energies

Article

How Much Excess Heat Might Be Used in Buildings? A Spatial Analysis at the Municipal Level in Germany

Markus Fritz [1,2,*], Ali Aydemir [2] and Liselotte Schebek [1]

[1] Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Strasse 48, 76139 Karlsruhe, Germany
[2] Chair of Material Flow Management and Resource Economy, Institute IWAR, Technical University of Darmstadt, 64287 Darmstadt, Germany
* Correspondence: markus.fritz@isi.fraunhofer.de; Tel.: +49-721-6809-249

Abstract: Excess heat can make an important contribution to reduce greenhouse gas emissions in the heating and cooling sector. Due to the local character of heat, the local excess heat potential is decisive for using excess heat. However, the spatially distributed potential and the subdivision of the potential into different subsectors have not been sufficiently investigated in Germany. Here we analyse the excess heat potential in Germany according to different subsectors and spatially distributed to the municipal level. We use data of more than 115,000 records on exhaust gas and fuel input from over 11,000 industrial sites. We calculate the site-specific excess heat potential and check its plausibility using the fuel input of the respective industrial sites. Finally, we compare the excess heat potential with the residential heat demand at the municipal level. Our results show that the excess heat potential in Germany is about 36.6 TWh/a, and that in 148 municipalities, the annual excess heat potential is greater than 50% of the annual heat demand. In conclusion, there is a large potential for excess heat utilisation in Germany. In some regions, more excess heat is available throughout the year than is needed to provide space heat and hot water.

Keywords: waste heat; excess heat; spatial analysis; industrial energy demand; heat demand; industrial subsectors

Citation: Fritz, M.; Aydemir, A.; Schebek, L. How Much Excess Heat Might Be Used in Buildings? A Spatial Analysis at the Municipal Level in Germany. *Energies* **2022**, *15*, 6245. https://doi.org/10.3390/en15176245

Academic Editor: Chi-Ming Lai

Received: 15 July 2022
Accepted: 23 August 2022
Published: 26 August 2022

1. Introduction

Increasing energy efficiency in all sectors is an important pillar of achieving the EU's climate protection goals and ensuring security of supply in the coming years. Industry is responsible for about a quarter of the final energy demand in the EU. More than 70% of this is used to provide heating and cooling, of which more than 80% is used to generate process heat [1]. Large amounts of this energy are released into the environment in the form of unused excess heat [2,3]. From a technical point of view, industrial surplus heat can be described as heat generated during an industrial process and cannot be used for the actual goal of the production process [4]. From a societal perspective, it can be described as heat that is a by-product of industrial processes and is currently not used but could be used in the future by society and industry to increase energy efficiency [5].

However, there are different technical and non-technical barriers to using industrial excess heat [6]. Technical barriers are temporal imbalance, local discrepancy and quality mismatch [7]. These barriers can be overcome through technical developments. However, as mentioned above, there are also non-technical barriers. These are mainly the economic viability and long payback periods of excess heat use [6,8,9], trust and transfer of information [8], lack of know-how and capacity [6,9] and the binding character of contracts [6,9]. However, some factors promote the implementation of projects for external excess heat utilisation [6]. These are the commitments of individuals, the commitments of local actors such as politicians, innovative business models where the industrial company does not have to cover the upfront investment and solutions that ensure the long-term management of excess heat.

There are several ways to use this excess heat [5,6,10]. First, the excess heat can be used internally in the process in which it is generated. This means that the excess heat is recovered and reused. Second, the excess heat can be fed and used in other processes or plants. This can be done either internally in the same plant or externally in another plant or district heating networks. Third, the excess heat can be converted into other forms of energy. For example, excess heat can be converted into electricity via Organic Rankine Cycles (ORC) or into cooling energy via adsorption systems.

1.1. Literature Overview

The methodological spectrum to calculate the amount of excess heat ranges from estimation approaches based on key parameters [4,11,12] to empirical works, such as that by Brückner et al. [13] for Germany based on an emissions survey. In addition, there are also studies that analyse the role of industrial excess heat for district heating, whereby the industrial excess heat quantities taken so far are based only on estimations based on key parameters [14–16]. For these analysis on excess heat potentials, a distinction can be made between bottom-up and top-down analyses. Bottom-up analyses [2,11,17,18] show a lower potential than top-down analyses [4,12]. Some works deal with the potential assessment of excess heat to cover the space heating demand [17,19]. In a few studies, spatial characteristics are taken into account, and the distribution via district heating networks or other technologies is examined [9,17]. Potentials for the use of industrial excess heat have been analysed in the literature for individual countries [13,18,19], for several countries [14,20] or on a global level [21]. To determine the excess heat potential in industry, a distinction can generally be made between top-down and bottom-up approaches.

In top-down analyses, the possible amount of excess heat is determined based on sector-specific data. In Groß and Tänzer [12], a potential of excess heat of approx. 280–300 TWh/a is determined for the 12 most energy-intensive industrial sectors in Germany. Pehnt et al. [4] estimate the potential of excess heat potential in Germany at around 130 TWh/a. Here, the results of a Norwegian study were transferred to the German industrial structure. Persson et al. [16] also determined the excess heat potential for Europe based on an emission-based assessment by subsector. The excess heat potential for Europe is 812 TWh/a, and the excess heat potential for Germany is 157 TWh/a. Aydemir et al. [15] show an excess heat potential of 94 TWh/a for Europe for the energy-intensive industry sector. This study does not include a specific value for Germany.

In recent years, however, bottom-up analyses have become increasingly common, in which the excess heat potential is determined based on plant-specific data. The advantage here is that these analyses are often based on real data, and the accuracy of the results is therefore higher. In Brückner [2], the usable potential of industrial excess heat was determined from data on the emissions declaration in accordance with the 11th Regulation for the Implementation of the Federal Emission Control Act (11. BImSchV) in Germany. In this work, the lower limit value for the possible potential of excess heat utilisation in Germany is estimated to be approx. 60–70 TWh/a. The data basis for this is the emission data from the 11. BImSchV from 2012. Steinbach et al. [18] determine a theoretical excess heat potential of 37.5 TWh/a using a similar methodology. Blömer et al. [9] also analyse the excess heat potential in Germany using a similar method based on emission data from 2016, showing a theoretical excess heat potential of 52–63 TWh/a. In Manz et al. [14], the excess heat potential for the EU was determined using emissions data from the EU ETS and E-PRTR databases. The results are given for three different temperature levels and two different scenarios for internal heat recovery. For Europe, a potential of 267 TWh/a is shown for the scenario with no further internal heat recovery and a reference temperature of 25 °C. For Germany, this potential amounts to 43 TWh/a. In comparison, it becomes clear that the bottom-up analysis delivers a significantly lower value than the top-down analysis. Table 1 shows a summary of all the results from the literature.

In Hering et al. [17], it is shown that approx. 80% of the available excess heat occurs in a temperature range below 300 °C. These values for Germany are in similar ranges to the data for Europe determined in the HotMaps project [11,22]. In these data, 25% of excess heat occurs in a temperature range of 100–200 °C and 63% in a temperature range of 200–500 °C. These analyses are also consistent with the results of the analysis in Section 3 of this paper. This low-temperature heat cannot be used in many industrial production processes [23–25]. Therefore, this heat is mainly suitable for the provision of space heating and hot water supply in buildings and thus for use in district heating networks. Some works therefore analyse the potential of using industrial excess heat in district heating networks. In Cooper et al. [19], this potential is investigated for the United Kingdom. The results show that about one third of the available excess heat can be used in district heating networks, taking into account the spatial structures. In Hering et al. [17], the theoretically available potential was listed as 52–63 TWh/a in the low and medium temperature range (<300 °C) for Germany. However, if this heat is used exclusively in existing heat grids, the potential is 9–11 TWh/a. This means that additional infrastructure would have to be built to use about 82% of the available heat. The same applies to the analyses in Steinbach et al. [18], where the potential of excess heat for use in heat grids is quantified at 22.3 TWh/a. It is assumed that no additional temperature upgrading takes place by means of heat pumps. If this possibility is taken into account, an additional potential of 9.8 TWh/a is shown. In Blömer et al. [9], the potential of 52–63 TWh/a is reduced to 11 TWh/a if the excess heat is to be fed into existing heat grids.

