (Wolf and Blesl, 2016; Kosmadakis, 2019; Wolf et al., 2012), which neglected the technical process specificities. Due to the process-specific nature of HTHPs, a bottom-up approach was developed (Marina et al., 2021), which included process- and technology-specific characteristics such as temperature requirements of specific processes. Following the bottom-up approach, we first identify technically relevant processes in the sub-branches of the food and beverage industry that have the highest heating demands. We

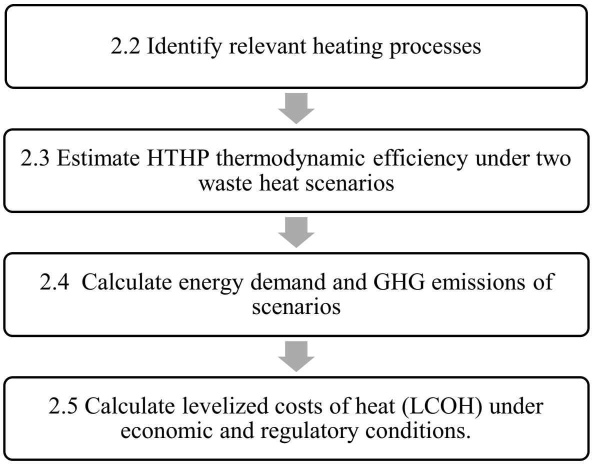

Fig. 1. A flowchart illustrating the main methodological steps.

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then scale up these processes with the specific process heat demand and production statistics, which, together with the emissions resulting from the evaluated processes, form the baseline scenario. Next, we assess the technical integrability of the HTHPs under two waste heat scenarios, distinguishing two temperature levels of the heat source, and the associated greenhouse gas (GHG) emission abatement potentials. Lastly, for two differently sized HTHPs, we evaluate their economic integrability under the two waste heat scenarios.

2.2 presents relevant background information about the German food and beverages industry and outlines relevant industrial processes for our study and required technical information. 2.3–2.5 details the technical and economic assessment methods and systemic modelling parameters. 2.6 describes the sensitivity analysis that explores the uncertainty of our main estimates considering different sources of uncertainty in critical parameters.

2.2. German food and beverages industry

Following the Statistical Classification of Economic Activities in the European Community (NACE), the manufacturing industry of food products (C10) and beverages (C11) include the manufacturing of food products, animal feed products, and beverages and purposively excludes the tobacco industry. In Germany, the five most energy-intensive food and beverage branches are 1) Production of sugar, 2) Processing of dairy, 3) Production of bakery products, 4) Processing of meat, and 5) Production of beer (Fleiter et al., 2013; S. Gühl et al., 2020). In 2018, they accounted for half of the total final energy consumption of the food and beverages industry (Destatis 2018). Moreover, the share of renewable energy in these five branches is negligible (1%), whereas the share of fossil fuels was as high as 70% in 2018 (Destatis 2018). The GHG emissions arising from the five sub-branches are estimated to be 9333 kt CO_2-eq. in 2020 (Fleiter et al., 2013).

We further identified eight thermal-energy-intensive industrial processes that dominate the heating demand in these five most energy-intensive branches, for which HTHPs are technically suitable (<250 °C) (Table 1). The most thermal energy-intensive processes are pasteurisation, cooking, evaporation, and drying, which often require removing large quantities of water, and typically rely on heat from fossil fuel combustions. In Germany, these industrial processes primarily receive heat from efficient on-site natural gas combustion, such as through combined heat and power (CHP) in large sugar plants and natural gas-fired boilers in smaller production facilities. In the food and beverages industry, one product is often not associated with a single production process but rather with varying production techniques depending on the traditional recipes and traditions of the company itself, usually not disclosed to the public. Therefore, the specific heating demand is approximations of industrial averages, based on industry literature, and for simplification, the products are associated with concrete process technologies. The production volumes are taken from industry reports and statistical data sources and are assumed to represent an average production year (see **Fig. A1 -A5** in the SI for detailed assumptions).

Table 1
Selected thermal energy-intensive processes from five food and beverage industry sub-branches and their typical process temperatures and exhaust temperatures.

Sub-branch and process	Process temperature (°K) (T_p)	Exhaust temperature (°K) (T_w)
Sugar		
Evaporation & Crystallization (Rademaker and Marsidi, 2019)	408.15	323.15
Dairy		
Evaporation & Spray drying (Pierrot and Schure, 2020)	453.15	348.15
Ultra-High Temperature Treatment (Pierrot and Schure, 2020)	415.15	353.15
Bakery		
Baking (S. ZREU 2000)	453.15	423.15
Pasteurisation (S. ZREU 2000)	475.15	463.15
Meat		
Sausage thermal treatment (FAO 2007)	353.15	318.15
Beer		
Mashing (Oehler et al., 2021; Fleiter et al., 2013)	373.15	349.15
Wort boiling (Oehler et al., 2021; Fleiter et al., 2013)	373.15	373.15

The food and beverages industry also has crucial socioeconomic implications in Germany. Economically, it is the fourth-largest industrial sector in Germany (BVE 2020b). Dominated by small- to medium enterprises (SMEs), the food and beverages industry plays a crucial role in securing employment after the coal exit in the heavily coal-dependent regions, such as Rheinisches Revier, Mitteldeutsches Revier, and Lausitz (Agora Energiewende 2017).

