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Notes

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Abstract

Using industrial excess heat for residential heating can increase energy efficiency and thus be part of the solution to achieving the EU's climate targets. However, industrial plants are often located in industrial areas and thus away from residential areas. Therefore, the excess heat has to be transported to the end-using households. In this paper, we determine the economic excess heat potential for residential heating in Germany, considering different transport technologies. For this purpose, we develop a bottom-up optimisation model, which identifies the technology with the lowest transport cost for over 6,000 excess heat sources. In addition, an optimisation is carried out to maximise the amount of used excess heat, taking into account cost thresholds. Our results show that about 12-17 TWh of excess heat can be utilised up to the cost threshold of 0.1 €/kWh. We see that district heating is the most selected technology for cost optimisation. When optimising the amount of excess heat used, however, it becomes apparent that the technologies sewer networks and sorption cycles are also used. The technologies for using industrial excess heat are available, but the next step must be market penetration and up-scaling.

Contents

1 Introduction

To ensure security of energy supply in the coming years and to achieve the EU's climate protection goals, increasing energy efficiency in all sectors is of great importance. Industrial final energy demand accounts for a quarter of final energy demand in the EU, of which more than 70 % is used to provide heating and cooling. Of this, the largest share is the provision of process heat (cf. (European Environment Agency 2020)). Large amounts of this energy are released unused into the environment in form of excess heat (Brückner 2016; Aydemir und Fritz 2020).

Using this industrial excess heat can increase energy efficiency and thus be part of the solution to achieving the EU's climate targets. When analysing excess heat potential, a distinction can be made between top-down (Groß und Tänzer 2010; Pehnt et al. 2010) and bottom-up (Steinbach et al. 2021; Brückner 2016; Blömer et al. 2019) analyses. In top-down analyses, the possible amount of excess heat is calculated based on industry-specific data. In bottom-up analyses, the possible amount of excess heat is calculated based on plant-specific data. For Germany, the analyses of the potential range from 37 TWh (Steinbach et al. 2021) to 300 TWh (Groß und Tänzer 2010). In Germany, approx. 80 % of the available excess heat has a temperature of less than 300°C (Hering et al. 2018). Fritz et al. (2022a) also show that approx. 63 % of Germany's available excess heat occurs at a temperature of less than 200 °C. For this reason, using excess heat for residential heating can be an important option for reducing greenhouse gas emissions, as only low temperatures are required there. Residential buildings account for about a quarter of final energy demand in the EU, of which about 80 % is required to provide residential heating (space heating and hot water) (European Commission 2018). This heat demand could be partially covered by using industrial excess heat.

However, industrial plants are often located in industrial areas and thus away from residential areas. Therefore, the excess heat has to be transported to the end-using households. In the EU and Germany, district heating networks are mainly used for this purpose (Fritz et al. 2022c; Hummel et al. 2014; Fang et al. 2013). However, studies show that transporting excess heat from industrial plants to households is also possible with other technologies (Ma et al. 2009; Xu et al. 2019; Fritz et al. 2022b). The construction of district heating networks is capital-intensive, and in certain circumstances, using another technology may make more technological and economic sense. Existing studies often focus on the presentation and technical comparison of the technologies but do not carry out an economic assessment (Ma et al. 2009; Vallade et al. 2012). These studies show that, from a technical point of view, technologies other than district heating can be technically used for heat transport and can achieve lower heat losses and thus increase efficiency. Other studies show that district heating is not always the most cost-efficient solution for heat transport (Fritz et al. 2022b; Gao et al. 2019; Chiu et al. 2016).

Overall, the literature indicates a considerable excess heat potential and that technologies other than district heating for transporting excess heat may also be technically feasible for its utilisation. However, the literature has not systematically investigated which technology could be useful for which excess heat sources and which economic implications result from the use of industrial excess heat from exhaust gases. However, these aspects are of great importance to spread the use of industrial excess heat.

The aim of this paper is to close this gap in the literature and to determine the economic excess heat potential for residential heating in Germany, taking into account different transport technologies. For this purpose, a bottom-up optimisation model is developed, which identifies the technology with the lowest transport cost for each excess heat source. This makes it possible to analyse the amount of excess heat that can be used at the lowest possible cost. As input data for the model, data on excess heat sources from Fritz et al. (2022a) and data on heat demand from the open source project HotMaps are used. In addition, a sensitivity analysis is carried out for the transport distance, as the costs are strongly dependent on the transport distance. Finally, in addition to optimising the costs, an optimisation of the technology and the respective demand areas with which the largest amount of excess heat can be used for each existing excess heat source based on different cost thresholds is carried out. Previous work has either not used site-specific real data for the analyses of excess heat potential or has not taken different transport technologies of excess heat into account. Therefore, our research differs in several aspects. First, our analysis is based on georeferenced real data from which the available excess heat is calculated. Second, we compare different transport technologies, including competing technologies, to district heating networks. Third, we perform two different optimisations to calculate the maximum amount of excess heat based on a cost threshold and the minimum transport costs.

2 Technologies for thermal energy transport

In this paper, different technologies for the transport of excess heat are considered. In general, transport technologies for heat can be divided into physical and thermochemical heat transport technologies. Fritz et al. (2022b) analyse the technical and economic parameters of different heat transport technologies. Four promising technologies are examined in more detail. These four technologies are also used in this paper and are presented below. A detailed description of the technologies can be found in Fritz et al. (2022b).

