Exploring the Potential of Urban Manufacturer's Waste Heat for the Residential Heating Transition in Germany

A Spatial Analysis Across Four Federal States

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Exploring the Potential of Urban Manufacturer's Waste Heat for the Residential Heating Transition in Germany. A Spatial Analysis Across Four Federal States

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Abstract

Urban manufacturing is increasingly discussed as a contributor to sustainable urban development, particularly through its potential to supply industrial waste heat for district heating networks (DHN). This paper examines whether urban manufacturing in Germany can provide a meaningful source of waste heat for residential heating. Drawing on novel data from the *Plattform für Abwärme* (PfA), which reports over 19,000 industrial processes across 2,668 sites, we analyse the spatial distribution, sectoral composition, and residential proximity of waste heat sources. After filtering for relevant sites (≥50 °C, ≥12 h daily availability), we assess their distribution across urban, suburban, and rural contexts and conduct a spatial analysis for four federal states—Baden-Württemberg, Bavaria, Lower Saxony, and North Rhine-Westphalia. Our results show that manufacturing accounts for 62% of all reported waste heat sources, with 51% located in towns and suburbs and only 22% in densely populated cities. Notably, 82% of identified sites in the four states lie within 500 metres of residential areas, indicating substantial potential for DHN integration. However, marked regional differences in sectoral composition demonstrate that opportunities are uneven and strongly context dependent. We conclude that industrial waste heat offers a significant but supplementary contribution to Germany's heating transition. Realising this potential will require overcoming technical, governance, and socio-economic barriers, while recognising that defossilisation and sectoral transformation may alter future availability.

Keywords: *district heating networks, urban manufacturing, urban production, waste heat, residential heating, urban industrial waste heat*

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1 Introduction

Urban manufacturing is increasingly recognized as a vital component of sustainable urban development (ARL 2024; BBSR 2024). Its sustainability effects are partly attributed to mixed-use development, which reduces the need for extensive commuting and relies on lower-emission processes (Park 2023). Beyond these aspects, urban manufacturing holds promise in reducing the environmental impact of cities and towns when it functions as an integrated part of the urban system. Sustainability can emerge from synergies within and between industries, particularly in energy use, recycling, and the utilisation of local secondary resources, as frequently discussed in the literature on *urban symbiosis* (Fraccascia 2018; Afshari et al. 2018).

Recent sustainability research has been critiqued for frequently generalising from specific case studies, overemphasising isolated findings, or assuming that small-scale studies are applicable to broader economic systems. A recent review on the concept of 'degrowth' found nearly 90% of 561 papers were grounded more in opinion than empirical evidence (Savin and van den Bergh 2024).

We encounter similar tendencies, especially in applied fields such as urban planning (Angstmann et al. 2025). In these fields, the main aim of research is often not only to analyse and theorize but also to develop and propose applicable solutions for pressing problems. We as researchers do as well contribute to this development by referencing small-n case studies or when perpetuating conceptual solutions found in the scientific discourse that are not yet proven on the large scale. One instance is the assertion that urban manufacturing reduces transport emissions (Hertwig et al. 2024; Juraschek 2022; Barni et al. 2018). While the idea appears logical, more critical studies reveal these benefits to be marginal (Tsui et al. 2021). Despite this, the idea is often perpetuated in policy papers, frameworks, and strategies – often without referring to specific evidence. This harbours the risk of inflating sustainability claims beyond context-specific applicability and creating an echo chamber within the planning and sustainability discourse (Angstmann et al. 2025).

A key area where urban manufacturing may contribute to system-level sustainability is through the provision of waste heat. Waste heat can supply district heating networks (DHN), providing energy to residential buildings, supporting a more sustainable urban infrastructure (Hüttenhain and Kübler 2021). While energy intensive industries have been supplying waste heat to DHN for many decades, the topic currently gains new traction as German authorities currently engage in municipal heat planning. Building on previous arguments past (Bathen et al. 2022; Beckamp 2021; Croxford et al. 2020; Haselsteiner et al. 2019; Juraschek et al. 2018), we argue that industrial locations, and urban manufacturing specifically, can enhance urban sustainability by generating waste heat that is applicable for residential heating and other uses.

In this paper, we aim to analyse the role geographical vicinity between manufacturing and residential uses ('Urban Manufacturing') could play in enhancing urban sustainability. While this this does not solve the problem that the ecological sustainability of urban production is often not sufficiently supported by empirical evidence, it at least provides empirical material one idea perpetuated in the context, namely the potentials of Urban Manufacturing as a source of waste heat.

Previous studies conducted in diverse regional contexts have identified significant amounts of potentially available waste heat that can be repurposed for other industrial processes or residential heating (Adisorn and Schüwer 2025; Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg 2020; LANUV 2019). Furthermore, various implemented or planned initiatives demonstrate how industrial waste heat from different sources can be utilised in urban environments to enhance sustainability. These range from small-scale pilot projects to the integration of energy-intensive industries into existing and evolving heat networks, such as waste heat provided by Aurubis in Hamburg, Thyssen Krupp Steel Europe in Duisburg, and Manner in Vienna (Bathen et al. 2022; Croxford et al. 2020; Haselsteiner et al. 2019). Moreover, several future projects are in the planning stages, including those by Evonik in Herne, Henkel in Düsseldorf-Holthausen, GMH Group in Gröditz, and the MiRo refinery in Karlsruhe.

The discussion about DHN, has in the last years been predominantly framed from techno-economic perspective. Fontaine and Rocher (2021) point to an emerging, yet underexplored, interest in waste heat recovery within social sciences, particularly in energy geography. While recent studies in social sciences, regional research and urban planning have address governance and planning challenges of local heating systems (Bush and Bale 2019; Gabillet 2015; Hawkey and Webb 2014; Rocher 2014; McKenna and Norman 2010). More recent studies on regional waste heat potentials include valuable analyses of technological, organisational and economic barriers and challenges (Adisorn and Schüwer 2025; Schüwer and Adisorn 2025; LANUV 2019). Nevertheless, a comprehensive examination of potentials and barriers for industrial waste heat recovery and utilisation by social and spatial sciences remains lacking. As interest in extending green district heating (DH) solutions grows among local authorities, integrating social and spatial sciences becomes increasingly urgent to address questions of acceptance, governance as well as spatial, and socio-economic dimensions critical for successful implementation. This is where we aim to connect with this paper.

In this publication, we analyse data from Germany to critically assess whether urban manufacturing can truly contribute to urban sustainability by acting as a source of waste heat for residential heating. To achieve this, we utilise novel data on potential industrial heat sources in Germany, made available through the '*Plattform für Abwärme*' (PfA) (BAFA and BfEE 2025c). We provide an overview of reported waste heat sources and their distribution across Germany, with particular attention to four federal states: Baden-Württemberg (BW), Bavaria (BY), Lower Saxony (LS), and North Rhine-Westphalia (NRW). Our analysis focuses on the proximity of these potential waste heat sources to residential areas to offer a comprehensive view of the data and highlight existing blind spots.

As geographers and spatial planners, we cannot provide in-depth analyses of technological systems or industry-specific processes. Nonetheless, from our point of view, a spatial and context-sensitive perspective can significantly contribute to understanding the regional distribution of potential waste heat locations. Previous research from engineering sciences and studies commissioned by regional authorities have often relied on simulations, projections, or technology assessments to infer waste heat availability at regional or national scales (Schüwer and Adisorn 2025; Adisorn and Schüwer 2025; Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg 2020; LANUV 2019). However, we contend that the true potential of waste heat can only be accurately evaluated at the local scale, where the spatial relationship between waste heat supply and demand is critical.