Table 1. Excess heat potential of existing studies and information on the method and level of detail.

Study	Excess Heat Amount (TWh/a)	Based On	Spatial Resolution	Subsectors Differentiated	Analysing the Role of Excess Heat for DH
Groß and Tänzer [12]	280–300	Rough key figures	National	no	no
Pehnt et al. [4]	130	Key figures from a Norwegian study	National	yes	no
Persson et al. [16]	157	Key figures and publicly available empirical data	Site specific	yes	no
Aydemir et al. [15]	94	Publicly available empirical data	National	no	yes
Brückner [2]	60–70	Key figures and comprehensive empirical data	Federal state	yes	no
Steinbach et al. [18]	37.5	Comprehensive empirical data	Municipal level	no	yes
Blömer et al. [9]	52–63	Comprehensive empirical data	Site specific analysis but no publication	no	yes
Manz et al. [14]	43	Publicly available empirical data	Site specific	yes	yes
This study	36.6	Comprehensive empirical data	Site specific and municipal level	yes	yes

These theoretically available potentials do not take economic aspects into account. Hummel et al. [26] shows that above all, the distance between source and sink, the return temperature of the heat network, the amount of excess heat available and the temporal availability of the excess heat are decisive for the economic viability of the installation, and that in most cases the costs per kWh of heat are lower than in conventional district heating networks.

The results of the literature research show that there have been many analyses of the potential of industrial excess heat utilisation in recent years. However, most of these studies only show the results for one region or one country, and very few studies show the results geo-referenced to the municipality level. Furthermore, the existing studies rarely distinguish between subsectors, and the temporal availability of excess heat is only analysed in one study [9]. Only one of the studies [3] analysed takes into account the presence of sulphur dioxide in the flue gas. However, this is an important aspect, as in the presence of sulphur dioxide in the flue gas, the flue gas can only be cooled down to a temperature of approx. 135 °C. However, this study only analyses the excess heat potential for one federal state in Germany and does not show the results at the municipal level.

1.2. Our Contribution

The aim of this paper is to give an overview of the regional distribution of excess heat from exhaust gases in Germany and to evaluate the amount of excess heat from exhaust gases according to different subsectors, which makes it possible to transfer the results to other countries. In order to make a comprehensive statement about the usability of excess heat, we also analyse the temporal availability of excess heat in the individual subsectors. In addition, an analysis of the available excess heat in relation to the space heating demand is carried out at the municipal level. For this purpose, we processed existing data from the emissions obligation in Germany and calculated the available industrial site-specific excess heat quantities. In addition, the presence of sulphur dioxide is taken into account, which increases the reference temperature for calculating the amount of excess heat. This is followed by a plausibility check of the excess heat data based on the fuel input. Finally, we carry out spatial analyses of the available excess heat in general and by subsectors.

Previous work has either not analysed the amount of excess heat in a regionalised way for the whole of Germany, has only investigated the presence of sulphur dioxide in one federal state or has only used EU-ETS and/or EPRTR data in regionalised analyses. Therefore, our research differs in several aspects.

First, our analysis is geo-referenced for the whole of Germany, and we additionally compare the available excess heat with the space heating demand at the municipality level. Secondly, we take into account the presence of sulphur dioxide, which reduces the excess heat potential. Thirdly, the analysis is broken down by the most important economic sectors, which makes it possible to transfer the results to other countries. To the best of the authors' knowledge, this has not been done in the literature before.

2. Data and Methods

2.1. Data

The data sets used in this paper originate from the data collection of the 11th BImSchV in Germany from 2016. In this data collection, all operators of plants that require a permit must submit a declaration on the emissions generated and fuels used (c.f. 11th BImSchV). The data were requested from the 16 federal state offices in Germany and then collated. In total, data were collected from 15 of the 16 federal states in Germany. For each federal state, a data set on the exhaust gas records at the chimneys and a data set on the fuels records are available. The data set of the exhaust gas records is structured in such a way that there is one row in the data set for each process of a source (plant). These rows are coded with an ID for the process, an ID for the source (plant) and an ID for the site. This means that a source that contains several processes represents several rows in the data set, and a production site can in turn contain several sources. All data entries also contain the coordinates of the respective sites.

The data set consists of 98,270 exhaust gas records, which in turn can be assigned to 39,023 sources. On the other hand, there are 18,147 fuel records, which also correspond to 18,147 sources. The data set for the exhaust gas records contains many variables, of which only seven are relevant for the analyses in this paper. These are the process ID, the source ID, the site ID, the temperature T, the volume flow V, the operating time O and the sulphur dioxide content of the exhaust gas. The fuel record data set also contains several variables, but only the following four are relevant for the analyses in this paper. The source ID, the site ID, the amount of fuel M and the calorific value H.

For further analysis, the data must be processed and cleaned, as some data rows do not contain records of the temperature T, the operating time O or the volume flow V. The process of data cleaning and plausibility checking is shown in Figure 1.

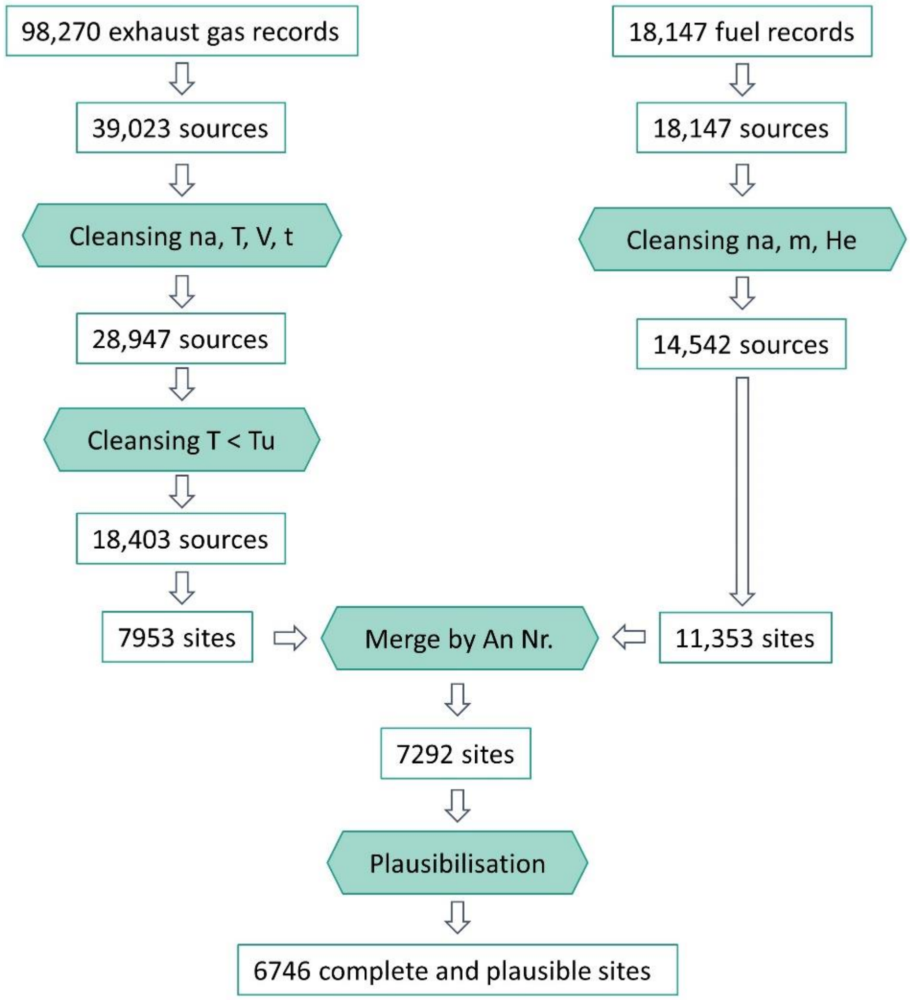

Figure 1. Method of data cleansing.