2.3. HTHP thermodynamic efficiency

The Carnot Efficiency measures the theoretical thermodynamic maximum, or coefficient-of-performance, achievable by a heat pump given the temperatures of the heat source and the heat sink (De Kleijn Energy Consultants and Engineers 2021) (Eq. (1)).

$$COP_{\mathrm{Carnot}} = \frac{T_{\mathrm{p}}}{T_{\mathrm{p}} - T_{\mathrm{w}}} \tag{1}$$

COP = coefficient-of-performance (–)
T_W= temperature of the heat source (K)
T_P =temperature of the heat sink (K)

While the Carnot Efficiency describes the theoretical maximum in ideal conditions, the real COP typically lies within a range of 50%−70% of the ideal COP (Marina et al., 2021; Hita et al., 2011). In this study, we assume a default systems efficiency (η) of 60% (Eq. (2)). We test a wider range of the ratio in sensitivity analyses later on.

$$COP_{\mathrm{real}} = \eta \times COP_{\mathrm{Carnot}} \tag{2}$$

η = systems efficiency (–); default value 0.6

Moreover, we calculate the COPs under two distinct waste heat scenarios based on T_w. The Worst-Case scenario assumes low-grade waste heat available at 45 °C for all food and beverage manufacturing processes (Hita et al., 2011). The Best-Case scenario assumes waste heat available at average exhaust temperatures found in industrial reports (Table 1). Because the waste heat temperatures and volumes can differ significantly among production sites, realistic estimates are likely to lay within the two extremes rather than at the extremes.

The waste heat scenarios are to represent different temperature levels of the heat source: the Worst-Case being average waste heat temperature levels available in the food and beverages industry (45 °C) and the Best-Case being process exhaust temperature. Finding reliable estimates of the availability and utilisation of waste heat streams per production facility proved difficult as the industry is marked by a large amount of small-to-medium family enterprises. Therefore, we work under the assumption that waste heat is available in two different temperature ranges and assume that sufficient waste heat is available and not yet used for other purposes, e.g., heat exchangers.

2.4. Energy demand and GHG emissions: a systemic modeling

The thermal energy demand of the baseline scenario is calculated by multiplying the specific heating demand of products produced by the selected processes with the production volumes in Germany (Eq. (3)) (Table A2 in the SI).

$$Q_{\mathrm{D}} = \sum_{i} SHD_i \times PV_i \tag{3}$$

Q_{D} = Thermal energy demand (kWh/yr)
SHD = Specific heating demand (kWh/unit)
PV = production volume of products produced by selected processes (unit/yr)
i = specific product

The electricity demand for powering HTHPs in the heating processes depends on the real COPs and Q_{D} (Eq. (4)).

$$E_{\mathrm{el}} = \frac{Q_{\mathrm{D}}}{COP_{\mathrm{real}}} \tag{4}$$

E_{el} = Electricity demand (kWh/yr)

Eq. (5) calculates the GHG emissions that stem from the electricity demand by multiplying E_{el} with the emission factor for electricity in Germany in 2018, 468 g CO_2-eq./kWh (Statista 2021).

$$GHG_{\mathrm{el}} = E_{\mathrm{el}} \times EF_{\mathrm{el}} \tag{5}$$

GHG_{el} = GHG emissions from electricity (g CO_2-eq./yr)
EF_{el} = emission factor for electricity in Germany in 2018 (g CO_2-eq./kWh)

Subtracting GHG_{el} from the GHG emissions stemming from the combustion of gas (201 g CO_2 /kWh (UBA 2018)) in the baseline scenario (Eq. (6)) results in the GHG emission abatement potential (Eq. (7)).

$$GHG_{\mathrm{gas}} = EF_{\mathrm{gas}} \times Q_{\mathrm{D}} \tag{6}$$

GHG_{gas} = GHG emissions from natural gas (g CO_2/yr)
$EF_{\mathrm{gas}}\mathrm{EF}_{\mathrm{gas}}$ = emission factor for natural gas (g CO_2/kWh)

$$EAP = GHG_{\mathrm{gas}} - GHG_{\mathrm{el}} \tag{7}$$

EAP = GHG emission abatement potential

2.5. *Assessing the levelized cost of heat*

We assess the economic performance of HTHPs using the levelized cost of heat (*LCOH*) approach, considering the investment, maintenance, and operational costs or savings associated with implementing the HTHPs. Based on the widely adopted concept of levelized cost of energy (*LCOE*) (Badouard et al., 2020), *LCOH* assesses the costs of heat produced by the various thermal energy technologies and helps compare their economic performances. Table 2 presents all parameters used to calculate the *LCOH* according to Eq (8).