To evaluate the proximity of industrial waste heat sources to urban regions and, more specifically, residential areas, our research is guided by the following research questions:

- What role could the manufacturing sector play in Germany when it comes to waste heat locations? (RQ1)
- What proportion of relevant manufacturing is in cities, towns and rural areas? (RQ2)
- Which and how many of the relevant manufacturing locations are located within proximity to residential areas? (RQ3)
- Are there different regional characteristics concerning distances and manufacturing branches? (RQ4)

2 Overview of DHN in Germany

As of 2024, the heating systems for German residential buildings were primarily gas-based (56.1%), followed by oil (17.3%), and district heating (15.5%) as significant contributors, with smaller shares from electric heat pumps (4.4%), wood and biomass, electricity and other sources (6.3%) (bdew 2025). In contrast, Denmark offers an exemplary model of a country with widespread low-carbon DH, as two-thirds of the households are connected to these networks and with 89% of the energy in Danish DH being climate-neutral (AGFW 2023, p. 22).

2.1 Status quo & prospects

Across Germany, there are approximately 4,184 district heating networks (2022), with about 1.3 million buildings connected to these (2020) (AGFW 2024). Notably, around 30% of the heat generated within these networks is derived from renewable energy sources and unavoidable waste heat (AGFW 2024). Projections indicate substantial changes in the generation structure of district heating by 2030. In 2020, only 3% of district heat was sourced from unavoidable waste heat, accounting for a total production of district heat of 124 TWh. By 2030, this is expected to rise to 7% of 157 TWh, with projections suggesting that by 2045, unavoidable waste heat could comprise 13% of the projected 189 TWh of district heat production (AGFW 2024).

Among Germany's federal states, NRW and BW boast the most extensive DHN. In 2022, NRW had 476 DHN covering 6,570 km, and BW had 896 networks spanning 4,406 km. Comparatively, these figures represent a significant expansion from 2020, when NRW had 317 networks covering 4,390 km and BW had 828 networks spanning 4,193 km (AGFW n.d)[1].

To gain a nuanced understanding of the DHN in Germany, it's essential to consider the various types and their corresponding temperatures. Currently, networks operating at temperatures between 90-110 °C comprise 37% of the infrastructure, followed by those above 110 °C at 31%. Medium temperature networks, operating between 60-90 °C, account for only 23%. In recent years, there has been a decline in steam-based systems, while expansions in low-temperature networks have been minimal (see Table 1).

Type (°C)	DHN (km) 2020	DHN (km) 2022	Development (km)
Water 90-110	11,634	13,762	+2,128
Water ≥110	9,752	11,403	+1,651
Water 60-90	7,160	8,038	+878
Steam	2,557	2,026	-531
Water <60	149	154	+5

Table 1: Length of District Heating Networks in Germany according to the Different Types of Networks (Source: AGFW n.d)

2.2 Defining criteria for our analysis

Different definitions and classifications exist for DHN types, leading to potential discrepancies in analysis. While some researchers and organisations adopt specific classification systems (IEA DHC 2024; Revesz et al. 2020; Jebamalai and Joseph Maria 2019; Østergaard and Svendsen 2017; Lund et al.

[1] The states of NRW and BW also stand out in terms of heat storage, with capacities of 4,989 MWh and 4,542 MWh, respectively, accounting for 15.1% (NRW) and 13.7% (BW) of the total storage capacity of 33.1 GWh in Germany (AGFW 2023, p. 35).

2014; nPro Energy n.d.), the AGFW's categorisation (see above) based on temperature differences highlights this diversity. This variety raises the important question of which temperature thresholds should be used in a rigorous analysis of potential energy efficiencies (see Annex A for a comparison)

DHN are frequently subdivided into different generations based on specific heat qualities, infrastructure, and year of establishment (Lund et al. 2014): The 1st Generation (1880-1930) includes steam networks that operate at very high temperatures and high pressures. While they pioneered the introduction of district heating technology, their widespread use is now limited due to inherent inefficiencies and operational challenges. The 2nd Generation (1930-1980) consists of high-temperature water networks, which operate at temperatures over 100 °C. The transition from steam to hot water in these networks has enhanced safety measures and reduced energy expenditures. The 3rd Generation (1980-2020) features hot water networks with operating temperatures below 100 °C. These networks have become the most prevalent due to their optimised energy efficiency and compatibility with renewable energy integration. The 4th Generation (2020-2050) involves low-temperature networks operating at approximately 30 to 70 °C. Such networks have been shown to reduce heat losses, enhancing their efficiency and sustainability (Lund et al. 2014). Some authors recently proposed a 5th Generation, so called cold networks, that operate at temperatures below (< 35 °C) and thus, closer to ambient temperatures (Revesz et al. 2020). These systems have the capacity to integrate a variety of low-temperature heat sources from the environment, such as geothermal energy. They feature end-user heat pumps and, in contrast to previous generations, also provide cooling. The term 5th Generation DHN is, however, debated in scientific discourse as some describe it as a sub-class of 4th Generation DHN (IEA DHC 2024; Lund et al. 2021).

2.2.1 Waste heat characteristics: Temperatures & runtime

Building on the framework of district heating generations, we chose to include sites with at least one waste heat source at a minimum temperature of 50 °C and those featuring at least one heat source operating for a minimum of 12 hours daily. This temperature aligns with most definitions of the lower supply temperature for 4th Generation DHN, while also encompassing higher temperatures that may be applicable for previous generations (Revesz et al. 2020; Götz 2018; Østergaard and Svendsen 2017; Lund et al. 2014). Our objective with these thresholds is to account for temperatures relevant to both current and future extensions of 4th Generation DHN. Although some researchers propose a threshold as low as 20 °C (Pelda et al. 2020), we consciously chose not to include temperatures below 50 °C in our detailed analysis. This decision was made because such low temperatures would require further subdivision for an in-depth analysis regarding their applicability for heating, cooling, or both. The exclusion of these lower temperatures is also driven by data considerations. Companies with waste heat temperatures of 25 °C or lower are not mandated to report their data to the PfA Database (BAFA and BfEE 2025c). Consequently, although some data on lower temperature outputs and potentials exist, they tend to be inconsistent as they are mostly submitted by companies also reporting higher temperature processes.

2.2.2 Distances for waste heat integration into DHN

Terms such as 'district heating network' (*Fernwärmenetz*) and 'local heating network' (*Nahwärmenetz*) are often used interchangeably, lacking clear definitions or distinctions. This raises questions about the distances between supply sources and demand locations. In water-based heating networks, the average pipeline length per household connection is approximately 66 meters as of 2022 (AGFW 2023). However, making generalised statements about the length of connection lines and the economic operation of these networks is challenging, as site-specific decisions depend on existing infrastructure and projected energy demand.

While there is limited data on household connections, finding specific data on distances significant to energy suppliers is even more difficult. A model-based study concluded that in urban centres like Stockholm, integrating smaller volume heat sources (below 2 MW) into a DHN is economically viable for distances of 2–3 km, and up to 5 km for high-volume sources like data centres (Kumar et al. 2025). Nonetheless, factors such as topological features, demand, and conventional heating energy costs can challenge these results or justify greater distances and investments in connecting infrastructure. Generally, losses from extended transport pipelines diminish the efficiency of district heating systems. Increased pumping power requirements and heat losses along the pipeline lead to considerable energy losses, especially when a significant portion of DH is generated outside urban areas. Therefore, local heat generation is more energy-efficient (Böhmer and Gössl 2009). However, networks transporting heat over distances up to 30 kilometres do exist in Germany, indicating that constructing new transport lines longer than 20 km can be economically viable for cost-effective heat sources with high output (Schmitt et al. 2015, in Engelmann et al. 2021).