The first technology are **district heating (DH) networks**. Many studies show that district heating networks will play an essential role in the decarbonisation of the heat sector (Hummel et al. 2014; Lund et al. 2010; Rezaie und Rosen 2012; Lund et al. 2014; Werner 2017). Currently, district heating networks are the most common technology for the external use of industrial excess heat. In Fritz et al. (2022c), 45 companies were identified that feed excess heat into district heating networks. When excess heat is used via district heating networks, the heat is delivered to one or more consumers via pipelines. Water is used as the heat transport medium, resulting in a sensible heat capacity of 4.2 KJ/kg*K.

The second technology are **phase change materials (PCM)**. In these materials, energy is absorbed through a phase change from solid to liquid and rereleased through a phase change from liquid to solid. This means that heat transfer takes place at a nearly constant temperature, which makes it useful as a heat storage (Castro Flores et al. 2017; Thomson und Claudio 2019). Unlike DH networks, PCMs must be transported by road, rail or ship. Transmission by pipe is not possible. The PCM material should be selected depending on the intended use and the temperature required. In this study, the PCM sodium acetate trihydrate is used, achieving a thermal efficiency of 90 % (Deckert et al. 2014). An advantage of PCM is the high specific heat capacity of 73.3 kWh/t. A disadvantage, however, is the relatively low thermal conductivity and the high price.

The third technology are **liquid-gas absorption cycles**. Here, excess heat is converted into chemical energy by changing the concentration of a solution (Ammar et al. 2013; Gao et al. 2019; Kang et al. 2000). This technology is also a pipe-bound technology and is similar in function to a sorption heat pump. The absorber is on the user side, and the generator and condenser are on the source side. The advantage is that the transport takes place at ambient temperature, so no thermal insulation of the pipes is necessary. Various substances can be used for absorption cycles. In the literature, the ammonia-water cycle is considered the most promising working pair in terms of price and efficiency (Kang et al. 2000). For this reason, it is used in this paper for comparison with the other technologies. The energy transport density for this technology is 127.75 kJ/kg (Gao et al. 2019).

The fourth technology is **excess heat distribution through sewer networks (ESN)**. With this, the excess heat is fed into the sewer through heat exchangers or the wastewater produced. This raises the temperature in the sewer to up to 35 °C. Initial analyses show that odour nuisance can be ruled out at these temperature increases. The excess heat can be transported along the flow path to the consumers via the existing sewer system. There, the heat is extracted using heat exchangers and serves as a heat source for a heat pump. This increases the coefficient of performance (COP) of the heat pump and reduces the amount of electricity required. An advantage of this technology is that no additional pipeline infrastructure needs to be built, and there is a double use of the existing infrastructure. A disadvantage, however, is that the technology depends on the amount of wastewater available and the pipe routing. As with district heating, water is the transport medium, resulting in a sensible heat capacity of 4.2 KJ/kg*K.

3 Data and Methods

3.1 Data

The data used in this paper can be divided into three categories. Data on excess heat sources, data on heat demand and data on individual transport technologies are used. In the following, the data basis of these three categories is explained in more detail.

The data on excess heat sources is based on the data set used in Fritz et al. (2022a). They calculate the amount of available excess heat in Germany based on a site-specific data set. This data set is based on the emission declarations of the 11th BImSchV in Germany from 2016. In these emission declarations, all operators of plants requiring a permit provide information on the exhaust gases produced and the fuels used. The data is collected and maintained in the individual state offices of the federal states. The data set used in this paper contains data from 15 of the 16 federal states in Germany. A total of 98,270 exhaust gas records and 18,147 fuel records are available, resulting in 6,746 complete and plausible sites after the data processing described in Fritz et al. 2022. For 657 sites, no or incorrect coordinates are available, resulting in 6,089 mappable, complete and plausible sites. For each of these sites, the amount of excess heat is calculated based on the temperature *T* of the exhaust gas, the volumetric flow *V* of the exhaust gas, the operating time *O* of the site and the assumption that the heat capacity of the exhaust gas corresponds to the heat capacity of nitrogen at 100 °C:

$$Q = \mathrm{V} * \mathrm{O} * 1.3\left(\frac{kg}{m^3}\right) * 1.04\left(\frac{kJ}{kg * K}\right) * (\mathrm{T} - T_r) \quad (1)$$

It is assumed that the temperature T_r to which the excess heat can be cooled down is 35°C. If sulphur dioxide is present in the exhaust gas, the minimum temperature T_r is 135 °C (cf. (Fritz et al. 2022a)).

The data on residential heat demand is based on the open source data set of the EU project Hotmaps. The method for generating this dataset is described in Pezzutto et al. (2019) and is publicly available for download[1]. The data are available as raster data with a resolution of 100 m x 100 m and cover the space heating and hot water demand in residential buildings. This data is combined with further data from OpenStreetMap (OpenStreetMap contributors 2021), which contains information about the residential areas. The data from OpenStreetMap is based on the layer "landuse" and all areas that have the identifier "landuse=residential" were filtered, which allows all residential areas to be identified. After data processing, the result is a dataset that contains residential areas in the form of polygons with additional information on heat demand.

This paper uses the four technologies presented in section 2 (DH, PCM, Sorption Cycles, ESN) for the analysis. The technical and economic parameters of these technologies are based on the analyses in Fritz et al. (2022b). The economic parameters are particularly relevant here, as they allow the calculation of the respective costs for transporting excess heat.