The data on the exhaust gas flows are available divided into the individual processes. The data on fuel input are only available at the source level. For this reason, the 98,270 entries for the exhaust gas flows were summarised in a first step based on the ID of the source. This resulted in 39,023 sources for the data on the exhaust gas flows. From these data, all entries were removed that did not contain information on temperature T, volume flow V or operating time O, or if these entries were marked with “na”. After cleansing this data, 28,947 sources remained. The next step was to check whether the temperature of the exhaust gas was higher than the reference temperature. For exhaust gas flows containing sulphur dioxide, this reference temperature is 135 °C; for the remaining exhaust gas flows, it is 35 °C. After this cleansing, 18,403 sources remained. These were merged by their site ID, resulting in 7953 sites.

As described above, the data on fuel inputs are only available at the source level. From these data, all entries were removed that did not contain information on mass (m) or calorific value (He), or the entries were marked with “na”. This resulted in 14,542 complete sources. These were merged by their site ID, resulting in 11,353 sites. Subsequently, the data records for the exhaust gas flows and fuel flows were merged by means of the AN No. (Site ID).

After data cleansing and plausibility checks (for the method of plausibility checks, see Step 2 in the methods section), a total of 6746 production sites remained in the data set.

In order to compare the data with the heat demand in the respective regions, data on the amount of excess heat as well as on the demand for space heating and hot water were used. For this purpose, the data on heat demand from the EU-funded HotMaps project were used [22]. In this project, an approach was developed that relates information on the local built environment to the energy demand for space heating, space cooling and hot water production. For this purpose, a spatial distribution function was derived that distributes the nationally available heat demand data at the hectare level. The central idea is that energy demand correlates with population size within a given area, economic activity and climatic conditions. The data are available up to a resolution of 100 m × 100 m for the entire EU.

2.2. Methods

The aim of this paper is to determine the spatially resolved excess heat potential from exhaust gases in Germany and to compare the available excess heat with the heat demand in the individual municipalities. For this purpose, our analysis followed the following three steps:

1. Calculation of excess heat from exhaust gases.
2. Plausibility check with fuel data.
3. Spatial analyses of excess heat and comparison with the heat demands.

In the first step, excess heat was calculated and spatially resolved at the industrial site level based on the available data. The following nomenclature was used for the designation of the individual variables: The volumetric flow $V_{s,j,i}$ describes the volumetric flow of the exhaust gas record with number i, which is associated with source j, which in turn belongs to production site s. The same nomenclature was also used for the operating time O and the temperature T.

To calculate the excess heat, we first determined the amount of excess heat for all exhaust gas records using Formula (1). We assumed that the heat capacity of the exhaust gas corresponds to the heat capacity of nitrogen, since most of the exhaust gas consists of nitrogen. For this we used the constant value 1.04 kJ/kg × K, which corresponds to the heat capacity of nitrogen at 100 °C [27]. The weighted mean value of the exhaust gas temperature in our data set was 128 °C.

$$Q_{s,j,\,i} = V_{s,j,i} \times O_{s,j,i} \times 1.3\left(\frac{kg}{m^3}\right) \times 1.04\left(\frac{kJ}{kg \times K}\right) \times \left(T_{s,j,i} - T_r\right) \tag{1}$$

where $Q_{s,j,i}$ (kJ) is the energy quantity of the corresponding excess heat source i, which belongs to source j, which in turn belongs to production site s. T_r describes the reference temperature to which the exhaust gas can be cooled down. For the exhaust gas streams in which sulphur dioxide is present, this is 135 °C; for all other exhaust gas streams, it is 35 °C. Based on this, the amount of excess heat for the corresponding sources j was calculated using Formula (2).

$$Q_{s,j} = \sum_i Q_{s,j,i} \tag{2}$$

where $Q_{s,j}$ (kJ) describes the energy quantity of the exhaust gas from the corresponding source j, which belongs to the production site s. Finally, the amount of excess heat of the exhaust gas for the entire production site s was calculated using Formula (3).

$$Q_s = \sum_j Q_{s,j} \tag{3}$$

where Q_s (kJ) describes the energy quantity of the exhaust gas of the corresponding production site s.

In the second step, the calculated amounts of excess heat were checked for plausibility using the information on the fuel use of the respective industrial plants. The fuel data set is only available at source level, which is why no comparison can be made at process level.

For this reason, the energy quantity of the fuels used in the respective sources j was first calculated using Formula (4).

$$EC_{s,j} = M_{s,j} * H_e \quad (4)$$

$EC_{s,j}$ (kJ) corresponds to the amount of energy that is brought into the source j by the fuel. $M_{s,j}$ (kg) describes the amount of fuel, and H (kJ/ton) is the net calorific value of the fuel. This information is completely available in the fuel input data set. Finally, the amount of energy of the fuel input of the entire production site s was calculated using Formula (5).

$$EC_s = \sum_j EC_{s,j} \quad (5)$$

For the plausibility check, the ratio between the amount of energy of the fuel used and the amount of energy in the exhaust gas in form of excess heat was calculated using Formula (6).

$$ER_s = \frac{Q_s}{EC_s} \quad (6)$$

If this ratio was greater than 0.6, the plant was marked as implausible, as it could not be assumed that such inefficient plants are in operation. Older systems can sometimes have excess heat quotas as high as this [28].

The third step was the spatial analysis of the amounts of excess heat. For this purpose, the data on heat consumption from the HotMaps project were intersected with the spatial information of the municipalities (LAU level). This means that a total heat demand could be determined for each LAU region in Germany. Subsequently, the existing amounts of excess heat in the respective municipal area were compared with the heat demand in this municipal area. This made it possible to identify regions in which a large amount of the heat demand could be covered through the use of excess heat.

3. Results

The first part of the results describes the available excess heat in Germany. First, the total excess heat potential from exhaust gas is presented for Germany and then divided into the respective subsectors. In addition, there is an analysis of the operating hours, i.e., the availability of excess heat over time at different temperature levels. The second part presents the results of the spatial analysis. On the one hand, the absolute distribution of excess heat and, on the other hand, the relative distribution of excess heat in relation to the heat demand are analysed.

3.1. Results by Subsector

Figure 2 shows the cumulative amount of excess heat as a function of temperature. The total amount of excess heat in our analysis is 36.6 TWh/a. A large proportion of the excess heat is generated in the low temperature ranges in particular. Approx. 33% of the excess heat is generated up to a temperature of 100 °C and approx. 63% up to a temperature of 200 °C. This shows that, above all, a large proportion of the excess heat is generated in the low temperature range. This shows that especially the use of excess heat in low temperature ranges can be of great benefit. A distribution of the available excess heat in 100 °C steps is shown in Appendix A.