Given the lack of clear and transferable data on waste heat distances within DHN and connecting to the discussion on urban manufacturing introduced in Chapter 1, we adopted distances employed in previous research on urban manufacturing. Our analysis of four German federal states focuses on specific radii of less than 500 meters (and below 1,000 meters for contextualisation), when evaluating potential heat sources. This approach aligns with our definition of 'urban manufacturing' as 'near-residential' manufacturing (Meyer and Schonlau 2024). We chose the 500-meter radius based on the ‘Land Use and Public Transport Accessibility Index’ (LUPTAI), which assesses accessibility to a diverse array of facilities and activity destinations. Proximity to residential areas is crucial for managing emissions and land use conflicts, and also for assessing walking distances between residential zones and potential employers or customers (Pitot et al. 2006). While specific, case-by-case calculations might employ different distances depending on expected heat potential, heat source characteristics, and local demand, our aim with this approach is to provide a general overview of urban industries' potential in the heating transition in Germany.

3 Methods & Data

In our analysis we followed multiple steps to engage with the research questions introduced in chapter 1 (Figure 1).

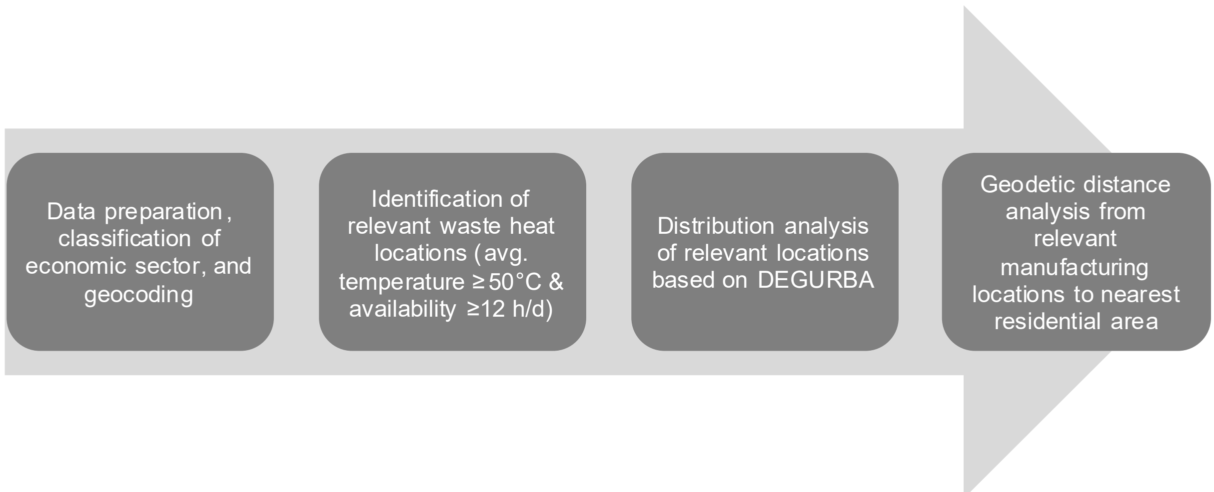

Figure 1: Methodological approach (Source: own depiction)

In a first step, we consolidated the primary dataset used in this study by verifying reported locations and assigning processes and locations to designated economic sectors and activities. The dataset originates from the '*Plattform für Abwärme*' (PfA), which provides a novel overview of industrial waste heat potential in Germany. The platform serves to enhance energy efficiency by making waste heat data publicly accessible, aiming to facilitate its usage. It includes data reported from companies that consume more than 2.5 gigawatt-hours of energy annually. Initial submissions were required by January 1, 2025. The PfA provides specific details for each site, including company names, site addresses, process descriptions, annual heat quantities, average output temperatures, and weekly and yearly availability profiles, as well as further information relevant to potential demand, such as predictability. The platform includes data from 2,668 companies and includes information on 19,065 processes, with a total annual waste heat volume of 160 TWh (BAFA and BfEE 2025a). The PfA aims to facilitate matchmaking, allowing entities with heat demand to identify and leverage available waste heat sources, thus supporting municipal heat planning and local or regional industrial decarbonisation initiatives. To verify the dataset, we consulted various sources, including corporate websites, the commercial register (*Handelsregister*), LinkedIn, Google, and databases like Creditreform. We then executed geocoding in ArcGIS to accurately map and aggregate the location of each waste heat source.

Second, we filtered the dataset to include only locations with high potential, those with waste heat temperatures of 50 °C or above and daily availability of 12 or more hours (see Chapter 2) [2]. This filtering allowed us to identify relevant locations for an initial analysis[3].

In the third step, we analysed the distribution of these potential waste heat sources across different types of regions. Therefore, we employed the 'Degree of Urbanisation' (DEGURBA), which classifies settlement areas into cities (> 50,000 inhabitants and a density of > 1,500 inh./km^2), towns and suburbs (5,000-50,000 inhabitants and a density of >300 inh./km^2), and rural areas (< 5,000 inhabitants and outside urban clusters) (DG Regional and Urban Policy et al. 2018), as provided by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR 2025). This classification helped us determine whether the sources were located in either urban or rural environments.

Finally, we examined the geodetic distance between relevant manufacturing locations and the nearest residential area within four federal states, using this distance to residential areas[4] as a proxy for 'urbanity'. We then conducted a comparative analysis across the four federal states – BW, BY, LS, and NRW – to highlight spatial patterns and sectoral variations.

Through this structured approach, we aim to offer a comprehensive understanding of the spatial distribution and utilisation potential of industrial waste heat. Our analysis contributes to advancing urban sustainability and the decarbonisation of the heating sector in Germany.

[2] Of the processes in the original Pfa-Dataset, 85% have reported runtimes of 12 hours or more, and 56% of the waste-heat-generating processes operate continuously for 24 hours. Most of these processes feature average temperatures equal to or exceeding 50 °C (56%), with 32% reaching temperatures of at least 100 °C, and only 9% having average temperatures of 200 °C or higher. When applying both runtime and temperature criteria at the process level, 47% of the processes qualify as relevant BAFA and BfEE 2025a. However, since this study primarily focuses on the locational level—and considers the theoretical possibility of pooling multiple processes at a single firm location for heat provision, storage, or buffering—the criteria are applied at the location level. This approach results in including locations with multiple qualifying processes, as well as locations where one process meets the ≥12-hour runtime criterion while another achieves higher temperature levels.

[3] In order to make more practical decisions regarding heating network planning and investment, it would be necessary to include additional information regarding the sources (e.g., potential heat providers and characteristics such as monthly/daily volumes, predictability, and long-term availability) as well as the respective regional contexts (e.g., existing network structure, population density and heating demand, building structure, etc.) or if there are any existing internal or external processes already utilising the waste heat potential.

[4] Based on Object type 41001 / AX_Wohnbauflaeche as provided in the Basis-DLM

4 Results

The geolocated dataset of all locations listed in the PfA encompasses information from 4,662 company locations (Figure 2). The manufacturing sector represents the largest share, with 2,890 entries accounting for a substantial 62% of the original dataset. This dominance underscores the significant of manufacturing in generating waste heat within urban and industrial environments. The retail and commerce sector follows, with 770 entries contributing 16.5% of the total dataset. This segment is primarily comprised of retail (658) and wholesale (95) locations equipped with refrigeration systems or refrigerated warehouses. The utilities sector makes up 11.5% of the dataset, with 539 locations, including energy companies (433) and waste management companies (106). Meanwhile, the service sector constitutes 10% of the dataset (463), primarily featuring hospital and clinic locations with their own energy production (237), as well as laundry services (75), IT and communications companies operating data centres (62), and public swimming pool operators (13).