3.2 Methods

Using industrial excess heat can reduce greenhouse gas emissions in the heating sector. The research aim of this paper is to determine the excess heat potential for providing residential heating in Germany, taking into account different transport technologies. For this purpose, we calculate the LCOTH for using industrial excess heat for approx. 6,000 excess heat sources, considering four different heat transport technologies (DH, PCM, Sorption Cycles, ESN).

[1] https://gitlab.com/hotmaps/building_footprint_tot_curr

Our model is based on an extensive data set of real excess heat sources. In addition, heat demands from the open source project hotmaps are used in a resolution of 100 m x 100 m, which are aggregated to residential area level. The aim of the model is to find the solution with the lowest LCOTH for each source.

The individual steps of the model are as follows. For each excess heat source we:

1) Find the closest sink that can consume all of the excess heat;
2) Design the heat distribution networks with the sinks closer or equally close to that sink;
3) Calculate the levelised costs of transported heat (LCOTH) for each network
4) Select the cheapest network

After this, we aggregate the results for Germany. In the following, the steps are described in more detail.

The **first step** is identifying the nearest sink for each excess heat source that can consume the entire excess heat. This is done to keep the computing time of the model as short as possible. Once this sink has been identified, this sink and all sinks closer to the source are taken into account for the next step. To limit the calculation time, only the nine closest sinks are considered. If no sink can consume all the excess heat, all nine sinks are used for the next steps.

In the **second step**, the heat distribution networks are generated for each source based on the results from the first step. This consists of the excess heat source (point), one or more sinks (points) and connections (lines) between these points. This results in up to 2^x-1 networks for each source, where x is the number of sinks to be considered. With nine sinks, this results in up to 511 possible networks. The source and the sinks are connected to a minimum spanning tree using the prims algorithm for each possible network. This means that all nodes (sources and sinks) of the network are connected and the sum of the lengths of the connections is minimal. After that, the transported amount of excess heat is calculated for each connection.

In the **third step**, the LCOTH of the networks for each of the four technologies are calculated. This cost calculation is based on the method presented in Fritz et al. 2022. Here, the LCOTH are calculated based on the capital expenditure (CAPEX) and operating expenditure costs (OPEX). The CAPEX is calculated according to Konstantin und Konstantin (2018) as the annuity for one year:

$$CAPEX = Invest * \frac{(1+i)^t * i}{(1+i)^t - 1} \tag{2}$$

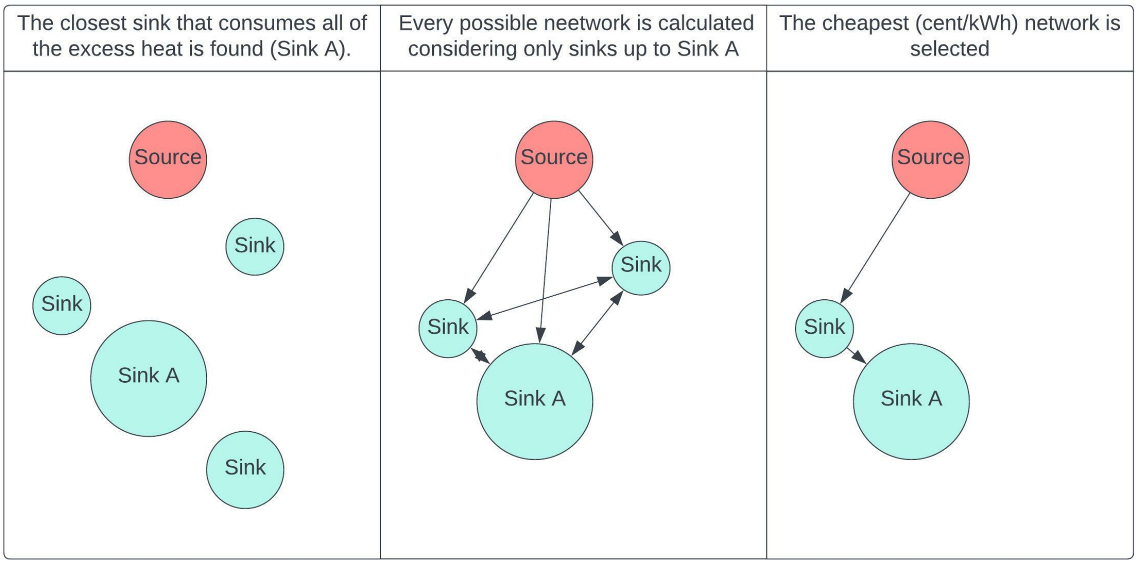
where i is the interest rate and t the time period under consideration. In our case, we assume that the interest rate is constant at 2 % for all technologies. t corresponds to the lifetime of the individual technologies. For DH this is 20 years; for PCM 12 years; for Sorption Cycles 30 years and for ESN 20 years (Fritz et al. 2022b). The OPEX of the individual technologies vary greatly and depends primarily on the amount of excess heat and the transport distance. The complete calculation basis of the OPEX can be found in (Fritz et al. 2022b). Based on this, the LCOTH are calculated. This is the sum of CAPEX and OPEX in relation to the amount of excess heat (Q) under consideration of losses (L):

$$LCOTH = \frac{\mathrm{CAPEX} + \mathrm{OPEX}}{\mathrm{Q} - \mathrm{L}} \tag{3}$$

The cost of the entire network corresponds to the cheapest sum of the costs of the respective connections.

In the **fourth step**, the cheapest network and thus also the cheapest transport technology for the respective source is determined. Figure 1 shows the individual steps of the method.