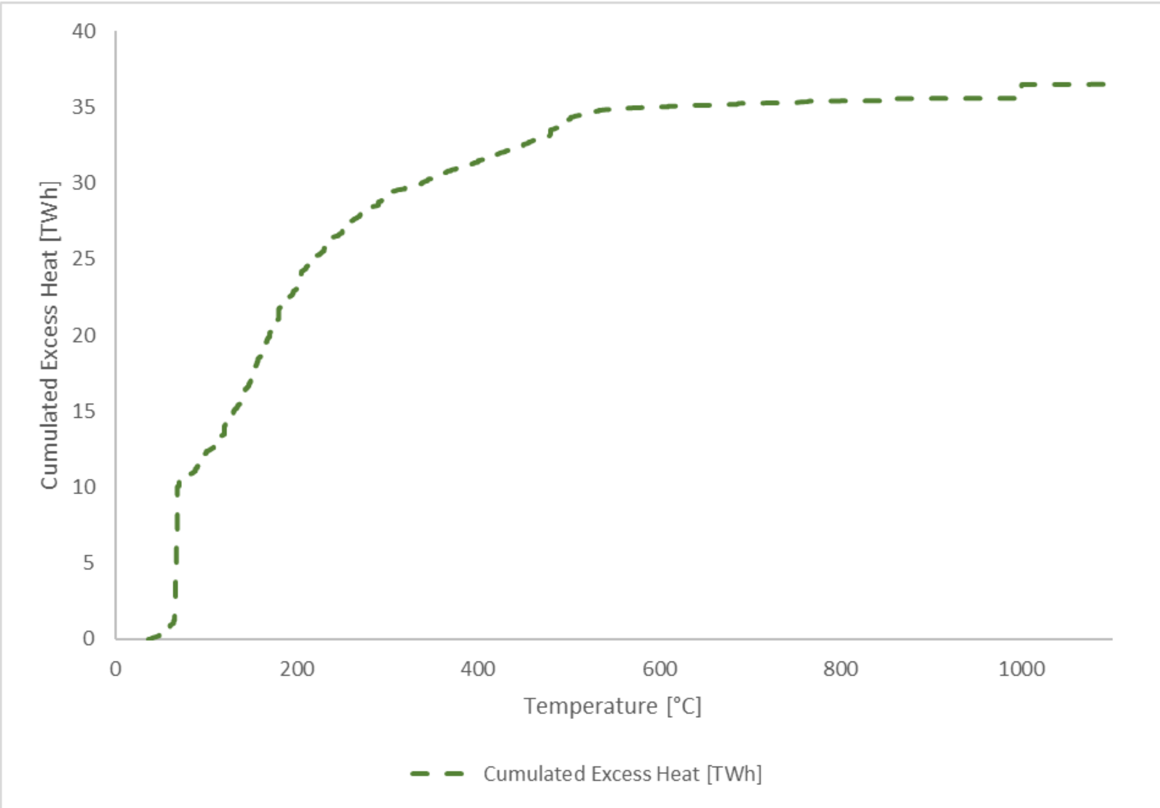

Figure 2. Cumulative excess heat by temperature level for the 6746 plausible sites in the data set.

Figure 3 shows the available excess heat by subsector. The representation corresponds to Figure 2 of the cumulative amount of excess heat by temperature level. This also shows that the excess heat in the subsectors is mainly available in low temperature ranges (<200 °C). One exception is the subsector of basic metals. Here, the increase in excess heat is lower with increasing temperature. This is because many processes with high temperatures are used in this subsector. Especially in the two sectors with the greatest excess heat potential in the flue gas ("other non-mineral products" and "chemicals and chemical products"), the temperature level of the excess heat is relatively low. This is also the case for the sub-sector of "coke and refined petroleum products", although there are a few plants in the 1000 °C range that also generate large amounts of excess heat. It should be noted that the energy production sub-sector was not taken into account in the presentation. This is mainly due to the fact that Germany has decided to phase out coal, and thus large parts of the available excess heat in this sector will disappear in the next few years.

Continuous availability is of great importance for the use of excess heat. For this reason, some industrial sectors are more suitable for the use of excess heat than others. Figure 4 shows the operating hours of the investigated plants by temperature level and subsector. For this analysis, only the five subsectors with the largest available excess heat in the exhaust gas were taken into account. The width of the respective coloured bars describes the frequency of the plants that have the respective operating hours. The thick black bar inside the coloured bars represents the range between the lower and upper quartile, and the white dot shows the median.

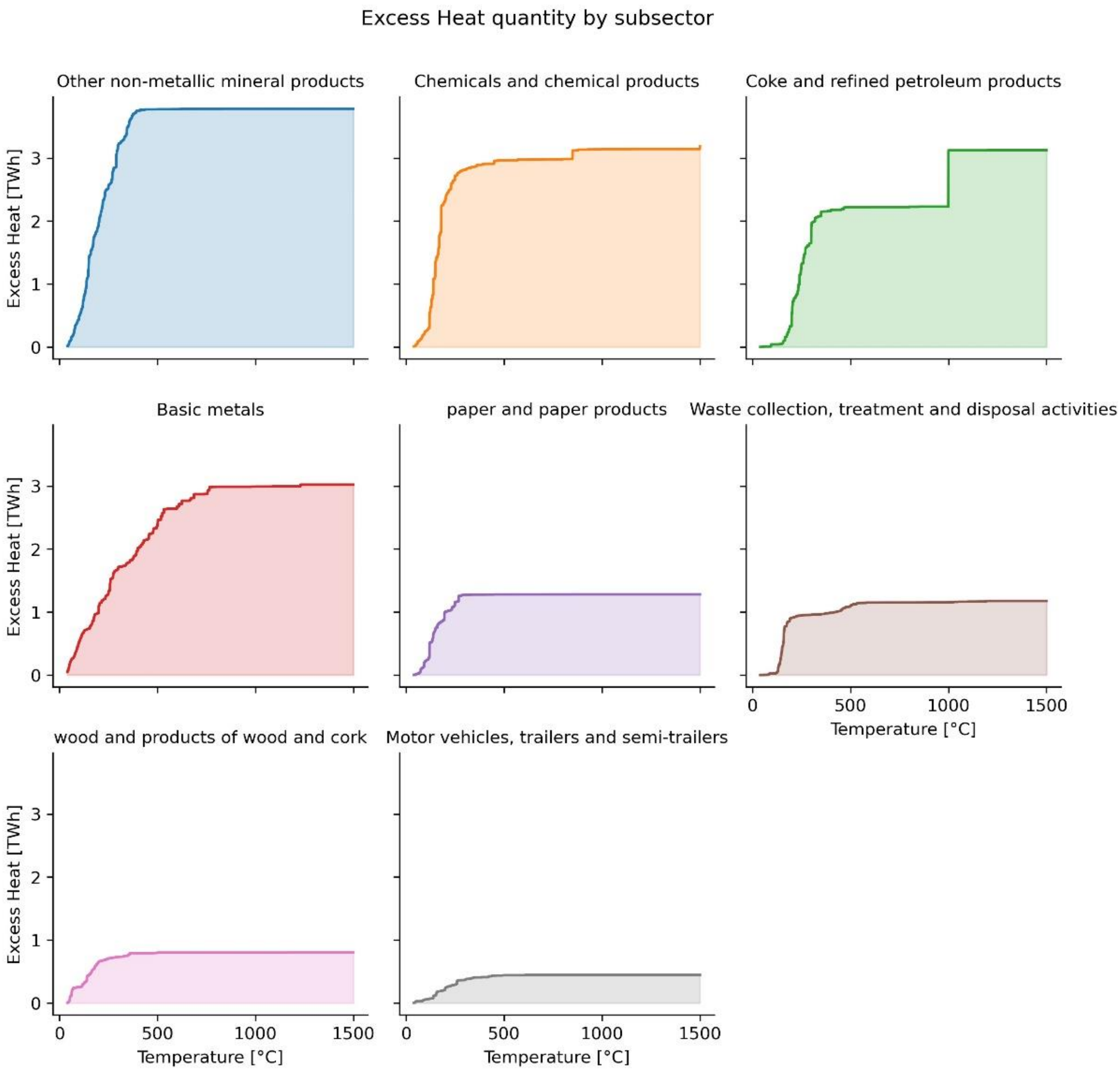

Figure 3. Excess heat quantity by temperature and subsector for the largest 8 subsectors (without the subsector of energy production).