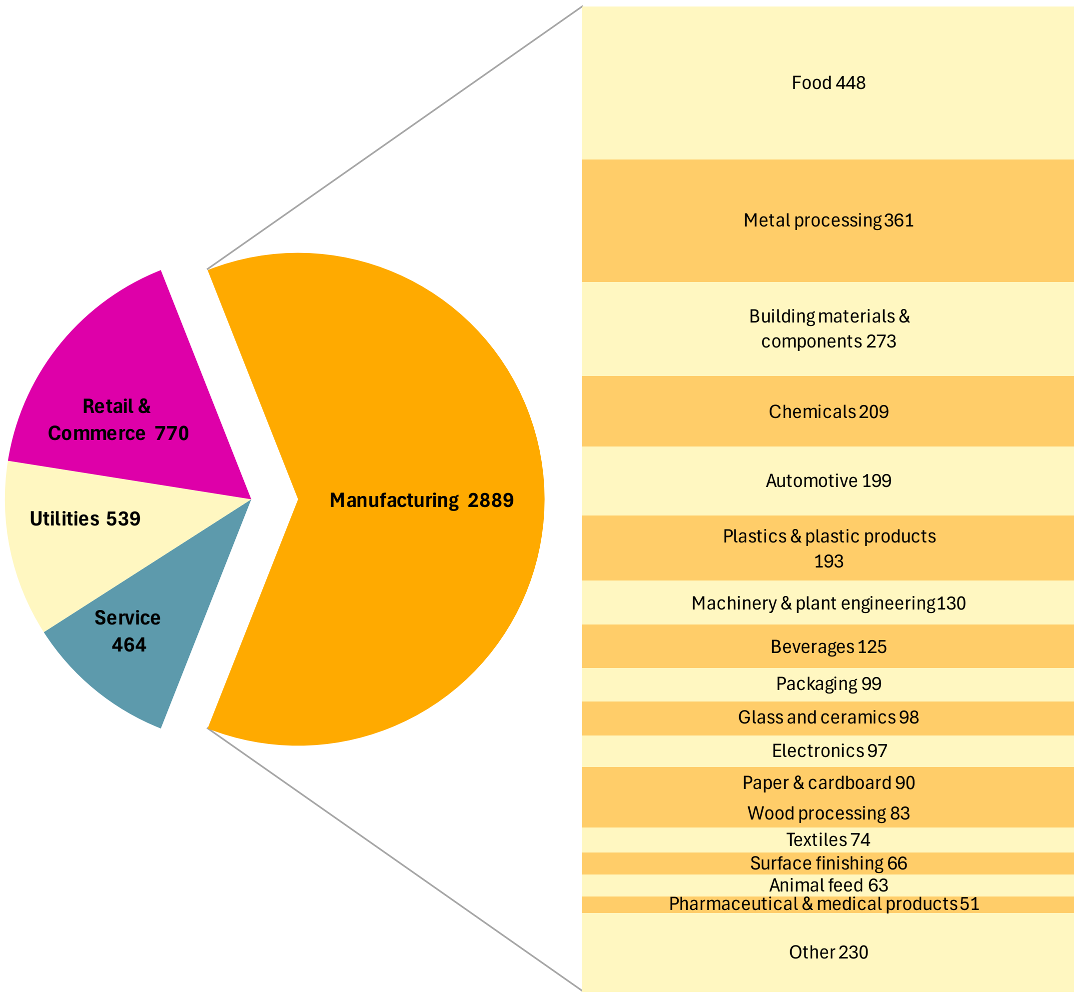

Figure 2: Companies listed in the PfA-Dataset [V1, 14.01.2025] by economic sector 2025 (Source: own depiction based on BAFA and BfEE 2025a)

In the following, we further filtered and analysed the dataset based on different criteria, aiming to answer the research questions introduced in chapter 1 and according to the methods in chapter 3 (see Figure 3).

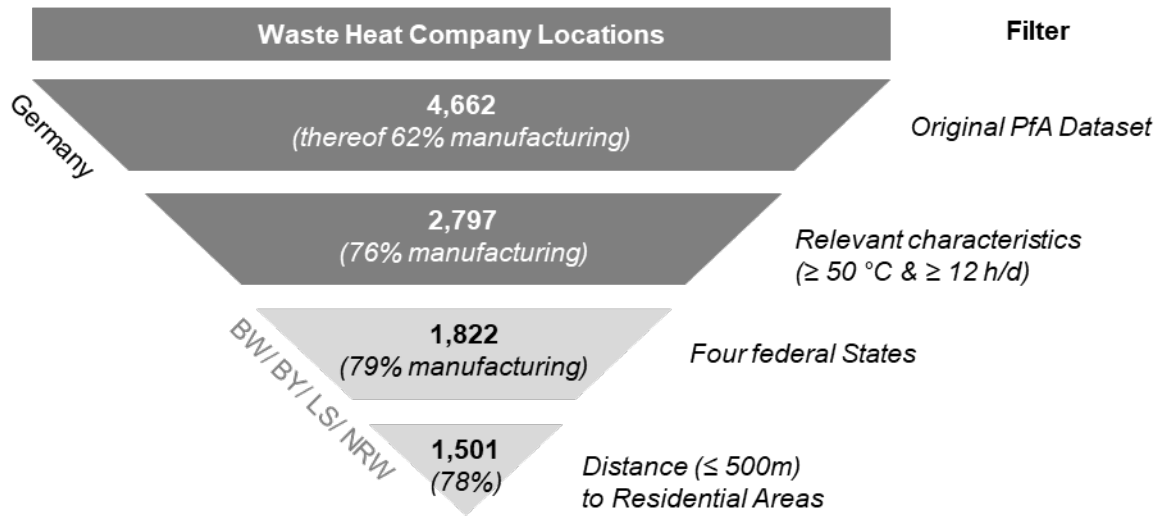

Figure 3: Levels of analysis and description of the dataset. (Source: own depiction based on BAFA and BfEE 2025a; Basis-DLM)

4.1 Role of manufacturing in (relevant) emitting waste heat sources (RQ1)

The manufacturing sector constitutes a substantial portion of the dataset, and we observe a diverse array of processes and manufacturing activities that generate waste heat (see Figure 2). Leading this category is food production, with 448 companies accounting for 15.5% of manufacturing entries. Metal processing follows with 361 companies, comprising 12.5% of entries, indicating its critical in industrial heat emissions. Other prominent contributors include construction materials and components with 273 entries (9.4%), the chemical industry with 209 entries (7.2%). The automotive sector is also noteworthy, with 199 entries or 6.9%, highlighting the energy-intensive nature of its processes. Additional notable contributions come from the plastics sector with 193 entries (6.7%), and machine and plant engineering with 130 entries (4.5%). These sectors illustrate the diverse industrial base of the German manufacturing landscape that is mirrored in the database entries.

The filtered dataset reveals a total of 2,797 relevant locations with processes exhibiting specific waste heat characteristics (temperature of ≥ 50 °C, runtime of ≥ 12 h/d) – in the following named 'relevant'. Within this subset, the manufacturing sector accounts for the majority, with 2,118 locations (76%). The service sector represents 246 locations, while the utilities sector comprises 373 locations. A notable reduction occurred in the retail and commerce sector, largely due low temperature reported outputs (e.g., ≤ 25 °C from refrigeration units). Figure 4 presents the distribution of these relevant PfA company locations across Germany by economic sector.

Figure 4: Relevant PfA locations by economic sector in Germany in 2025 (Source: own depiction based on BAFA and BfEE 2025a; Basis-DLM)

4.2 Distribution of relevant manufacturing locations across German cities, towns & suburbs, & rural areas (RQ2)

The analysis by Degree of Urbanisation shows that the distribution of manufacturing companies roughly corresponds to the respective share of the population – though the proportion of companies located in cities is lower, while it is higher in towns and suburbs (see Table 2). In the following, we provide a spatial analysis regarding the distance to residential areas in four German federal states.