Figure 1: Steps 1 (left), steps 2 and 3 (middle) and step 4 (right) of the model



To carry out different analyses, it is possible to adjust different parameters for the modelling. The most important parameter is the maximum number of sinks to be considered per source. This increases the amount of excess heat that can be used, but also exponentially increases the computing time. In addition, it is possible to specify a cost threshold up to which potential networks are considered. If the transport costs of a network are above this threshold, this network is not considered.

A scaling factor for the transport distance can be specified in the model. This allows the transport distance to be modelled more realistically since a connection along the linear distance is often not possible. A sensitivity analysis for this factor can be found in chapter 4.2.

In addition, the model offers the possibility of optimising the maximum amount of excess heat. In this case, the aim of the model is to use as much of the available excess heat as possible under consideration of a cost threshold. This means that for each source, the technology is identified with which the most excess heat can be transported under consideration of the cost threshold. The results of this analysis can be found in chapter 4.3.

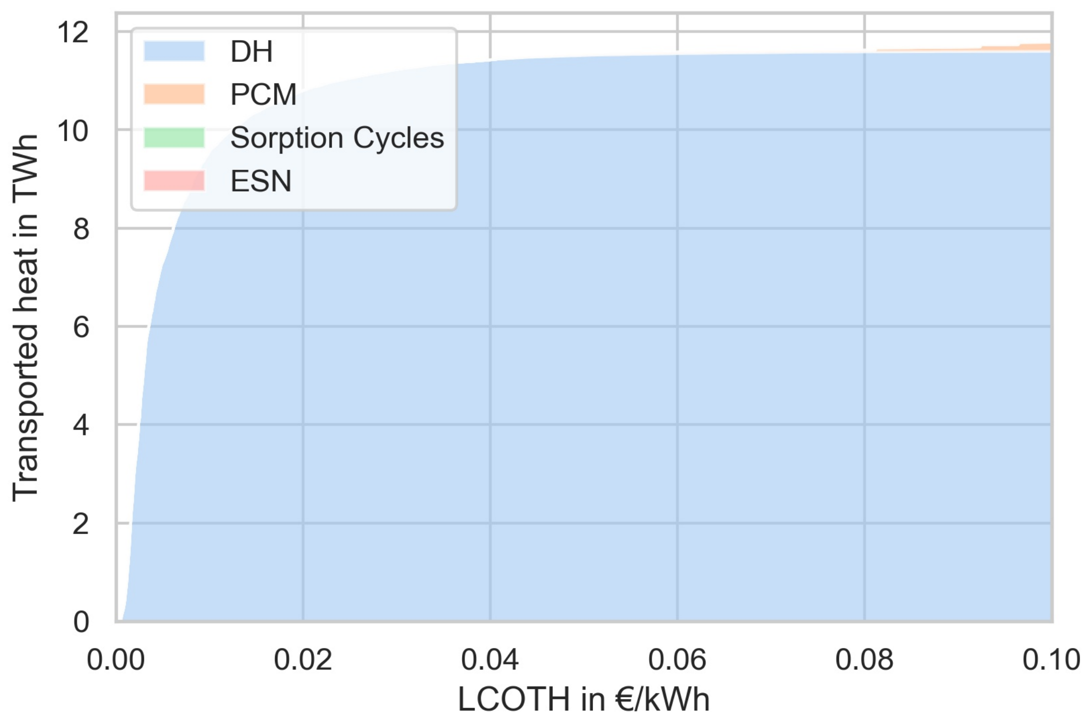
4 Results

4.1 Cost Optimisation

This section presents the modelling results using cost minimisation and a cost threshold of 0.1 €/kWh. This value results from the analyses in Fritz et al. (2022b) in which the transport costs of excess heat were compared to a gas boiler. Due to this restriction, out of the 6,089 excess heat sources, only 5,861 networks exist in which a network configuration has a lower LCOTH than 0.1 €/kWh. To limit the calculation time, a maximum of 9 sinks are considered for each source, resulting in up to 511 possible distribution networks per technology for each source. This means that up to 2,044 distribution networks are calculated for each source. For the cost optimisation, this threshold was reached for 727 networks. For each of these networks, only the amount of excess heat that the nine closest sinks can consume is used.

Figure 2 shows the cumulative excess heat that can be used up to the LCOTH of 0.1 €/kWh. These restrictions result in a usable amount of excess heat of 11.8 TWh. The respective colours show the respective shares of the individual technologies. This figure is very revealing in several respects. First, DH is the technology that was selected for the most excess heat sources. Second, most of the heat can be used at a very low cost. For LCOTH below 0.02 €/kWh, 10.8 TWh, which corresponds to 92 % of the total amount, can already be used. And third, ESN and Sorption Cycles are selected for no excess heat source for cost optimisation. This shows that the costs for these technologies are relatively high, and excess heat can be transported more cost-effectively with DH and PCM.

Figure 2: Cumulative LCOTH for cost optimisation



The transport distance is essential for the external use of industrial excess heat as both the investment and the operating costs depend on it (Fritz et al. 2022b). Figure 3 shows a histogram of the distances between excess heat source and sink. The blue line indicates the number of networks where DH has the lowest LCOTH, and the orange line shows the number of networks where PCM has the lowest LCOTH. The black dashed line marks the median value of the distance, which is approx. 720 m. 4,045 networks, or 69 % of the networks, have a transport distance of less than 1,000 m. 5,553 networks, or 95 % of the networks, have a transport distance of less than 2,000 m. There is no clear difference between the individual technologies. Both technologies are represented in all distance ranges. This means no conclusion can be made about which technology is preferred based on the transport distance.