Due to the absence of market data for HTHP technology of manufacturers, we use the total cost estimate from Zühlsdorf et al. (Zühlsdorf et al., 2019) as a reference, given that it represents the most comprehensive HTHP cost estimate in the literature, based on component pricing and including investment and maintenance costs. As such, we estimate the economic costs per MWh of HTHPs in two capacities: 8.2 MW and 50 MW (Zühlsdorf et al., 2019) under the two waste heat scenarios (Eq. (8)). We then compare the *LCOH* estimates to the operating costs of the gas-fired baseline scenario to assess the economic feasibility of implementing the HTHPs into the existing infrastructure.

$$LCOH = \frac{TCI \times CRF}{Q_{\mathrm{D}}} + \frac{ACE}{Q_{\mathrm{D}}} \tag{8}$$

$LCOH$ = Levelized cost of heat (euro/kWh)

Table 2
Economic Parameters for calculating LCOH.

	Symbol	Energy ([a]: Electricity, [b]: natural gas)	HTHPs (Zühlsdorf et al., 2019)
Energy cost (2018 industry price)	c_{el} *cgas*	[a]87 €/MWh, [b]26 €/MWh (BMWi 2018)	
Fuel excise tax (2018)	–	[b]1.42 €/MWh (OECD 2019)	
Investment cost_8.2 MW HTHP	*TCI*		15.35 million €, 1933 €/kW_{th}
Investment cost_50 MW HTHP	*TCI*		48.32 million, €959 €/kW_{th}
Interest rate	*I*		• 5%
HTHP service life	*N*		• 20 years
HTHP annual operating hours	*OH*		• 7000 h (2900 h for the sugar industry)

TCI = Total capital investment (euro)
CRF = Capital recovery factor (yr^{-1})
ACE = Annual cost of electricity (euro/yr)

The total costs consist of component costs and capital costs. For a detailed description of the main cost components, see (Zühlsdorf et al., 2019). The total capital investment of the number of HTHPs for meeting the total Q_{D} per year is multiplied by the capital recovery factor. The *CRF* is calculated with an interest rate (*I*) of 5% over a lifetime of 20 years (Eq. (9)).

$$CRF = \frac{I(1+I)^N}{(1+I)^N - 1} \tag{9}$$

I = interest rate (–); default value 0.05
N = lifetime (yr); default value 20

The operating expenses consist of electricity costs and specific taxes that apply. The annual cost of energy is calculated by multiplying the price by the annual operating hours and the electricity demand (Eq. (10)). The OH for the sub-industries is assumed to be 7000 h/yr, the industrial average for most sub-branches in the food and beverages industry (Zühlsdorf et al., 2019). The *OH* will be subject to change in the later sensitivity analysis.

$$ACE = c_{\mathrm{el}} \times OH \times E_{\mathrm{el}} \tag{10}$$

c_{el} = price of electricity (euro/kWh)

The carbon prices paid by the German industries consist of fuel excise taxes and, to a small extent, permit fees under the European Emission Trading Scheme (EU ETS). 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 usage 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 and 5 €/t-CO_2-eq., 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). 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 (UBA 2020). The other 4% concern 'other combustion plants'. Energy-intensive sugar plants are part of this, which leaves the other sub-branches examined in this study unaffected (UBA 2020). Hence, the food and beverages industry is assumed to be exempt from additional EU ETS costs.

2.6. *Sensitivity analysis*

Our analysis has to build on some assumptions. The energy and economic estimates are based on 2018 when the best available production and emissions information for the processes in focus is available. It is thus crucial to investigate the uncertainties that could arise from critical parameters underlying the analysis. Crucially, results from the analyses can extend the applicability of our study to much wider technical and economic settings than the German situation if the technical details such as temperature levels, exhaust temperatures, and specific heat consumption of the processes are comparable.

Four critical parameters are chosen for sensitivity analyses, and the upper and lower variation limit are shown in Table 3. The efficiency factor is vital in thermodynamic and energy calculations and for systemic comparisons. Thus, we explore how much its possible variations would affect our main findings by varying the efficiency factor for the HTHPs between 50% and 70%. The lower and upper values align with the range of efficiencies characterised by Hita et al. (Hita et al., 2011) and Marina et al. (Marina et al., 2021). In addition, the emission factor of electricity plays a crucial role in assessing the HTHP's emissions abatement potentials. To explore a plausible range of the emission factor in the European context, we choose the highest emission factor present in Europe in 2018 as the upper value observed in Estonia with 875 g/kWh (Carbon Footprint 2019); the lower value represents a total elimination of emissions, based on the example of Iceland with 0 g/kWh (Carbon Footprint 2019).