DEGURBA-Category	Number of German cities	Distribution of the German population	Distribution of waste-heat relevant manufacturers
Towns & suburbs	2680	42%	50%
Rural areas	8147	21%	24%
Cities	151	37%	25%

Table 2: Number of Municipalities and Share of Waste Heat Companies by Degree of Urbanisation in Germany (Source: own calculation based on BBSR 2025; BAFA and BfEE 2025a).

4.3 Proximity of the relevant manufacturing locations to residential buildings: Analysis for four federal states (RQ3)

In our spatial analysis, we focus on especially relevant waste heat locations, which met best our criteria based on temperature quality (≥ 50 °C) and operating hours (≥ 12 h/d). The previous type-analysis identified 2,797 locations distributed across all German federal states. Compared to other economic sectors, relevant manufacturing locations account for the largest share (76%) of potential waste heat sources in all German regions, which reasserts its role as a potential source for future waste heat solutions.

As the distribution is connected to local population size, a decentralised German economy structure and industrial history, most of the locations that can be seen as relevant are found in federal states with higher share of industry and larger amounts of population. Especially BW, BY, LS, and NRW emerge as significant contributors to our selected dataset of relevant locations (65% of all waste heat sectors), owing in part to their established industrial bases and extensive manufacturing sectors (68% of relevant manufacturing company locations in the dataset are in these states) (see Table 3).

Therefore, in the following we examine the manufacturing companies' spatial distribution in the federal states of BW, BY, LS and NRW.

Federal State	Service	Utilities (Energy & Waste)	Retail & Commerce	Manu-facturing	Sum
North Rhine-Westphalia	49	90	11	460	610
Bavaria	48	34	1	428	511
Baden-Württemberg	19	50	2	285	356
Lower Saxony	18	28	37	262	345
Hesse	21	28	2	106	156
Saxony	9	37		90	135
Saxony-Anhalt	15	21	2	97	135
Rhineland-Palatinate	11	12	1	98	121
Thuringia	13	11	1	86	111
Brandenburg	9	22		50	81
Schleswig-Holstein	6	7		52	65
Mecklenburg-Western Pomerania	5	9		28	42
Hamburg	6	9	1	16	32
Bremen	3	7		21	31
Saarland	6	5	2	17	30
Berlin	8	1		19	28
Unknown		*2*		*3*	*5*
Sum	246	373	60	2118	2797

Table 3: Number of companies according to relevant waste heat sectors across German federal states (Source: own calculation based on BAFA and BfEE 2025a).

4.3.1 Analysis of manufacturing locations

While 62% of the sites in the initial dataset belong to the manufacturing sector, their importance becomes even more pronounced when considering locations with higher heat quality and availability. In this subset, manufacturing accounts for 76% of all qualifying facilities. The relevance is further reinforced in urban contexts and in proximity to residential areas: within the four federal states analysed, manufacturing represents 79% of the relevant sites. Table 4 details these locations and their distances to residential areas. Across all four states, 82% of relevant manufacturing facilities are situated within 500 metres of housing, with only minor variation between three of the states. The highest concentration of near-residential manufacturing with waste heat potential is found in North Rhine-Westphalia (BW: 78%, BY: 79%, LS: 82%, NRW: 87%).

	Number of manufacturing locations within a distance of... (discrete distance intervals; all locations in brackets)					
Federal State	**≤100 m**	**101-250m**	**251-500m**	**501-1000m**	**>1000m**	Sum
Baden-Württemberg	52 *(82)*	85 *(104)*	84 *(98)*	49 *(54)*	15 *(18)*	285 *(356)*
Bavaria	125 *(157)*	115 *(134)*	98 *(114)*	65 *(77)*	25 *(29)*	428 *(511)*
Lower Saxony	81 *(113)*	71 *(95)*	64 *(78)*	41 *(50)*	5 *(9)*	262 *(345)*
North Rhine-Westphalia	147 *(209)*	147 *(183)*	106 *(134)*	53 *(71)*	7 *(13)*	460 *(610)*
Sum	405 *(561)*	418 *(516)*	352 *(424)*	208 *(252)*	52 *(69)*	1435 *(1822)*

Table 4: Number of relevant waste heat manufacturing company locations and their distance to residential areas by federal state. Numbers in brackets show all relevant economic sectors. (Source: own calculation based on BAFA and BfEE 2025a).

These findings suggest that there are indeed opportunities for leveraging industrial waste heat in municipal heat strategies, at least according to their distribution in the vicinity of residential areas, and that Urban Manufacturers as one source of waste heat may play a role in enhancing urban sustainability. However, as the four German regions are highly different in structure, looking at sectoral differences helps to better understand the role different branches of manufacturing that could serve as potential heat sources for urban DHN.

4.3.2 Analysis of manufacturing branches

Looking at the key sectors across subset of relevant 1,435 companies in the four federal states shows that most industry locations are in the vicinity of at least some form of residential area (population density is not analysed here). Sectors of which a large share of locations are near or nearest to residential areas (within a radius of 250 m) are beverages (75%), tools (70%), paper and cardboard (69%), metal processing (69% of the sectors locations within 250 m).

Figure 5 shows the average distance of relevant industries (with more than 10 occurrences in the dataset) it can be stated that especially the beverage production, metal processing as well as paper and cardboard production are near to residential areas, followed by glass and ceramics, textiles, packaging and machinery and plant construction. Animal food, fuels, surface finishing as well as mineral products are on the other end of the continuum with an average of more than 500m distance to residential use. While we could not execute a detailed analysis of the reasons for this, one can infer that this might be due to them being located in industrial areas for emission reasons (fuels, animal food), distant to residential use due to space demand or due to locations that are established at natural resource occurrences or mining pits (mineral products).

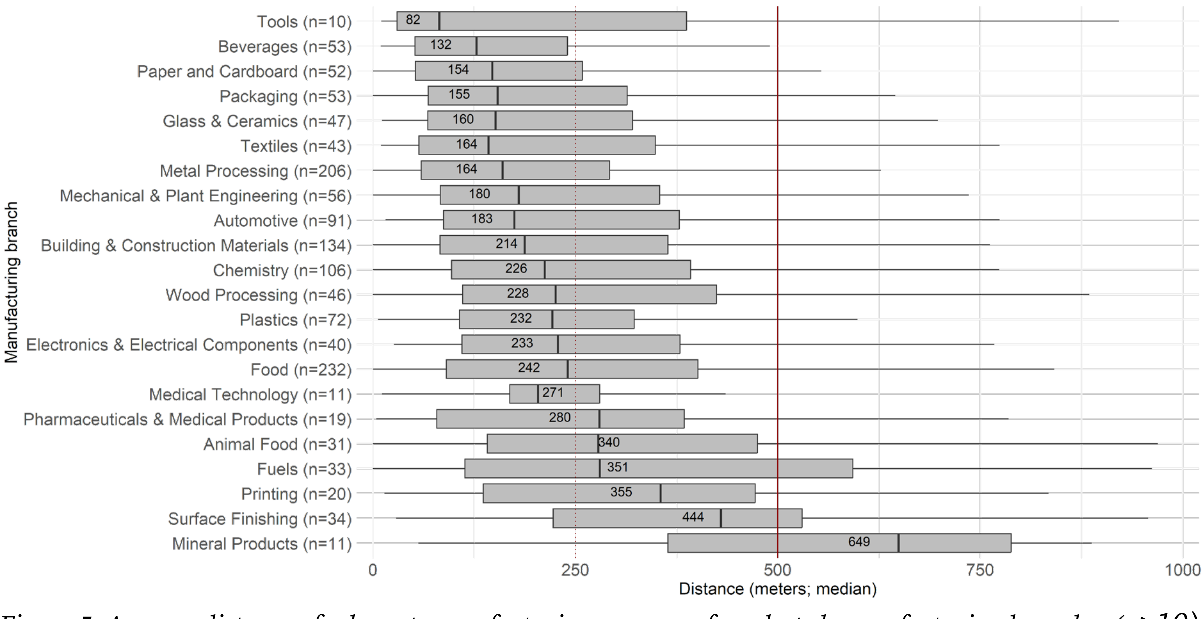

Figure 5: Average distance of relevant manufacturing company for selected manufacturing branches (n≥10). (Source: own depiction based on BAFA and BfEE 2025a).