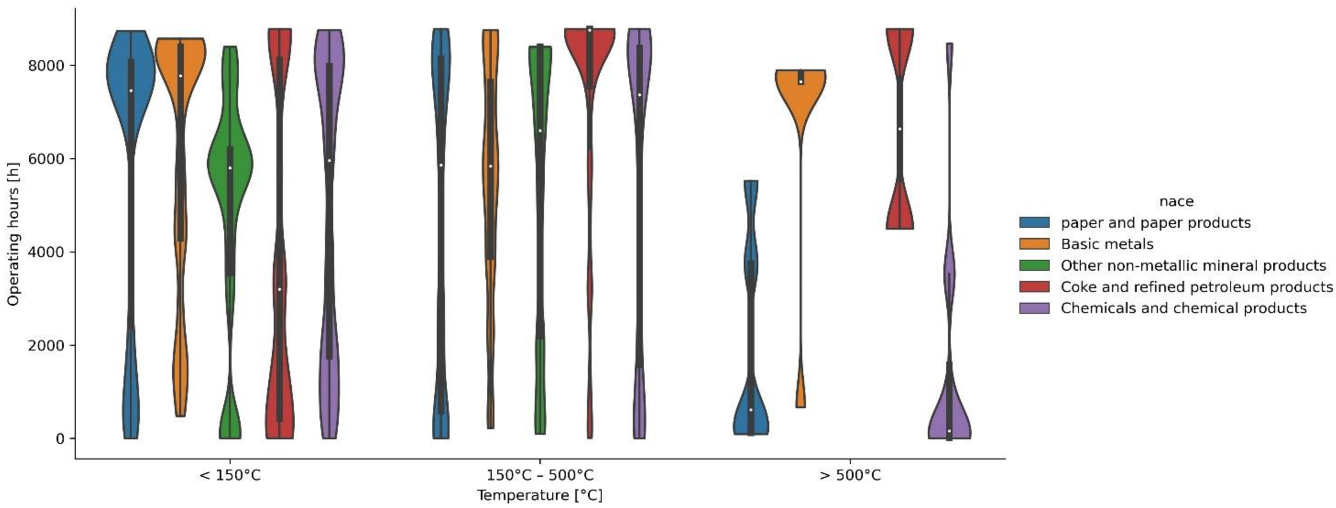

Figure 4. Operating hours by temperature level and subsector.

In the temperature range below 150 °C, the energy consumption of the “paper and paper products” and “basic metals” sectors is almost constant throughout the year. For the sector “other non-metallic mineral products”, this temperature range shows that the operating hours for many plants are constant at around 6000 h. In the “coke and refined petroleum products” sector and the “chemicals and chemical products” sector, there are plants in this temperature range that have both very high and very low operating hours.

In the temperature range from 150 °C to 500 °C, all plants in the respective sectors have both high and low operating times. This is also evident from the distribution of the quartiles, which lie between 1500 and 7000 h for the sectors in this temperature range. An exception is the sector of coking plants and mineral oil processing. This sector contains almost exclusively plants that have an almost continuous operating time throughout the year.

In the temperature range above 500 °C, there are relatively few plants in the data set. For the sectors “paper and paper products” and “chemicals and chemical products”, the plants in this temperature range only have low operating hours, and it can be assumed that these are peak load plants. These are not suitable for the external use of excess heat. In the “basic metals” sector, most plants in this temperature range have around 7000 operating hours. For the excess heat available here, both internal and external use would make sense. The sector “coke and refined petroleum products” includes plants with about 5000 h as well as plants that are in operation all year round. As with the “basic metals” sector, both internal and external use of excess heat can be useful here.

3.2. Spatial Results

For the off-site use of excess heat, it is particularly relevant in which regions it accumulates. Figure 5 shows a map of Germany in which the respective existing excess heat is depicted at the municipal level. The darker the colour of the respective municipality, the greater the excess heat available there. In total, there are about 11,000 municipalities in Germany [29]. Since no data are available for one federal state, 10,362 municipalities are analysed in this paper. In the data set, amounts of excess heat could be identified for 2768 municipalities (approx. 27%). There are 100 municipalities in Germany in which more than 50 GWh/a of industrial excess heat from exhaust gases is available. Furthermore, there are 70 municipalities in each of which more than 75 GWh/a of excess heat from exhaust gases is available. Some of these are municipalities in which a large number of industrial companies is located. However, there are also municipalities in which only a few industrial sites have a high amount of excess heat. Particularly in the Ruhr region in western Germany, it can be seen that large amounts of excess heat are available there. Many energy-intensive industries are located in this region. In the east of Germany, one can see that there are also some municipalities with very large amounts of excess heat. Some of these are municipalities with large power plants, which are often still powered by lignite. Some of the excess heat from these power plants is already being used for feeding into heating networks. With regard to the future use of excess heat, it must be taken into account that the decision has been made to phase out coal and lignite in Germany, and thus a long life time of the plants cannot be guaranteed.

Figure 6 shows the available excess heat at the municipal level in relation to the heat demand. The data on heat demand from the EU project HotMaps was used for this purpose. The colour gradation of the individual municipalities describes the ratio of available excess heat to heat demand. The darker a municipality is shown, the higher the quota. The analyses show that there is a total of 148 municipalities in Germany in which the available excess heat in the municipality could cover more than 50% of the heat demand over the whole year, and 61 municipalities even have amounts of excess heat that exceed the heat demand in these municipalities.

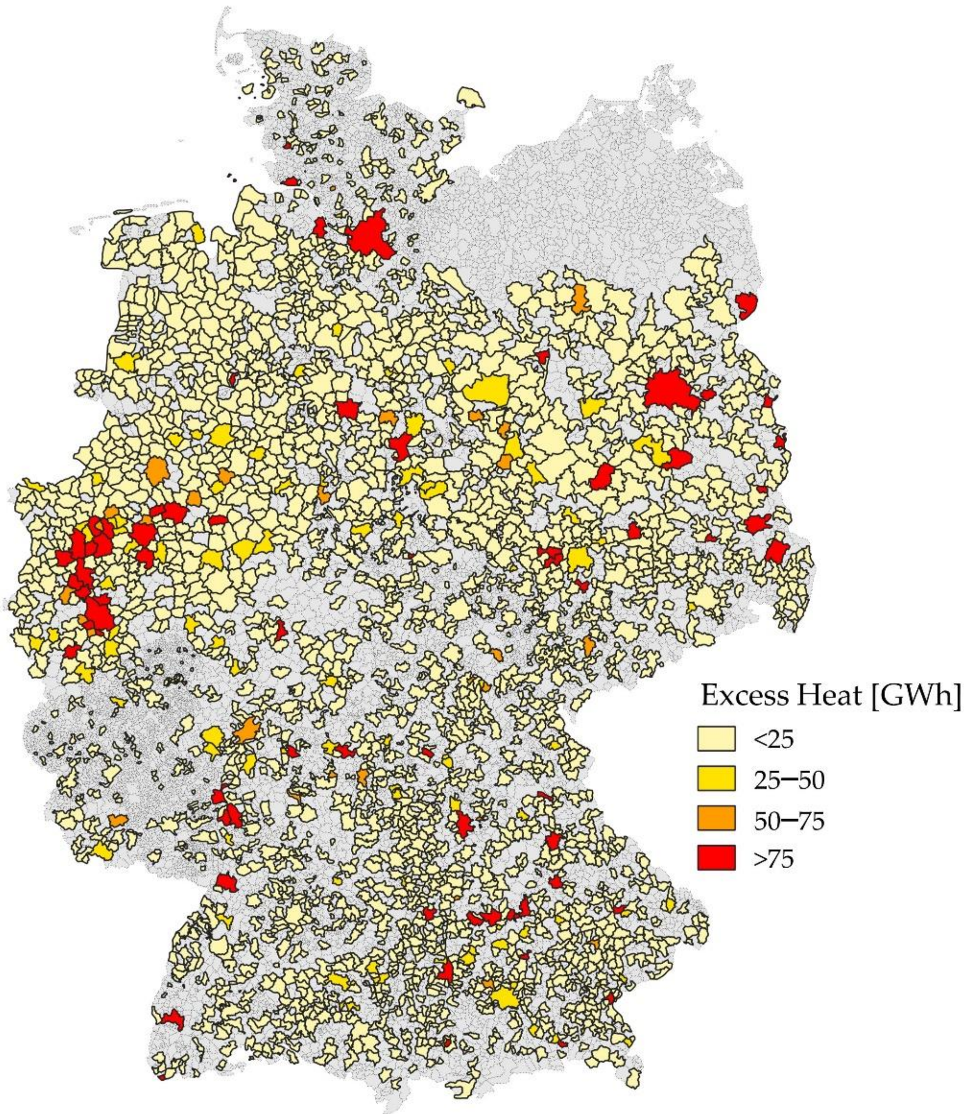

Figure 5. Available amounts of excess heat in GWh/a in Germany at the municipal level.

The analysis shows that there are no specific characteristics of the municipalities in which this rate is over 100%. Some of them are municipalities with many inhabitants and large industrial enterprises at the same time. In some cases, however, there are also municipalities with fewer inhabitants and smaller industrial enterprises.