The third parameter for the sensitivity analysis is the electricity price for industrial players. The electricity price that affects industrial players is highly volatile. In the German industrial landscape, some industrial players can pay three times the price for electricity than others due to exemptions from taxes and levies (OECD 2019). Further, forecasts for industrial electricity price developments vary significantly. Industrial associations claim that the coal exit in 2038 will push electricity prices to considerably higher values, whereas research institutes state that the coal phase-out and the switch to renewables will only have a small impact, if not even beneficial effects, on industrial electricity prices (Clean Energy Wire 2019). Due to the price uncertainties, the electricity price input is varied to a lower value of 42 €/MWh, as present in Luxemburg in the same year, and to an upper value of 150 €/MWh as present in Cyprus (BMWi 2018), to investigate which impacts the variations have on the economic profitability. The fourth parameter for the sensitivity analysis is the OH. The OH strongly depend on the sub-sector and the individual plant. Hence, a seasonal operation like in the sugar industry is assumed as the lower value of 2900 h/yr and a full operational year of 8760 h/yr as the upper value.

Table 3
Critical parameters and their variations explored in the sensitivity analysis.

Parameter	Symbol	Baseline value	Lower value	Upper value
Efficiency of HTHP (%)	η	60	50	70
Electricity emission factor (g CO_2-eq. /kWh) (Carbon Footprint 2019)	EF_{el}	468	0	875
Electricity price (€/MWh) (BMWi 2018)	c_{el}	87	42	150
Operating hours (hr/yr)	OH	7000	2900	8760

3. Results

3.1. *Technical evaluation*

The total thermal energy demand of the eight processes, which we identified as the most thermal energy-intensive and technically suitable for our study (see Table 1), is estimated to be 12 TWh per year. We presented process- and branch-specific energy demand estimates in Table A3 in the SI. Currently, most of the thermal energy is provided by combusting natural gas in Germany. Hence, the associated GHG emissions stemming from the processes are estimated to be 2419 kt CO_2-eq. Significantly, the eight processes alone accounted for 26% of the assumed total GHG emissions of the five most energy-intensive food and beverage branches (the branches are detailed in 2.2). In the Worst-Case waste heat scenario, considering sufficient waste heat being available at an industrial average of 45°C, the calculated COPs range between 1.7 – 4.8. In the Best-Case scenario, the resulting COPs range between 2.4 - 23. Note that, a higher COP >5 is not realistic due to technological component limitations and temperature lifts. Thus, we capped COPs at 5 and calculated the technical potential to apply HTHPs $<250\ ^\circ C$ in the eight thermal energy-intensive processes in the German food and beverages industry to be 12 TWh.

3.2. *Systemic evaluation*

The electricity needed to power the HTHPs lies between 3.3 - 5 TWh, owing to the significant deviation of COPs between the Worst-Case and Best-Case discussed above. A high COP means that the ratio between the amount of electricity used and the amount of usable energy is high. Consequently, the GHG emissions stemming from the electricity demand are 2367 kt CO_2-eq. and 1534 kt CO_2-eq. for the Worst-Case and Best-Case scenarios, respectively. 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. Fig. 2 compares the aggregated electricity demand, the associated GHG emissions, and the resulting GHG emissions abatement potential of both HTHP 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 the exhaust to enhance the energy efficiency of HTHPs.

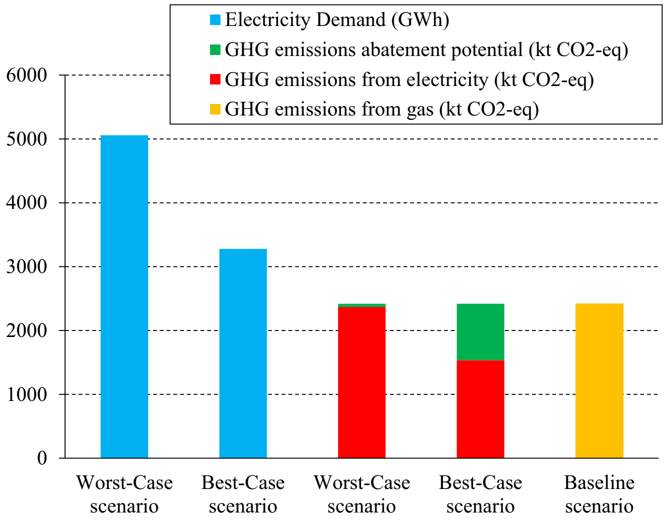

Fig. 2. Electricity demand, associated GHG emissions, and GHG emission abatement potential under the Best-Case and Worst-Case scenarios, and the GHG emissions of the natural gas baseline scenario.

In the Worst-Case scenario, three evaluated processes show 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. It must be considered 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. In the Best-Case scenario, all processes show lower GHG emissions from the electricity required than from the combustion of natural gas.