Figure 3: Histogram of the transport distance by technologies

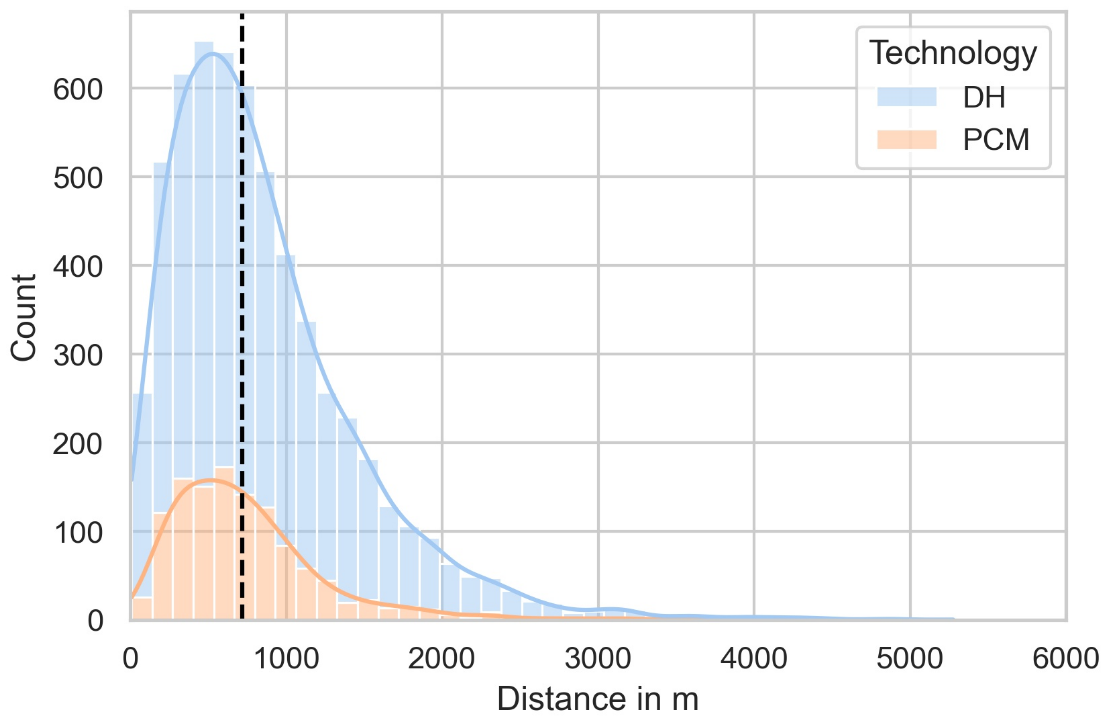


Figure 4 shows a histogram of the LCOTH resulting from the modelling. The blue bars show networks for which DH has the lowest LCOTH, and the orange bars show networks for which PCM has the lowest LCOTH. The black dashed line marks the median value of the LCOTH, which is about 0.019 €/kWh. It can be seen that DH has significantly lower costs compared to PCM. The first network in which PCM was selected as the cheapest technology has LCOTH of 0.038 €/kWh. The cheapest network with DH has LCOTH of 0.0002 €/kWh at a transport distance of 40 m. In total, the optimisation results in 4,653 sources for which DH has the lowest LCOTH and 1,208 sources for which PCM has the lowest LCOTH.