Differences between the four federal states key economic sectors, however, also appear in the dataset. With these key manufacturing sectors mattering differently in different regions.

Overall, reporting manufacturing branches with higher numbers of locations are also featured in the filtered dataset (e.g. with respective waste heat qualities and in close distance to residential uses. Metal production, food, and manufacturing of construction materials make up a large share of the total reporting industries in the four federal states (38%), as well as in the subset (41% <250 m and relevant).

An equal distribution across the full dataset as well as in the subset considering relevant industries in proximity to residential uses is however not the case across all branches. On the one hand, locations from the manufacturing branches chemicals, paper and cardboard, glass and ceramics, wood processing, textiles, fuels and printing are relevant in terms of waste heat qualities (temperature & runtime) more than 80% of the locations featured in the overall dataset (across four federal states) are also included in the subset relevant. However, of these only in the branches paper and cardboard as well as glass and ceramics (more than 50% of the locations) can be in direct distance to residential (250 m). On the other hand, manufacturing branches that include only some locations that qualify for waste heat according to our criteria in some cases provide proximity to residential. So, while only 10 out of 17 toolmakers based in our four federal states that reporting waste heat in the database can be seen as relevant from a quality of heat view, 7 of these are close to residential areas. The same is true for the beverages sector, where 40 out of 53 relevant locations are in direct vicinity to residential.

In many cases, a sectoral view does, however come too short to allow for broader conclusions as different sectoral clusters can be observed in different German regions.

4.4 Regional characteristics in between the four federal states concerning distances & manufacturing branches (RQ4)

In our spatial analysis of relevant manufacturing branches, we identified some with meaningful spatial relevance due to their proximity to residential areas (≤500 m). Their prevalence across the four federal states does however vary, especially when it comes to different types of manufacturers or manufacturing branches (Table 5 & Figure 6). Metal processing emerges as a key contributor, with 186 locations within 500 meters of residential zones, notably clustered in NRW with 103 entities (55%). The food sector (e.g., bakeries and dairies), features 190 locations within 500 meters, with substantial relevance in NRW (63), LS (58) and BY (46). Moreover, the construction materials sector has 108 entities near residential spaces, 37 in Bavaria and 29 in NRW. Additionally, the chemicals sector includes 85 entities within 1000 meters, with one sectoral cluster in NRW (33). Packaging producers (45) are, mainly located in BY (16), followed by BW and NRW, each 12), locations of the paper and cardboard industry can be found throughout all regions.

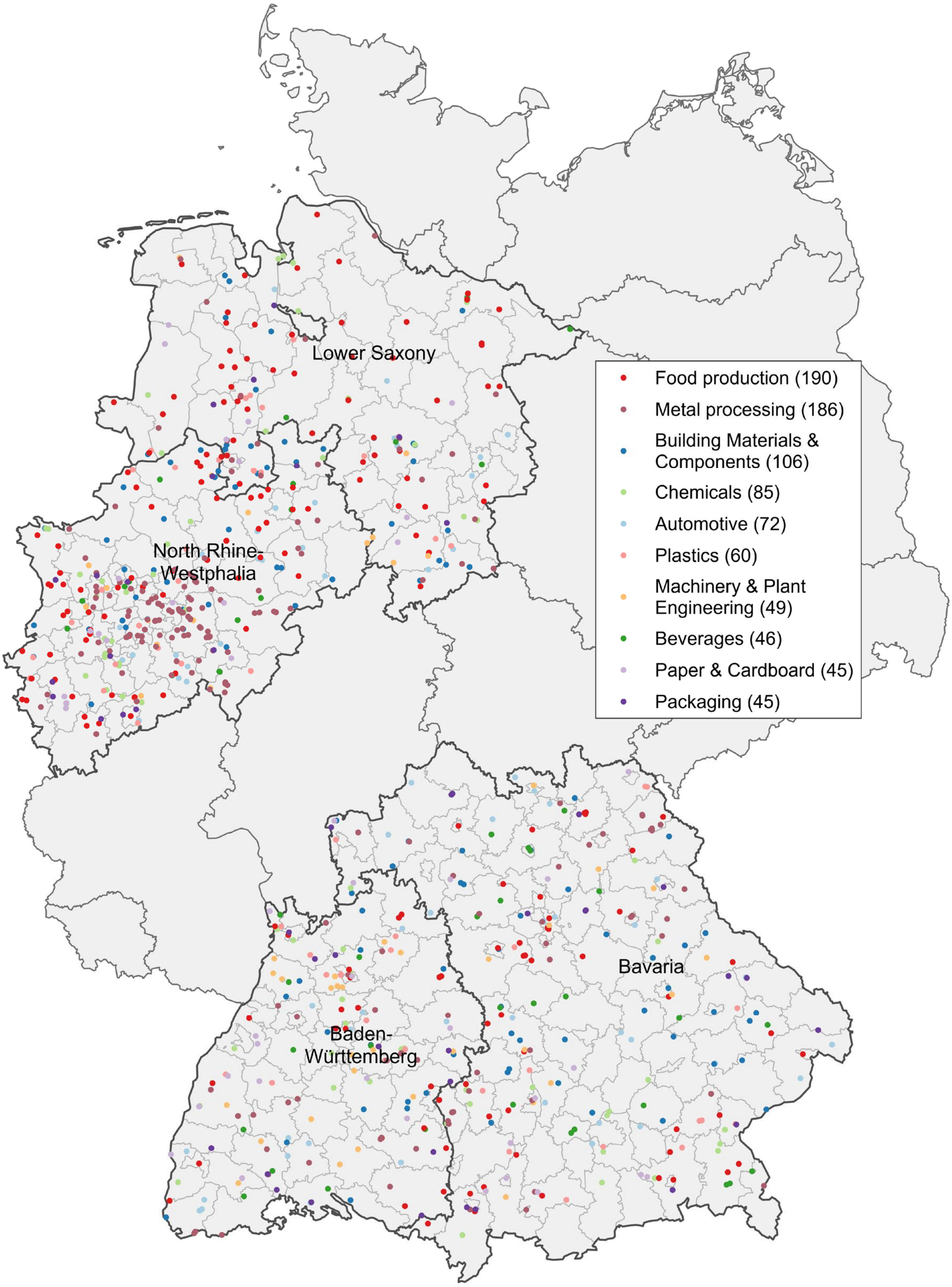

Figure 6: Top 10 Relevant Manufacturing Branches within 500m of residential areas in BW, BY, NRW & LS (Source: own depiction based on BAFA and BfEE 2025a)

Furthermore, some industries in near-residential locations are prevalently found in some federal states. When it comes to BY, especially surface finishing (11 out of 22), the beverage sector composed of for example breweries, mineral water companies (19 out of 46) as well as the automotive sector (27 out of 72) as well as glass and ceramics and printing (9 out of 16) are prominent branches. In NRW the metal processing textile sector (19 out of 36), wood processing (17 out of 36) and chemicals (39%). In

BW pharmaceuticals and medical products are especially relevant (7 out of 16) and engineering (20 out of 49). In LS the fuels sector (14 out of 18) and animal feed (11 out of 22) play a larger role.