When comparing the level of COPs and the GHG emissions abatement potential by replacing the on-site combustion of natural gas with German electricity, a COP of 2.3 marks the threshold for emitting fewer emissions from electricity than from gas. This comes from the fact that the GHG emissions for producing 1 kWh of electricity are 2.3 times higher than the GHG emissions from 1 kWh of natural gas. Consequently, applying HTHPs to the chosen processes in the Worst-Case and the Best-Case scenario could lead to a GHG emissions reduction of 0.6%−9%, respectively, concerning the total GHG emissions stemming from the five sub-branches investigated.

3.3. Economic evaluation

Fig. 3 compares the LCOH estimated for two HTHPs with different capacities under two waste heat scenarios against the operating costs of the baseline scenario of combusting natural gas. Compared to the HTHPs with the smaller capacity (8.2 MW), the larger HTHPs (50 MW) have lower LCOH and share of investment costs. The 50 MW HTHP has an LCOH of 35 €/MWh in the Best-Case scenario, thanks to the reduction in electricity costs of 13 €/MWh compared to the Worst-Case scenario. The 8.2 MW HTHP in the Worst-Case scenario has an LCOH of 58 €/MWh, of which electricity accounts for approximately 60%. Although the investment cost remains unchanged in the Best-Case scenario, the electricity costs decrease and result in an LCOH of 45 €/MWh for the small HTHPs. Moreover, the Best-Case scenario with the smaller HTHP is the only case where investment costs contribute to half of the LCOH. In the other cases, the costs stemming from electricity dominate the LCOH. Our results also show that the 8.2 MW HTHPs have an investment cost per MW nearly twice as high as that of the 50 MW HTHPs.

The most cost-efficient alternative occurs when a large HTHP (50 MW) is used with high temperatures from process heat. However, in the baseline case of using natural gas boilers, the cost of gas and the assumed average fuel excise tax for industrial players in Germany resulted in an LCOH of 27 €/MWh. Thus, the HTHPs are not cost-competitive in the current market. We note that the investment costs of the HTHPs include the up-front capital investment and maintenance of the systems, while the investment costs and maintenance costs of the gas-fired infrastructure are not considered.