Figure 4: Histogram of the LCOTH by technologies

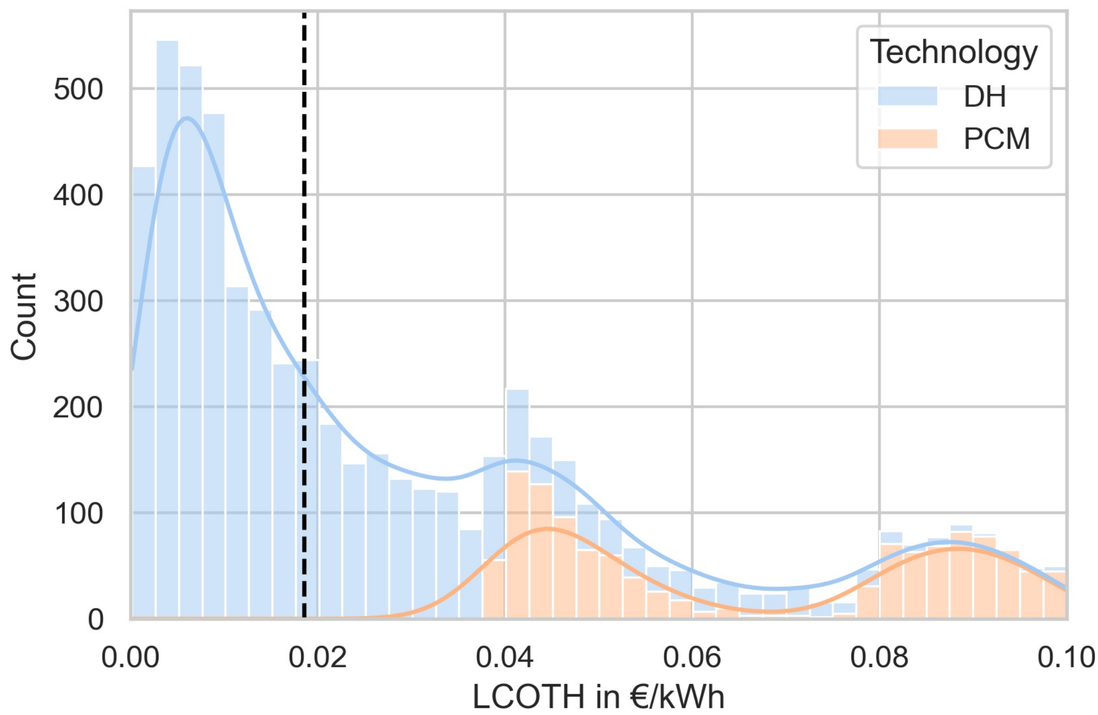
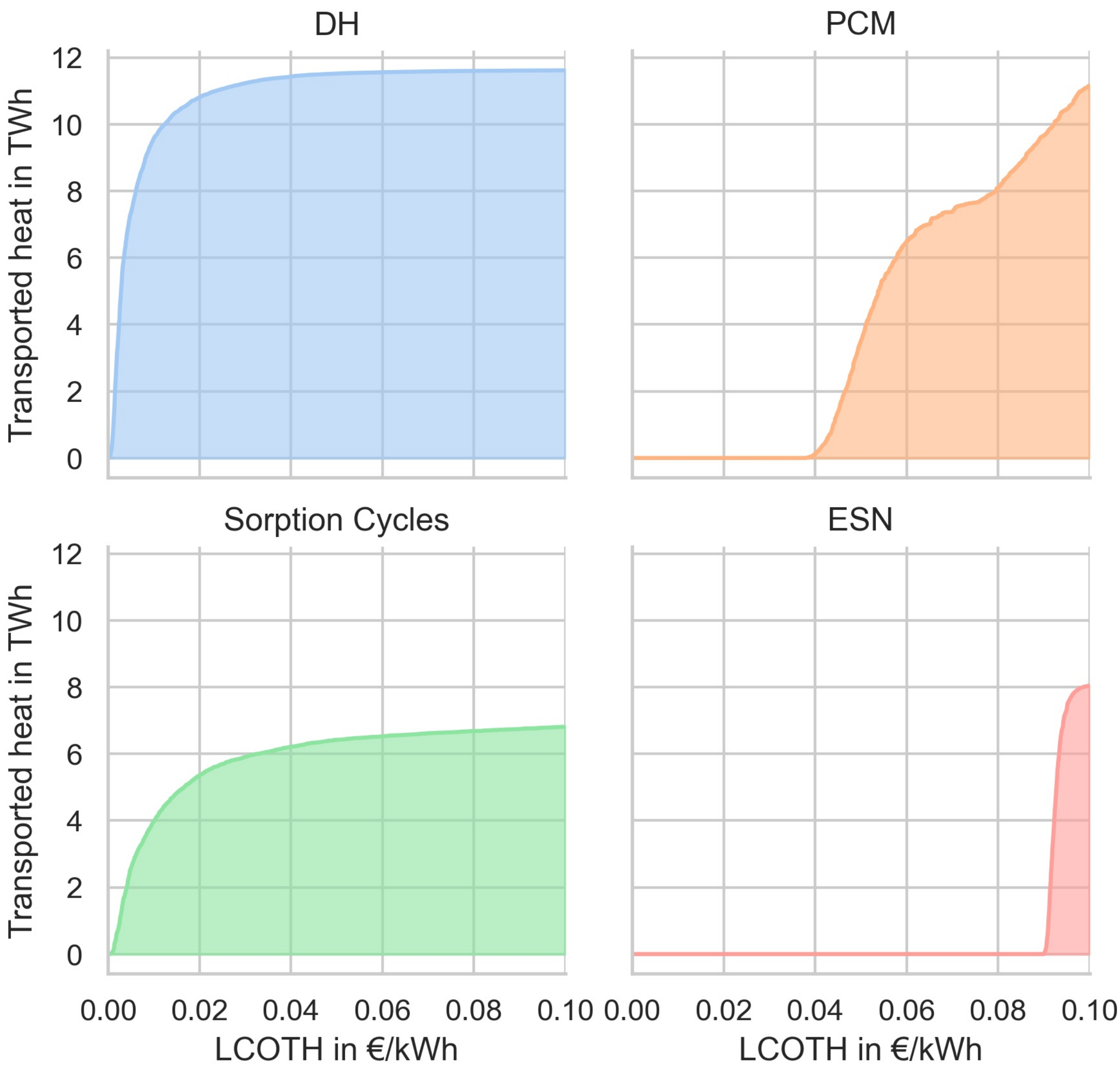


Figure 5 shows the cumulative excess heat quantity divided into the individual technologies, up to the LCOTH of 0.1 €/kWh. For each excess heat source, the option with the lowest LCOTH is determined for each technology. This means that each excess heat source might be present in all four technology grids. It can be seen that DH can transport the largest amount of excess heat up to LCOTH of 0.1 €/kWh. For PCM, it can be seen that no excess heat below 0.04 €/kWh can be transported, but up to 0.1 €/kWh, almost 11 TWh can be transported. For ESN, the LCOTH is relatively high, and excess heat can only be transported with LCOTH higher than 0.09 €/kWh.