Manufacturing Branch	BW	BY	LS	NRW	Share per Branch
Automotive	1,4%	2,3%	0,8%	1,7%	6%
Building Materials	1,4%	3,1%	2,0%	2,5%	9%
Chemicals	1,3%	1,9%	1,3%	2,8%	7%
Printing	0,3%	0,8%	0,1%	0,2%	1%
Electrical Components	0,8%	1,2%	0,3%	0,7%	3%
Beverages	0,9%	1,6%	0,4%	1,0%	4%
Glass & Ceramics	0,2%	2,0%	0,4%	0,9%	3%
Wood Processing	0,6%	0,8%	0,3%	1,4%	3%
Fuels	0,1%	0,0%	1,2%	0,3%	2%
Plastics	1,1%	1,3%	1,2%	1,5%	5%
Food	2,0%	3,9%	4,9%	5,4%	16%
Machinery & Engineering	1,7%	0,9%	0,5%	1,0%	4%
Metal Processing	2,3%	3,0%	1,8%	8,8%	16%
Surface Finishing	0,2%	0,9%	0,2%	0,6%	2%
Paper, Pulp & Cardboard	1,0%	1,2%	0,7%	0,9%	4%
Pharmaceutical & Medical	0,6%	0,3%	0,1%	0,3%	1%
Textiles	0,5%	0,7%	0,3%	1,6%	3%
Animal Feed	0,0%	0,5%	0,9%	0,4%	2%
Packaging	1,0%	1,4%	0,4%	1,0%	4%
Number of Locations	221	338	216	400	1175

Table 5: Distribution of urban manufacturing waste heat locations across four federal states in Germany (relevant locations ≤ 500 m) (Source: own calculation based on BAFA and BfEE 2025a).

Manufacturing may be responsible for a greater share of waste heat that can in the future be used to power DHN. However, it's important to consider regional differences in manufacturing branches that could be involved. While the data used for this analysis may provide a first glimpse on what industries may matter where, changes in regional economic composition connected to these industries may lead to different outcomes in different regions.

5 Discussion & critical engagement with the findings

In the following chapter, we discuss the findings in the context of the previous studies under special consideration of those focusing on the European or German national context.

5.1 Relevance & limitations of industrial waste heat data

The examination of industrial waste heat as a contributor to urban residential heating must critically engage with its data sources and inherent limitations. Traditional methodologies often utilised for estimating waste heat potential, such as the evaluation of exhaust gas data, emission data or process parameters allow for broad estimates on a regional or national scale but are often not taking into account spatial contexts, while analysis of small numbers of processes in closed environments, regional estimates based on sectoral data or surveys and modelling based on other datasets (e.g., emission data) are limited by their indirect nature and general applicability (Theisinger et al. 2022; Brueckner et al. 2017; Brueckner et al. 2014; McKenna and Norman 2010). The development of comprehensive databases like the PfA/BAFA dataset represents a significant advancement, providing crucial locational and qualitative data that enhance our understanding beyond estimates based on indirect data.

Despite these improvements, there are still uncertainties regarding the quality and quantity of individual waste heat sources persist when it comes to specific cases, which presents significant barriers to their effective integration into district heating systems (Pelda et al. 2020). Our analysis reflects these insights. While the new database provides more direct insight into existing waste heat sources, it remains limited by broader economic factors such as fluctuations in industrial production and company’s focus on their main processes (Adisorn and Schüwer 2025). These realities underscore the need for these waste heat sources to be viewed as complementary assets, rather than primary solutions, to urban heating (Brueckner et al. 2014).

5.1.1 Potential & barriers to industrial waste heat utilisation

The potential for industrial waste heat to support urban heating solutions is supported by numerous studies, as noted in the introduction. There are however, until now, only some systematic assessments of barriers for real-world development that analyse potentials and barriers in different regional settings (Adisorn and Schüwer 2025; AGFW 2020; Lygnerud and Werner 2017, 2018).

Economic and policy landscapes play pivotal in shaping waste heat recovery's feasibility (Fontaine and Rocher 2024; Fritz et al. 2022) as profitability over the long term and lower expenses for companies using excess heat are essential (Fritz et al. 2022).

District heating operators focus on long-term planning (10-20 years), while manufacturers' heat provision depends on their economic situation, energy prices, and technology, which can change frequently (Adisorn and Schüwer 2025; AGFW 2020). Typical waste heat agreements, furthermore, mainly prioritise the refinancing of new plant components and most projects have no margin for extra costs until depreciation of components is completed (AGFW 2020).

This underscores the need for robust policy frameworks to support waste heat integration, mitigating monopolistic controls by district heating operators that might resist incorporating industrial heat due to revenue concerns (Fritz et al. 2022). Furthermore, the question who should foster or implement the solutions remains unanswered generally (Adisorn and Schüwer 2025), as different actors such as the municipality, the companies that run relevant processes as well as local network operators are required to work together for successful implementation (Schüwer and Adisorn 2025; LANUV 2019). Addressing these barriers requires policies facilitating stakeholder interaction and investment certainty (Fontaine and Rocher 2024).

5.1.2 Challenges in times of transformation & global economic restructuring

The potential urban industries offer regarding waste heat utilisation, has, to be seen in the larger economic context. When looking at current economic developments in Western European Countries, a variety of analyses points in the direction that near-residential industries are declining (BBSR 2024). Space use conflicts, highly lucrative investments in residential space (Gärtner and Meyer 2025; Ferm 2023), emissions (e.g., noise, odour, vibration), logistics and traffic connected with modern ways of production (just-in-time, global production networks) and other developments change the location of production. Former near-residential, integrated manufacturing into city fabric, thus, has been shifted to industrial areas at the periphery or – in some cases – offshored (Meyer and Schonlau 2024). Individual case studies (Bathen et al. 2022; Croxford et al. 2020; Bauer and Lentes 2014) and concepts of cities (e.g., Bremen, Brussels, London, Vienna) denote that there may be potentials for urban manufacturing to enhance urban system wide efficiency by providing waste heat as a resource. However, an important consideration within the Western European context is whether reliance on industrial waste heat remains viable on the long run in allegedly de-industrialising nations such as Germany.

Another development influencing the manufacturing sector is the shift towards low-carbon economies. This plays out differently in different industries, with some being able to electrify former fossil fuel-based processes, while others have hard-to-abate processes that require a large-scale transformation of fuels, resources and processes (e.g., steel, chemicals and cement production).

Our findings suggest that manufacturing branches such as refineries, metals, chemicals, wood, and paper have substantial heat capacities. This is consistent with earlier analyses that identified these sectors as key contributors to DHN (Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg 2020; AGFW 2020; Lygnerud and Werner 2018). However, these industries are also facing transformational pressures, as highlighted by Lygnerud and Werner (2018), which makes their role as stable heat providers uncertain.

Although waste heat is considered CO_2-free because it is a by-product of another essential process (AGFW 2020), it largely stems from fossil energy sources, albeit indirectly. In this context, the question of lock-in arises, as it is sometimes claimed that additional profits from heat sales in the manufacturing sector could actively prevent or delay the decarbonisation and efficiency improvement of industrial processes (AGFW 2020). As inefficient processes, energy costs and fees for the CO_2 generated in the initial process are often higher than the revenue made from waste heat, some argue that this challenge may not be as significant as suggested (AGFW 2020). Nevertheless, when establishing waste heat utilisation from energy-intensive sectors transitioning to other technologies, this must be considered, as well as when it comes to the analysis of waste heat potential at a sectoral or regional level.