To make the HTHPs system economically competitive, a carbon tax

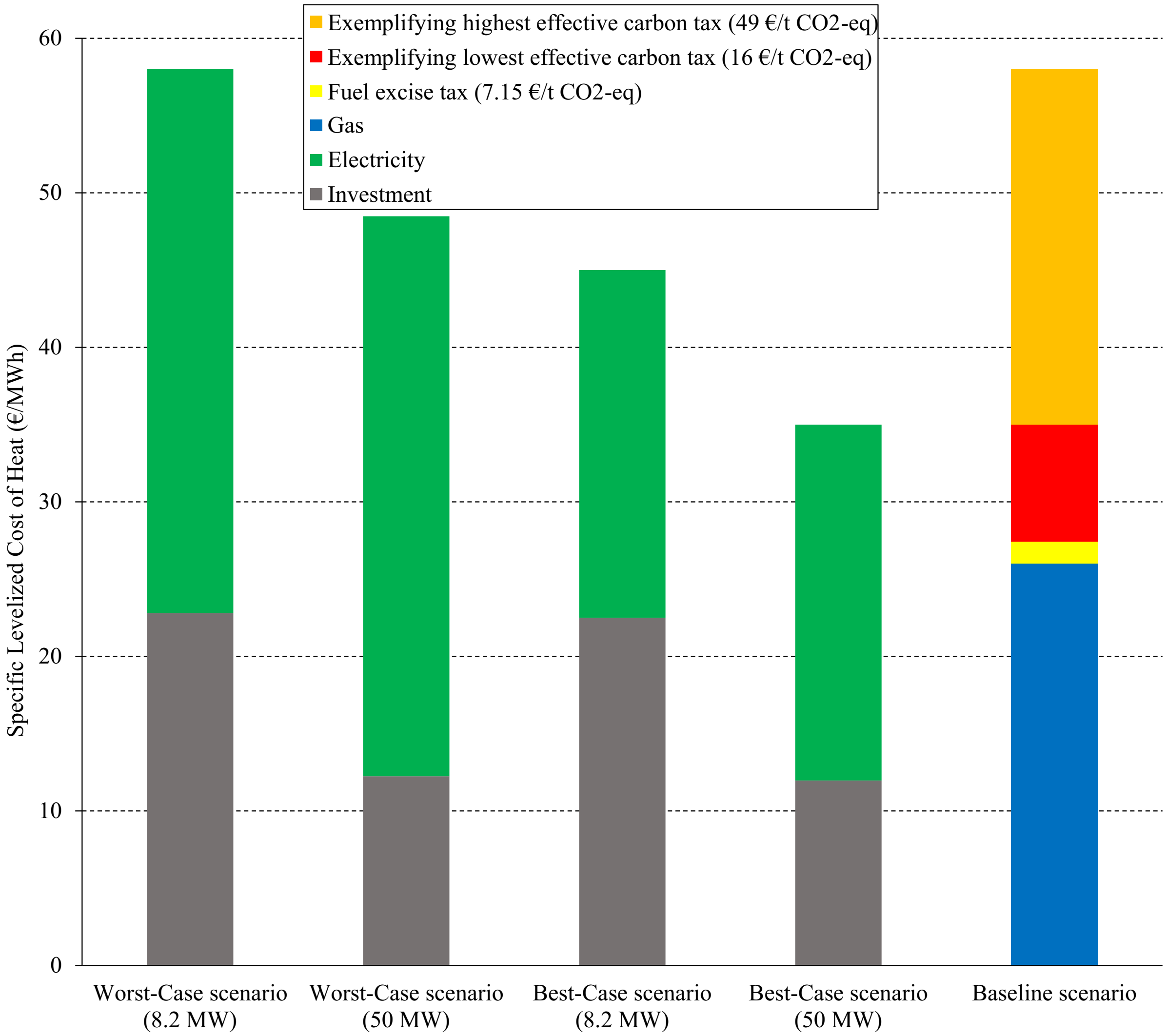

Fig. 3. Specific Levelized Cost of Heat in €/MWh for both waste heat scenarios and both sizes of HTHPs compared to the operational costs of the natural gas baseline scenario.

of 38–153 €/t CO_2-eq. is required. According to Zühlsdorf et al. (Zühlsdorf et al., 2019), without a CO_2 tax, the HTHPs were only competitive with natural gas boilers when the electricity costs are as low as 35 €−50 €/MWh. This is achievable for own-operated PV systems in many parts of the world already (OECD 2021a). In this analysis, the electricity costs are 87 €/MWh (BMWi 2018). The HTHPs scenarios in this study are also not competitive with the baseline scenario without adding a carbon tax.

This minimum required carbon tax we estimated lies at the lower end of the carbon pricing needed to reach the goals of the Paris Agreement: at least 33 €−66 €/t CO_2-eq. in 2020, and 41 €−83 €/t CO2-eq. in 2030 (OECD 2021b). However, by 2015, only 19% of German GHG emissions were taxed above 30 €/t CO_2-eq., most of which were not industrial (OECD 2021b). In 2018, the German Environment Agency (UBA) valued the damages caused by each ton of CO_2 eq. as 180 € (UBA 2018b). Germany did not have any specific carbon tax for the industrial sector, except for the fuel excise costs, showing that the political incentive for industrial decarbonisation is insufficient to produce large-scale change. The GHG emissions are not sufficiently priced to have neither an economic incentive for decarbonisation efforts from the industrial perspective nor to cover the costs resulting from the environmental impacts of each ton of CO_2-eq. exhausted.

3.4. Sensitivity analysis

To improve the robustness and applicability of our techno-economic assessment, we tested and showed how the results of our techno-economic metrics, i.e., COP, GHG abatement potentials, and LCOH, vary given a possible range of modelling parameters. When changing the HTHPs efficiency from 60% to either 50% or 70%, the COP results change by the same percentage (Table 4). Moreover, COPs affect the technical evaluation and the electricity demand and hence the possible GHG emissions abatement. For instance, the lower efficiency of 50% increases GHG emissions by 20% in the Worst-Case and Best-Case scenarios, while a higher efficiency of 70% reduces GHG emissions by 15% under both scenarios.

Compared to the baseline scenario, the HTHPs' net environmental benefits hinge on the local electricity emission factor (Fig. 4a). With a low emission factor of 0 g/kWh, the GHG emissions abatement potential under the best and worst cases both lay at 2419 kt CO_2 eq., which is the total amount of GHG emissions stemming from the combustion of natural gas. Yet, for the Worst-Case scenario, the GHG abatement potential decreases rapidly with a rising emission factor due to lower energy efficiency. With the higher electricity emission factor, both scenarios exhibit more GHG emissions from electricity than from the combustion of natural gas. The GHG abatement potential for the Worst-Case scenario is four times less than for the Best-Case scenario for the upper emission value, indicating the electricity emission factor as a critical sensitivity parameter for assessing HTHPs' decarbonisation potentials. The Worst-Case scenario reaches 0 abatement potential only with a slightly increased emission factor than the German electricity mix in 2018, while the Best-Case scenario shows net benefits until a significantly larger emission factor. Hence, we expect robust GHG abatement potential when using efficient HTHP systems in regions with a wide range of electricity fuel mixes.