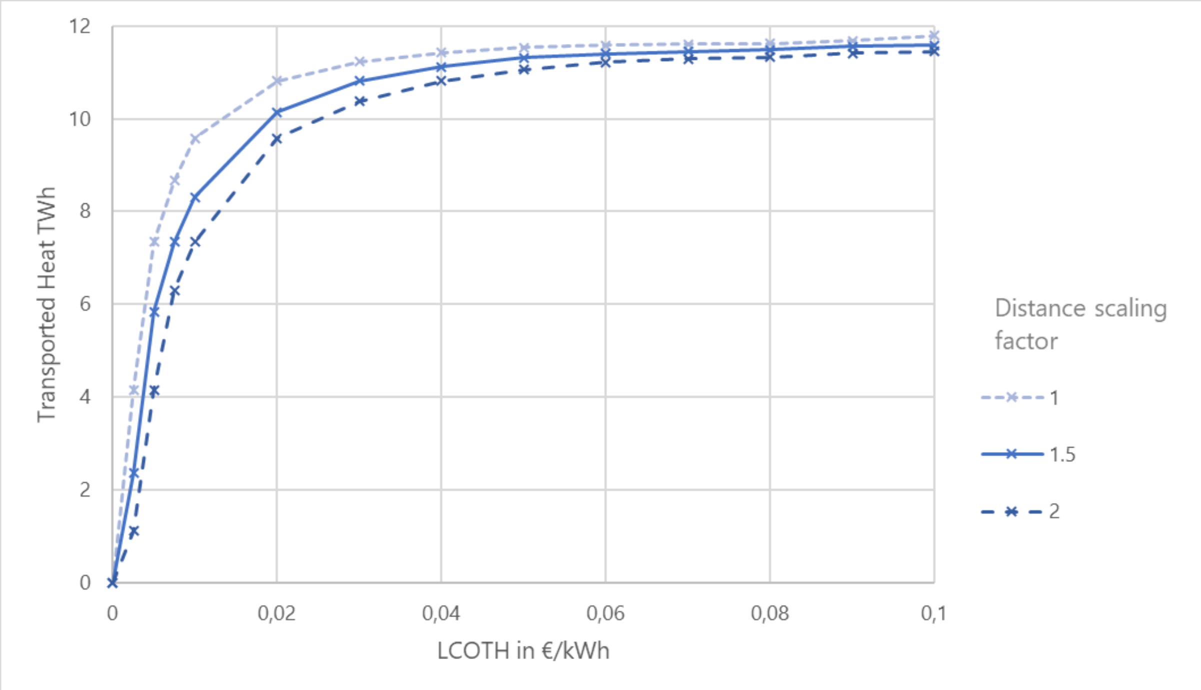
Figure 5: Cumulative LCOTH for cost optimisation for each technology



4.2 Sensitivity Analysis

In the results of the previous section, the linear distance is used to determine the transport distances. In reality, however, the transport distances are higher, which is why a sensitivity analysis for this parameter is carried out in this section. For this purpose, the calculations from chapter 4.1 are carried out again, and scaling factors of 1.5 and 2 are used for the transport distance. Figure 6 shows the results of this analysis. The figure shows the cumulative amount of heat that can be transported depending on the respective LCOTH. The results show that the total amount that could be transported up to 0.1 €/kWh changes only minimally. In the case of double the transport distance, the total quantity is reduced by approx. 0.3 TWh, which corresponds to a reduction of approx. 3 %. However, it can be seen that more significant deviations occur mainly in the range of lower LCOTH. For the value up to 0.005 €/kWh, the deviation for the case of double the transport distance is 3.2 TWh, which corresponds to a reduction of about 43 %. The results also show that there is no noticeable change in the choice of technologies. Even for 1.5 times and 2 times the transport distance, DH is selected for about 75 % of the sources and PCM for about 25 % of the sources.

Figure 6: Sensitivity analysis of the transport distance



4.3 Heat amount optimisation

In contrast to the results from section 4.1, this section presents the results of the optimisation according to the maximum amount of excess heat used. A cost threshold is taken into account, meaning that networks with LCOTH above this threshold are not considered. These analyses also set the cost threshold to 0.1 €/kWh. Figure 7 shows the cumulative excess heat that could be used under these conditions. The total amount of excess heat that can be used up to a cost threshold of 0.1 €/kWh is 16.5 TWh. This is 4.7 TWh more than with the pure cost optimisation (c.f. Figure 2). It can be seen that in this case, the technologies ESN and sorption are also used. For DH and Sorption, it can be seen that excess heat can also be used at meagre costs. Below 0.04 €/kWh, a total of 5.8 TWh can be used. For the ESN technology, it can be seen that significantly higher costs are incurred for this technology. In this cost range, however, most excess heat can be used for many sources using ESN.