Assessing the real contribution of specific waste heat solutions to energy and carbon efficiency needs to be conducted on a sectoral or case-specific basis. Industrial transformations can impact the viability of certain sectors or technologies that generate waste heat. Electrification of processes may increase efficiency and enable greater operational flexibility according to demand, which can result in lower excess temperatures and reduced hours of waste heat availability. While repurposing waste heat from industries such as steelmaking and petrochemicals may be efficient in replacing other heat sources, it should not justify prolonging the lifespan of broadly inefficient or otherwise unsustainable technologies, such as blast furnaces. This has been broadly discussed in the context of carbon lock-in (Unruh 2002, 2000) but also from a perspective of uncertainty (Lygnerud and Werner 2018) especially for investors connected to the probability of industrial waste heat point sources stopping their activity in times of transformation, either due to technology phase out or due to the closure of industrial sites in some locations. Here, long-term investments in infrastructure meet middle-term changes in the industrial structure or strategy of relevant actors or their reaction to changing political contexts or external shocks (Jakobsen and Fløysand 2025).

Transformation, however, also may create novel sources and opportunities for new waste heat utilisation. With a variety of industries aiming to source or utilise hydrogen in their processes to defossilise, integrating waste heat from not industrial electrolysers into DHN constitutes an emerging opportunity for sustainable energy systems and, thus, an emerging field of research (Kayali 2023; Miljanovic and Jonsson 2022). Although these configurations face challenges with heat load management and system efficiency, both studies highlight economic viability under optimal conditions. Most recent assessments of national potential in Austria estimate that electrolysis waste heat could meet up to 12% of Austria's 2030 district heating demand if integrated effectively, especially in low-temperature systems (Böhm et al. 2021). However, success depends on strategic placement near heat sinks to reduce energy losses and operational considerations for seasonal variability. So different studies underscore the technical feasibility and economic promise of electrolysis waste heat integration.

The whole field has, thus, to be seen as highly evolving in the context of industrial structural change as well as politically driven transformation from or to certain green(er) technologies. Here a more decentralised heat system relying on several sources (not only fossil power plants as it has been in the past) may enhance resilience but may also cause challenges as the future development of key industrial actors (anchors) from certain sectors can't be fully anticipated. Simultaneously it allows to integrate future sources, not yet anticipated.

In this context, questions for further research arise concerning the long-term availability of waste heat currently recovered from processes that may change in the medium-term. As deindustrialisation and the shifting of industrial activities across space are highly sectoral processes, it is important to reflect this in future regional waste heat potential analyses.

5.2 Limitations of this study & call for research

In the field of industrial waste heat utilisation, this study uncovers promising opportunities and spatial dynamics within certain German regions. However, further research is necessary to enhance and refine the insights gained from this analysis.

Expanding this analysis to cover the entire country of Germany and not just four federal states could yield significant insights, especially given the regional variations in the prominence of DHN. For example, areas such as the eastern lignite mining regions, where large power plants have historically played a crucial in residential heat generation (e.g., Leipzig), might present distinct opportunities and constraints. However, this broader scope was not feasible in this study due to a lack of comprehensive data on residential areas across Germany and funding constraints tied to the study's scope as an unfunded research project.

The dataset used in this study may not comprehensively represent all relevant companies that contribute to industrial waste heat. As this research coincided with the early stages of the reporting platform's implementation, there is potential for increased participation among companies in the future. Furthermore, only 80% of the listed companies agreed to disclose this information publicly (BAFA and BfEE 2025c). This analysis only utilises data that way available in early 2025. Newer actualisations of the dataset may provide a more detailed picture, as the updated version 2 from July 2025 lists 25,596 processes with a volume of 243 TWh/a distributed across 6,358 company locations (BAFA and BfEE 2025b). Revisiting this analysis after the platform has gained broader recognition and usage by businesses, potentially incentivised by non-compliance fees, could provide a more accurate portrait of the German waste heat landscape. Especially as the relevance of different sectors, such as

IT centres and services or new technologies, may grow over time, necessitating further updates to the dataset to capture these evolving dynamics.

While this study provides valuable insights at a macro level, it lacks company-specific or site-specific details, such as the technology readiness of individual companies and the classification of hybrid entities (e.g., commerce/logistics, manufacturing/logistics). Additionally, it does not account for local contextual factors that can greatly influence the feasibility and implementation of waste heat recovery solutions. These factors include space availability for infrastructure development, actual heat demand in specific locations, the presence of current or potential network operators (both city-wide and localised), and existing heat transmission infrastructure.

Previous research also states that municipal heating networks based on waste heat as well as other projects in the context of urban symbiosis, depend heavily on context-specific factors (Neves et al. 2020). Therefore, using manufacturing heat may be a viable solution in some but not in all cases where industry and residential uses are co-located.

For each network-type a different context (technology, availability of infrastructure, etc.) may be more suited (AGFW 2020), which cannot be fully considered in geographical analyses covering large areas.

In summary, addressing these limitations through further research – enriched by a more comprehensive dataset, detailed local analyses, and a broader national perspective – will significantly contribute to understanding and leveraging industrial waste heat as a vital component of urban energy transitions.

6 Conclusion

We conclude with answers to our previous mentioned research questions.

RQ1: The manufacturing sector constitutes a predominant source within the waste-heat dataset, representing 62% of all identified waste heat-emitting sites. Its relevance is even higher, when considering further parameters such as process duration and temperature levels.

RQ2: Owing to Germany's pronounced spatial decentralization, industrial facilities with waste heat potential are distributed across diverse locational typologies. Only 22% of relevant manufacturing enterprises are situated within densely populated urban centres, whereas 51% are located in less densely populated towns and suburban areas. Nonetheless, the presence of these industries in peri-urban or rural contexts does not disqualify them as relevant when it comes to supply waste heat to district heating networks, as Germany's location is also distributed across the country.

RQ3: A substantial majority (68%) of manufacturing entities generating significant waste heat in Germany are concentrated within the federal states of Baden-Württemberg (BW), Bavaria (BY), Lower Saxony (LS), and North Rhine-Westphalia (NRW), encompassing 1,435 locations. Of these, 1,175 sites (approximately 82%) are situated within a 500-meter radius of residential areas, thereby indicating potential for direct integration into urban heating systems.

RQ4: The four federal states analysed, however, differ in their spatial-infrastructural, and sectoral composition. NRW exhibits a predominance of metal processing and food industry installations proximal to residential zones; LS similarly demonstrates a high concentration of food processing facilities near inhabited areas. Conversely, automotive manufacturing alongside construction materials, glass, and ceramics predominate in BY, while machine and plant engineering is more prevalent in BW. These findings suggest that solutions tailored for specific regional contexts or manufacturing branches may lack generalizability across differing industrial landscapes. Moreover, ongoing processes of industrial decarbonization and structural transformation imply that currently applicable interventions based on certain sectors that are identified as key sectors in this study may require dynamic adaptation over time due to meaningful changes within these sectors and processes used in these.

In summary, industrial waste heat represents a significant yet supplementary resource for advancing urban heating transitions. Accordingly, the initial hypothesis – that urban manufacturing can contribute to system-level sustainability by supplying waste heat to local heat networks – can be affirmed in general terms.

However, the effective integration of waste heat as an urban resource necessitates overcoming substantial technical and socio-economic challenges through further research, especially in collaboration between engineering disciplines and spatial and social sciences. In particular, energy geography, regional studies, and urban planning offer promising perspectives on the regional implementation of novel solutions, acceptance by residents, as well as when it comes to potential challenges related to lock-in effects and cross-sectoral interdependencies. Facilitating stakeholder engagement, enhancing policy instruments, and aligning technological capabilities with societal demands will be essential for successful implementation. Future research should prioritize localised, context-specific investigations as well as sectoral studies (e.g. of specific manufacturing branches) that integrate spatial and social dimensions to foster resilient and sustainable utilisation of waste heat within urban energy systems but also acknowledged that not only the heat sector itself but different branches of manufacturing are subject to ongoing change due to defossilisation efforts, which poses risks but may also lead to new solutions.

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