We obtain two main observations from the sensitivity analysis results about changing electricity prices (Fig. 4b). First, by reusing more exhaust heat to enhance energy efficiency, the large HTHP can gain significant economic competitiveness. Secondly, low electricity prices can make the efficient HTHPs even more competitive with the baseline case while improving the economic feasibility of the less efficient HTHPs. The Worst-Case small and large HTHPs are more sensitive to rising electricity prices than the Best-Case HTHPs. This is because electricity demand increases due to the Worst-Case scenario's lower HTHP efficiency, making electricity cost a higher share in LCOH. When the electricity price drops to 42 €/ MWh, the LCOH under the Worst-Case scenario drops by 19 €/MWh, and in the Best-Case scenario by 12 €/MWh. At such a low electricity price, even the Worst-Case large HTHP becomes nearly cost-competitive to the baseline scenario without additional taxation or subsidy. On the other hand, assuming the initial electricity price or higher, no case is cost-competitive to the baseline scenario without extra tax. Moreover, the Best-Case large HTHP with the upper electricity price is still significantly more cost-competitive than the Worst-Case small HTHP under the initial electricity rate.

Table 4
Sensitivity analysis results for the modelling parameter COP.

	Initial estimate	Lower estimate	Upper estimate
Worst-Case	1.7 – 4.8	1.4 – 4	2 – 5.6
Best-Case	2.4 – 22.7	2 – 19	2.8 – 26. 4

Our results further show that operating hours (OH) can strongly influence the HTHPs' cost competitiveness (Fig. 4c). By increasing OH, the LCOH for the systems can drastically decrease, and the carbon taxation required to level the costs with the baseline case could also be reduced. The number of OH depends on the industrial branch and the plant itself and can vary greatly. The lower OH of 2900 h/yr, as often the case in seasonal operations like the sugar industry, results in a significant increase in LCOH in each scenario. The largest LCOH occurs for the Worst-Case small HTHP, reaching almost 90 €/MWh. By increasing the OH to a full year, the LCOH decreases by approx. 30 €/MWh. The large HTHP in the Best-Case scenario becomes more cost-competitive than the baseline scenario, and thus the required carbon tax could be decreased to create cost-competitiveness.

4. Discussion

Our results show that HTHPs can substantially contribute to industrial decarbonisation and support reaching the tightened industrial climate targets. HTHPs promote the transition to electrification and simultaneously reuse high-temperature waste heat streams to increase process efficiency. The HTHP market is entering a promising decade for manufacturers, researchers, and industrial players. The timely investment into low-carbon technologies such as HTHPs can radically 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 generating low-carbon process heat. More research is needed to demonstrate the dormant potential of HTHPs and their significant impacts on systemic transformation toward a low-carbon industry in Germany, Europe, and beyond.

Our Best-Case scenario results show that a combination of the two priorities, having an efficient fossil fuel-based energy system and decarbonisation of the energy system, is possible. Reusing high-temperature waste heat flows efficiently and enhancing energy circularity is essential for making HTHPs more attractive, improving the environmental benefits, and increasing the cost-competitiveness against optimised fossil fuel systems.

Current and future energy system plays a crucial role in determining the environmental benefits of heat pumps, as demonstrated in the parameter variation of the emission factor. Suppose the German electricity generation is still based mainly 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 2.3 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 phase-out, planned for the latest 2038, might lead to an increasing role of natural gas in the short run. The cost of natural gas could hence increase (Zühlsdorf et al., 2019). In the long run, the emission factor of electricity is expected to go

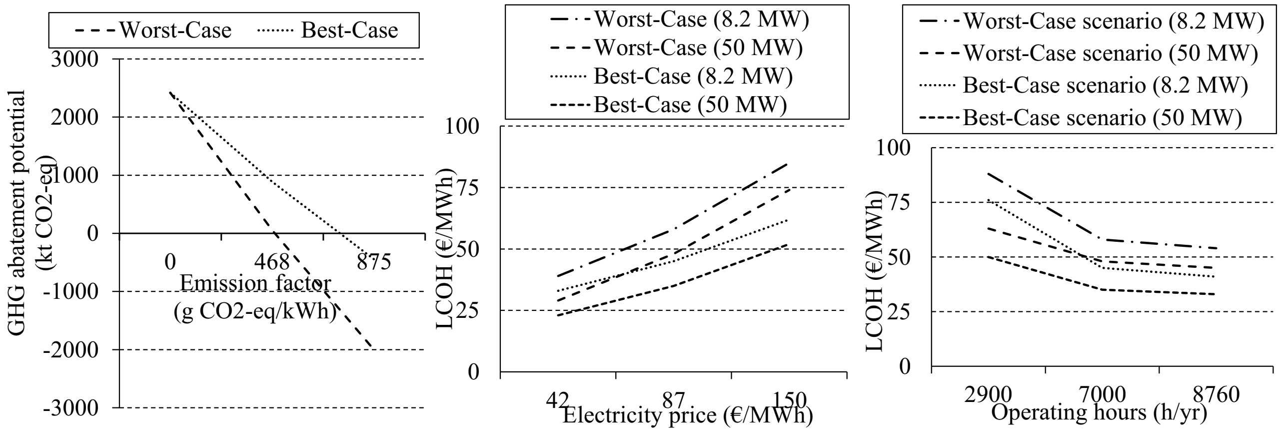

Fig. 4. (a) GHG abatement potentials under varying electricity emission factors. (b), (c) LCOH estimates given varying electricity prices and operating hours, respectively.

towards zero due to renewable energy generation, which could lead to the abatement potential of 2419 kt CO_2-eq., which is 26% of the total GHG emissions of the five sub-branches. Future research could benefit from a systematic review of the German policy targets for the energy sector to be compliant with the Paris agreement, assessing the GHG emission abatement potential and the costs thereupon. The increasing efficiency of gas-optimized infrastructure does not outweigh the limited development capabilities of this energy carrier and cannot 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.