However, it is noticeable that the regions from Figure 5 do not coincide with the regions from Figure 6. It is therefore not possible to make a general statement that the ratio of available excess heat to heat demand is correspondingly high in regions with large amounts of excess heat. In the Ruhr region in particular, large amounts of excess heat are available, but there is also a lot of people living there. For this reason, the heat demand in the municipalities in this region is very high, and thus the ratio of available excess heat to heat demand is correspondingly lower.

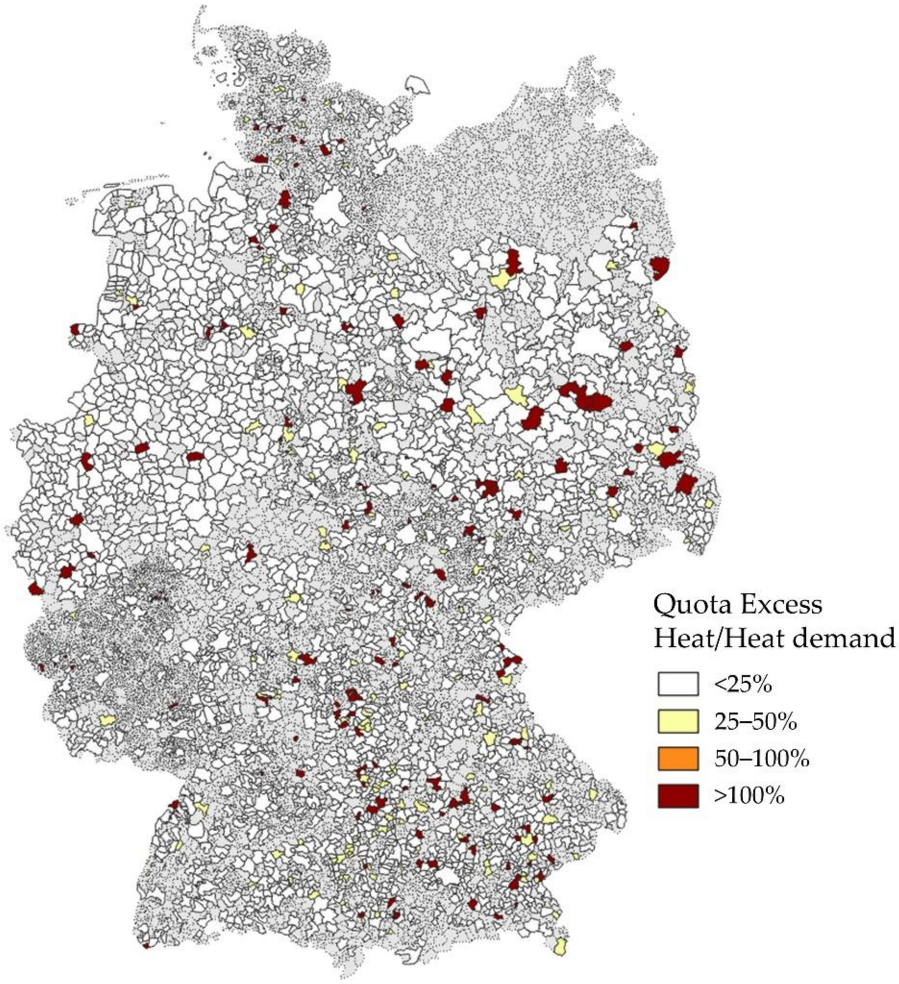

Figure 6. Spatial distribution of relative excess heat in comparison with heat demand.

4. Discussion

Our analysis is based on official emissions data from industrial companies in Germany. We corrected data entries and checked their plausibility with the help of fuel input data. Our results are based only on these complete and plausible sites. In this context, complete means that all the necessary information for calculating the excess heat quantities is available, and plausible means that the ratio of excess heat to fuel used is not greater than 0.6. However, it should be mentioned here that only the fuels used can be used for the plausibility check and not the electricity used. This means that processes that require large amounts of electricity (e.g., electric steel plants) are classified as implausible because they generate excess heat without the use of fuels. However, it can be assumed that this case does not occur at a particularly large number of production sites, as fuels are currently still mainly used to provide process heat. The initial data included 10,630 sites, of which 6746 could be classified as complete and plausible. This means that about 36.5% of the sites are not included in our analyses, which means that the actual excess heat potential may be higher. Overall, the data quality of the remaining data is very high, as it is plausible and based on real information from the industrial companies.

Our analysis is based on emission data from 2016. Due to the ongoing energy transition, industry will see changes in the respective production processes and production volumes in future years [30–32]. For this reason, when implementing measures to use excess heat, care must always be taken to ensure that sufficient excess heat will also be available in future years. However, it is also important that the use of excess heat does not create any lock-in effects, whereby inefficient or very CO_2-intensive plants are operated longer than necessary.

One example of this is the coal-fired power plants in Germany. In many existing power plants, excess heat is already being used, but there is still a lot of potential. However, since the decision has been made to phase out coal in Germany, this excess heat cannot be used in the long term. However, it would be possible to extend or build new district heating networks to use the excess heat from the coal-fired power plants, which could gradually be replaced by other heat sources such as other industrial excess heat, geothermal energy or large-scale heat pumps over the next few years.

In addition to changing production processes and production volumes, it is also possible to change production locations. It may be that in the future, companies will primarily search for locations where sufficient low-cost renewable energies are available or where the companies themselves can build large renewable energy plants to supply themselves. In this context, the planned construction of electrolysers is also of great importance. In many industries, hydrogen will be a central building block for the conversion of production processes [32]. It is therefore also possible that companies will in the future select locations where electrolysers can be built and operated at low cost. The location of electrolysers is also interesting in terms of the use of excess heat. Alkaline electrolysis and proton exchange membrane electrolysis produce excess heat in temperature ranges between 50 and 90 °C, which can be used for heating purposes, as can industrial low-temperature excess heat [33].

We have calculated the existing excess heat based on the temperature level, the volume flow, the operating hours and the presence of sulphur dioxide. For this we have made some assumptions, which are discussed in the following.

For the density and specific heat capacity of the exhaust gas flows, it was assumed that these can be approximated to the specific heat capacity of nitrogen. This assumption is sufficient for an aggregated estimate. For the exact determination of the heat capacities and densities of the exhaust gas flows, however, the concrete material composition would have to be known. However, this is not contained in the available data set. In a site-specific calculation, however, this information should be collected in order to enable an exact calculation of the amount of excess heat.

In addition, we assume in our calculation that the specific heat capacity is independent of the temperature. In reality, however, it is different at different temperatures. The difference between 35 °C and 800 °C is about 12% for nitrogen [27]. However, the difference between 35 °C and 200 °C is only about 1%. Since most of the excess heat is generated in this range, it can be assumed that this has no significant influence on the results.

The existing data set does not contain information on the composition of the exhaust gas, as described in the previous paragraph. For this reason, the water content of the exhaust gas is also unknown. Therefore, our analyses do not take into account the latent heat of condensation released by condensation of the water vapour in the exhaust gas. Future analyses could take this aspect into account if it can be collected. For the calculation of the site-specific excess heat on site, the latent heat of condensation should be taken into account in any case.

For the comparison of heat demand and excess heat supply at the municipal level, we only used annual values and not daily or hourly values. For this reason, it must be taken into account when interpreting the results that heat storage is indispensable for the full utilisation of the available excess heat. Nevertheless, an indication of particularly interesting and sensible areas for the use of excess heat can be identified on the basis of this first estimate. Future analyses could use hourly resolved load profiles or at least make a distinction between winter and summer to improve the accuracy of the analyses.

For the analysis of the potential of excess heat in this paper, we only consider the use for residential heating and no other possible uses, such as internal company use. For residential heating, however, the excess heat must be transported to the end users, who are often not in the direct vicinity of the excess heat sources. Nowadays, district heating networks are mainly used for this purpose [26,34]. For this reason, the existing district heating networks are also of great importance for the use of excess heat. Appendix B contains a map showing the share of buildings with district heating connections at the municipal level. It should be noted, however, that these data are based on the 2011 census. However, Fritz et al. [6] show that an existing district heating network is not a prerequisite for excess heat utilisation. New district heating networks are often built in the course of excess heat utilisation projects.

District heating networks are mostly operated at a temperature level of between 70 °C and 120 °C [5]. This means that for excess heat with a higher temperature level, the temperature level must be lowered to the required temperature. This can be done, for example, by means of heat exchangers, whereby the flow of water and the heat exchanger must be selected in such a way that the corresponding temperature level can be reached [5]. At lower temperatures, the heat can be raised to the required temperature by means of a heat pump [5].

5. Conclusions

We analysed over 115,000 data records and calculated the available amount of excess heat in the exhaust gas at the municipality level. To do this, we took into account whether there is sulphur dioxide in the exhaust gas, which reduces the amount of excess heat available. Our analyses show that, taking sulphur dioxide into account, a total of 36.6 TWh/a of excess heat from exhaust gases is available in Germany. Comparing the amount of excess heat available with the heat demand of the individual municipalities shows that for 61 municipalities in Germany, the amount of excess heat available over the whole year is greater than the total heat demand. From a policy perspective, our results show that there is a large potential for excess heat utilisation in Germany, and that especially in some regions, more excess heat is available throughout the year than the individual buildings need to provide space heating and hot water. Measures should be developed here to further promote the use of excess heat and, above all, to encourage cooperation between the companies producing the excess heat and the energy supply companies. The technical solutions for using excess heat are known. The challenge now is to initiate and implement concrete projects.

Author Contributions: M.F.: Conceptualization, Methodology, Validation, Formal Analysis, Data curation, Writing—Original draft preparation, Visualization. A.A.: Supervision, Methodology, Writing—Review and Editing. L.S.: Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Bundesministerium für Wirtschaft und Klimaschutz (BMWK.IIC6) and Forschungszentrum Jülich GmbH (PT-J.ESN4), grant number 03EN4015.

Data Availability Statement: The data used in this paper are confidential and can therefore only be presented in aggregated form as shown in this paper.

Acknowledgments: We would like to thank the state offices of the individual federal states in Germany for making the data available. Many thanks to Landesanstalt für Umwelt Baden-Württemberg (LUBW); Bayerisches Landesamt für Umwelt (LfU); Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin; Landesamt für Umwelt Brandenburg (LfU); Die Senatorin für Klimaschutz, Umwelt, Mobilität, Stadtentwicklung und Wohnungsbau Bremen; Behörde für Umwelt, Klima, Energie und Agrarwirtschaft Hamburg; Hessisches Landesamt für Naturschutz, Umwelt und Geologie; Landesamt für Umwelt, Naturschutz u. Geologie Mecklenburg Vorpommern; Staatliches Gewerbeaufsichtsamt Hildesheim; Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen; Landesamt für Umwelt Rheinland-Pfalz; Landesamt für Umwelt und Arbeitsschutz Saarland; Sächsisches Staatsministerium für Energie, Klimaschutz, Umwelt und Landwirtschaft; Landesamt für Umweltschutz Sachsen-Anhalt (LAU); Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein and Thüringer Landesamt für Umwelt, Bergbau und Naturschutz.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

Table A1. Available excess heat for different temperature levels.

Temperature (°C)	Available Excess Heat (TWh/a)	Percentage of Total Available Excess Heat (%)
100	12.2	33.1
200	23.1	63.1
300	29.0	79.2
500	34.1	93.2
800	35.5	97.0

Appendix B

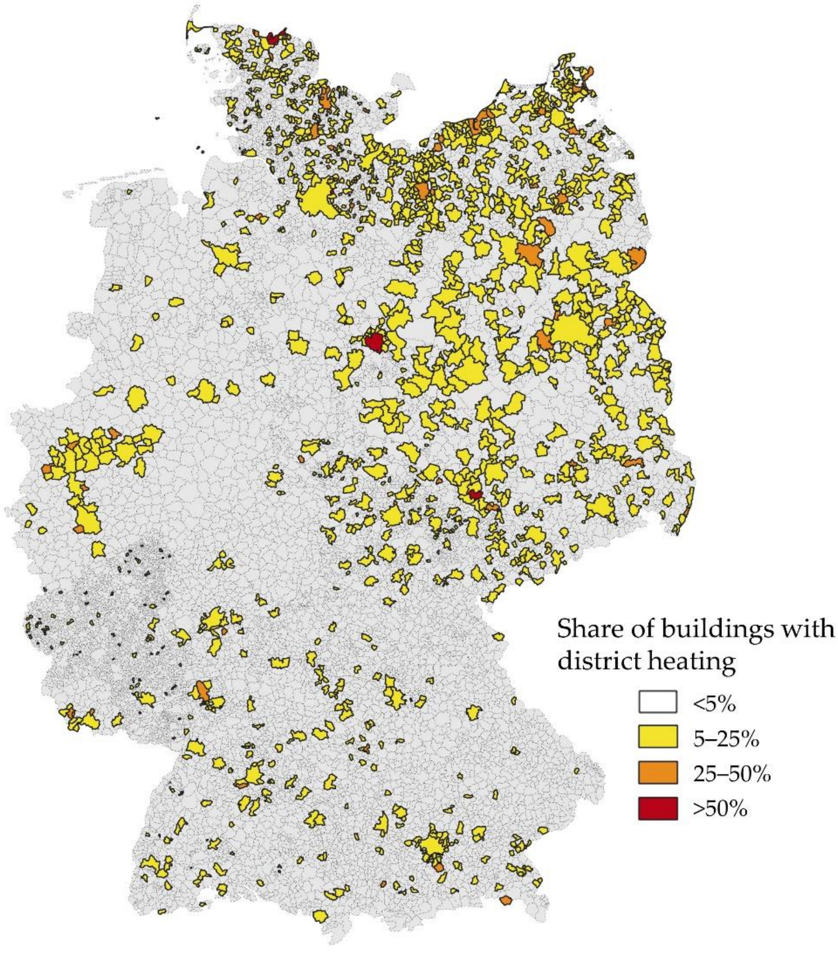

Figure A1. Spatial distribution of the share of buildings with district heating connection at the municipal level based on [35].

References

1. Eurostat. Energy Statistics—An Overview. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview (accessed on 15 May 2022).
2. Brückner, S. Industrielle Abwärme in Deutschland. Ph.D. Thesis, Technische Universität München, Munich, Germany, 2016.
3. Aydemir, A.; Fritz, M. Estimating excess heat from exhaust gases: Why corrosion matters. *Energy Ecol. Environ.* **2020**, *5*, 330–343. [CrossRef]
4. Pehnt, M.; Bödeker, J.; Arens, M.; Jochem, E.; Idrissova, F. Die Nutzung Industrieller Abwärme–Technisch-Wirtschaftliche Potenziale Und Energiepolitische Umsetzung: Bericht im Rahmen des Projekts "Wissenschaftliche Begleitforschung zu übergreifenden technischen, ökologischen, ökonomischen und strategischen Aspekten des nationalen Teils der Klimaschutzinitiative", IFEU, Fraunhofer ISI, IREES. Available online: https://www.ifeu.de/fileadmin/uploads/Nutzung_industrieller_Abwaerme.pdf (accessed on 17 May 2022).