The price of renewable electricity generation technologies will further decrease over the coming decades. The own generation of renewable electricity can have substantial economic benefits for industrial players: regarding emissions, the efficiency of electricity transmissions, and the 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, it would make HTHPs significantly more cost-competitive in the long run.

In Germany, the renewable energy law (EEG) is a levy added to the electricity price for private consumers and industrial consumers 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 in 2020 (Eurostat 2021). The economic analysis showed that electricity costs dominate 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 no longer fulfills its original intent. 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). This would relieve electricity consumers by lowering electricity prices, making sector coupling easier, and promoting electrification in the 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.

The investment costs of HTHPs and other emerging low-carbon technologies require significant up-front investments compared to the existing gas-optimised infrastructure. The IEA (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 level out the fluctuating electricity prices and help industrial players overcome the initial investment hurdle.

There are critical limitations in our analysis. No technical details such as pressure drops or heat losses have been incorporated in the current work. It would require a more detailed engineering approach or a case study at a plant level. The amount and temperature of waste heat available influence how much electricity is needed. Due to the lack of plant-specific data, the specific waste heat volumes have not been considered, assuming that sufficient waste heat flows are available and unutilized from the processes in the food and beverages industry (Hita et al., 2011). Plant-level engineering constraints could play an important role in determining the techno-economic feasibility of HTHPs, yet they are not considered in this systemic analysis aiming to assess the potential of large-scale HP implementations. To better inform HP designs and implementations, more detailed analysis is needed in the future to evaluate the integration of heat flows at the plant level, where various heat integration configurations can be considered. Energy efficiency improvements occur continuously in German industries, which means that the thermal energy demand of processes is likely to decrease over time. The same holds for the temperature value, at which exhaust heat will be available. The production volume of food and beverage products is expected to be stable or slightly increase due to a strengthening of the industrial sector. Therefore, the energy efficiency improvements and the enhanced production volumes can be assumed to level themselves. Further, the German industrial landscape and its industrial players are relatively stable in the long turn. As a result, the industry data from 2018 is reliable for the current study. Economic inputs such as electricity and gas prices fluctuate over time. By including a wide range of electricity prices, the emission factor for electricity, and the OH, our technical, economic, and systemic estimates are robust. Those 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. Lastly, the investment costs calculated by Zühlsdorf et al. (Zühlsdorf et al., 2019) are preliminary estimates. However, it is assumed that the HTHPs will range around 1000 €/kW_{th} (Nicke and Stathopoulos, 2021). The actual installation cost of HTHPs always depends on how they are integrated into existing processes and how systems need to be modified to perform optimally. Our analysis cannot consider the individual integration and hence used generalised investment estimates.

5. Conclusion

We presented a novel analysis of the techno-economic potential of integrating new HTHPs into process-level <250 °C in the German food and beverages industry. We systematically assessed the HTHPs' decarbonisation effects under two waste heat scenarios and considered two HTHP sizes. We show that applying the HTHPs to five sub-branches and their eight energy-intensive processes can meet the process heat demand of 12 TWh. The electricity required to operate the HTHPs lies between 3,3–5 TWh. By applying the HTHPs to the processes, up to 9% of current GHG emissions stemming from the five sub-branches can be abated. The HTHPs' GHG emission abatement potential can increase to 26% with a zero-emission electricity supply. Moreover, the LCOH lies between 35 €/MWh-58 €/MWh, dominated by electricity costs. A carbon tax of min. 38 €/t CO_2-eq. or a reduced electricity price of 42 €/MWh will make the HTHP systems cost-competitive with an existing optimised fossil fuel-based alternative.

CRediT authorship contribution statement

Marina Dumont: Conceptualization, Methodology, Investigation, Writing – original draft. **Ranran Wang:** Conceptualization, Writing – review & editing, Supervision. **Diana Wenzke:** Conceptualization, Resources, Supervision. **Kornelis Blok:** Conceptualization, Supervision. **Reinout Heijungs:** Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

We have shared all data and the model in the Supplementary Interative Plot Data

Acknowledgments

This research publication has been conducted at and is partially funded by the German Aerospace Centre (Deutsches Zentrum fuer Luft-Und Raumfahrt), specifically the Institute of low-carbon industrial processes in Cottbus, Germany.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106605.

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