5. Viklund, S.B.; Johansson, M.T. Technologies for utilization of industrial excess heat: Potentials for energy recovery and CO_2 emission reduction. *Energy Convers. Manag.* **2013**, *77*, 369–379. [CrossRef]
6. Fritz, M.; Savin, M.; Aydemir, A. Usage of excess heat for district heating—Analysis of enabling factors and barriers. *J. Clean. Prod.* **2022**, *363*, 132370. [CrossRef]
7. Schmidt, R.-R.; Geyer, R.; Lucas, P. The Barriers to Waste Heat Recovery and How to Overcome Them? 2020. Available online: https://ec.europa.eu/futurium/en/system/files/ged/20200625_discussion_paper_v2_final.pdf (accessed on 15 May 2022).
8. Päivärinne, S.; Hjelm, O.; Gustafsson, S. Excess heat supply collaborations within the district heating sector: Drivers and barriers. *J. Renew. Sustain. Energy* **2015**, *7*, 033117. [CrossRef]
9. Blömer, S. EnEff: Wärme -netzgebundene Nutzung industrieller Abwärme (NENIA): Kombinierte räumlich-zeitliche Modellierung von Wärmebedarf und Abwärmeangebot in Deutschland. Schlussbericht im Auftrag des Bundesministeriums für Wirtschaft und Energie. 2019. Available online: https://www.ifeu.de/fileadmin/uploads/Schlussbericht_EnEffW%c3%a4rme-NENIA.pdf (accessed on 13 May 2022).
10. Hirzel, S.; Sontag, B.; Rohde, C. Industrielle Abwärmenutzung. 2013. Available online: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2013/Kurzstudie_Abwaermenutzung.pdf (accessed on 11 June 2022).
11. Manz, P.; Fleiter, T.; Aydemir, A. Developing a Georeferenced Database of Energy-Intensive Industry Plants for Estimation of Excess Heat Potentials. In Proceedings of the ECEEE Industrial Summer Study Proceedings, Berlin, Germany, 11–13 June 2018.
12. Groß, B.; Tänzer, G. *Industrielle Abwärme-Eine Potentialstudie für Deutschland*; IZES-Institut für ZukunftsEnergieSysteme: Saarbrücken, Germany, 2010.
13. Brueckner, S.; Arbter, R.; Pehnt, M.; Laevemann, E. Industrial waste heat potential in Germany—a bottom-up analysis. *Energy Effic.* **2017**, *10*, 513–525. [CrossRef]
14. Manz, P.; Kermeli, K.; Persson, U.; Neuwirth, M.; Fleiter, T.; Crijns-Graus, W. Decarbonizing District Heating in EU-27+ UK: How Much Excess Heat is Available from Industrial Sites? *Sustainability* **2021**, *13*, 1439. [CrossRef]
15. Aydemir, A.; Fleiter, T.; Schilling, D.; Fallahnejad, M. Industrial excess heat and district heating: Potentials and costs for the EU-28 on the basis of network analysis. In *ECEEE Industrial Summer Study Proceedings*; European Council for an Energy-Efficient Economy—ECEEE: Berlin, Germany, 2020; p. 30.
16. Persson, U.; Möller, B.; Werner, S. Heat Roadmap Europe: Identifying strategic heat synergy regions. *Energy Policy* **2014**, *74*, 663–681. [CrossRef]
17. Hering, D.; Richter, S.; Blömer, S.; Pehnt, M. Industrielle Abwärmenutzung in Deutschland: Potenziale zur Nutzung in Wärmenetzen. *EuroHeatPower* **2018**, *47*, 14–19.
18. Steinbach, J.; Popovski, E.; Henrich, J.; Christ, C.; Ortner, S.; Pehnt, M.; Blömer, S.; Auberger, A.; Fritz, M.; Billerbeck, A. Umfassende Bewertung des Potenzials für eine effiziente Wärme-und Kältenutzung für Deutschland: Comprehensive Assessment Heating and Cooling Germany—Gemäß Artikel 14 Absatz 1 und Anhang VIII der Richtlinie 2012/27/EU. 2021. Available online: https://irees.de/wp-content/uploads/2021/03/Comprehensive-Assessment-Heating-and-Cooling_Germany_2020.pdf (accessed on 2 June 2022).
19. Cooper, S.; Hammond, G.; Norman, J. Potential for use of heat rejected from industry in district heating networks, GB perspective. *J. Energy Inst.* **2016**, *89*, 57–69.
20. Miró, L.; Brückner, S.; Cabeza, L.F. Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries. *Renew. Sustain. Energy Rev.* **2015**, *51*, 847–855. [CrossRef]
21. Forman, C.; Muritala, I.K.; Pardemann, R.; Meyer, B. Estimating the global waste heat potential. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1568–1579. [CrossRef]
22. Pezzutto, S.; Zambotti, S.; Corce, S.; Zambelli, P.; Garegnani, G.; Scaramuzzino, C.; Pascuas, R.P.; Haas, F.; Exner, D.; Lucchi, E.; et al. Hotmaps—Open Data Set for the EU28: Hotmaps—D2.3 WP2 Report. Available online: https://www.researchgate.net/profile/Simon-Pezzutto/publication/325604001_D23_WP2_Report-Open_Data_Set_for_the_EU28/links/5cee8c2da6fdcc791692c1ab/D23-WP2-Report-Open-Data-Set-for-the-EU28.pdf (accessed on 13 May 2022).
23. Aydemir, A. Ermittlung von Energieeinsparpotenzialen durch überbetriebliche Wärmeintegration in Deutschland. Ph.D. Thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2018.
24. Aydemir, A.; Rohde, C. What about heat integration? Quantifying energy saving potentials for Germany. In Proceedings of the ECEEE Industrial Summer Study Proceedings, Berlin, Germany, 11–13 June 2018; pp. 197–205.
25. Chinese, D.; Santin, M.; Angelis A de Saro, O.; Biberbacher, M. What to Do with Industrial Waste Heat Considering a Water-Energy Nexus Perspective. In Proceedings of the ECEEE Industrial Summer Study Proceedings, Berlin, Germany, 11–13 June 2018.
26. Hummel, M.; Kranzl, L.; Villotti, C. *Assessment of the Economic Viability of the Integration of Industrial Waste Heat into Existing District Heating Grids*; ECEEE: Stockholm, Sweden, 2014.
27. Langeheinecke, K.; Kaufmann, A.; Langeheinecke, K.; Thieleke, G. *Thermodynamik für Ingenieure*; Springer: Heidelberg, Germany, 2020.
28. Johnson, I.; Choate, W.T.; Davidson, A. *Waste Heat Recovery: Technology and Opportunities in US Industry*; BCS, Inc.: Laurel, MD, USA, 2008.
29. Statista. Anzahl der Gemeinden in Deutschland nach Gemeindegrößenklassen. Available online: https://de.statista.com/statistik/daten/studie/1254/umfrage/anzahl-der-gemeinden-in-deutschland-nach-gemeindegroessenklassen/#:~{}:text=Die%20Anzahl%20aller%20Gemeinden%20in%20Deutschland%20am%2031.12.2020%20betrug%2010.796 (accessed on 16 May 2022).

30. Fleiter, T.; Rehfeldt, M.; Neuwirth, M.; Herbst, A. Deep Decarbonisation of the German Industry via Electricity or Gas? A Scenario-Based Comparison of Pathways; In Proceedings of the ECEEE Industrial Summer Study Proceedings 2020, online. 2020. Available online: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2020/6-141-20_Fleiter.pdf (accessed on 16 May 2022).
31. Herbst, A.; Fleiter, T.; Rehfeldt, M.; Neuwirth, M.; Fahl, U.; Kittel, L.; Hufendiek, K. Deutschland auf dem Weg zur Klimaneutralität 2045-Szenarien und Pfade im Modellvergleich. 2021. Available online: https://ariadneprojekt.de/media/2021/10/Ariadne_Szenarienreport_Oktober2021_Kapitel4_Industriewende.pdf (accessed on 14 June 2022).
32. Neuwirth, M.; Fleiter, T.; Manz, P.; Hofmann, R. The future potential hydrogen demand in energy-intensive industries—a site-specific approach applied to Germany. *Energy Convers. Manag.* **2022**, *252*, 115052. [CrossRef]
33. Böhm, H.; Moser, S.; Puschnigg, S.; Zauner, A. Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials. *Int. J. Hydrogen Energy* **2021**, *46*, 31938–31951.
34. Fang, H.; Xia, J.; Zhu, K.; Su, Y.; Jiang, Y. Industrial waste heat utilization for low temperature district heating. *Energy Policy* **2013**, *62*, 236–246. [CrossRef]
35. Statistische Ämter des Bundes und der Länder. Ergebnisse des Zensus 2011—Wohnungen und Gebäude je Hektar: Ergebnisse des Zensus am 9. Mai 2011 in Gitterzellen. Available online: https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html (accessed on 15 June 2022).