Figure 7: Cumulative LCOTH for optimising the maximum amount of excess heat used

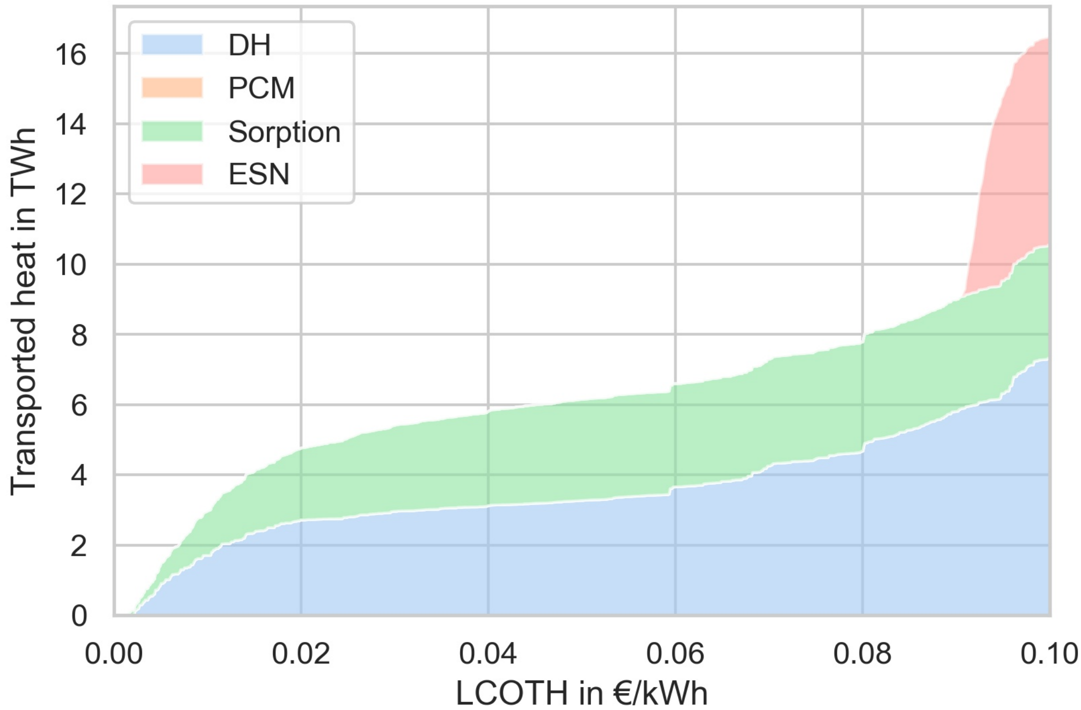
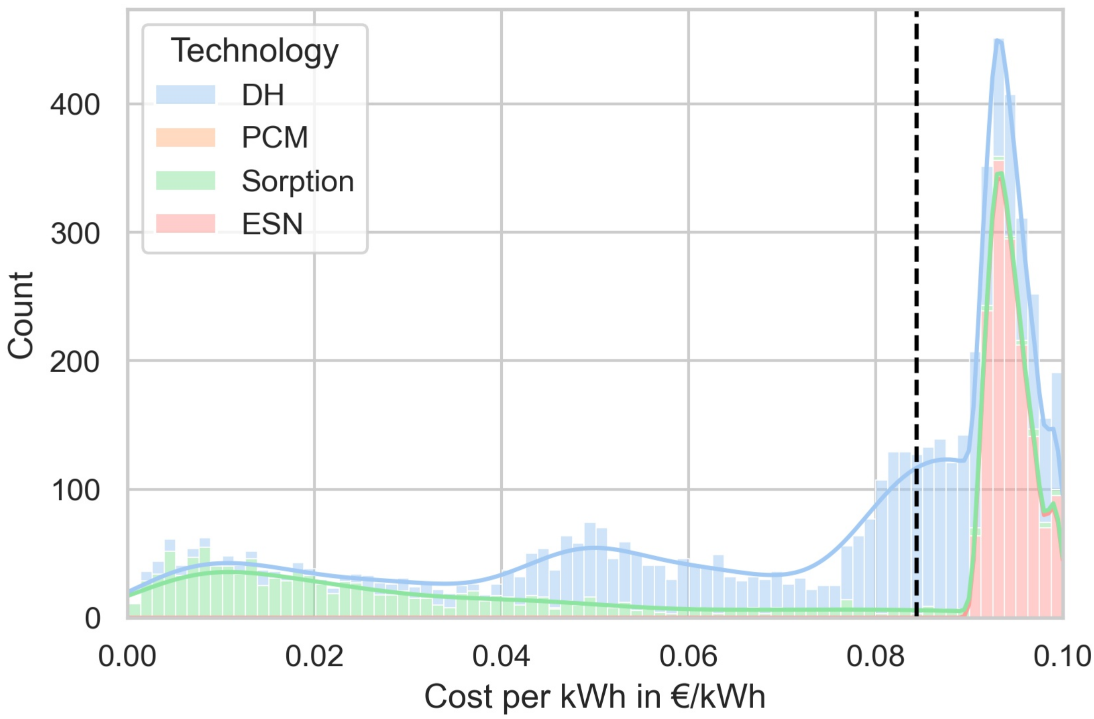


Figure 8 shows a histogram of the costs for the described optimisation according to the maximum amount of excess heat. In contrast to the results shown in Figure 4, it can be seen that the costs in this case of optimisation are significantly higher. The median is shown as a black dashed line and amounts to 0.084 €/kWh. This is 0.065 €/kWh higher than the median of the cost optimisation. This is due to the fact that the LCOTH for ESN are significantly higher than the LCOTH for DH. However, it can be seen that there are also sources in this optimisation where the LCOTH are significantly lower. In total, DH is selected for 3,169, sorption for 1,220 and ESN for 1,472 sources. PCM is not selected for any source.

Figure 8: Histogram of the LCOTH for optimising the maximum amount of excess heat used



5 Discussion

This paper analyses the potential and costs of using industrial excess heat for residential heating based on different technologies. For this purpose, we have developed a bottom-up optimisation model that creates the optimal distribution network for each excess heat source based on site-specific data, selects the respective technology and calculates the transport costs. However, our analysis makes some assumptions that are discussed in the following.

For our analyses, we use data from the open-source project HotMaps for the heat demand. This data set is disaggregated based on national energy statistics based on different indicators, which means that these values are only estimates and cannot provide an exact statement about the actual heat demand. In addition, these data are only available as annual values and not as daily or hourly values. Therefore, when interpreting the results, it must be considered that a seasonal heat storage is necessary to fully utilise the available excess heat. Future analyses should therefore collect real demand data and, if possible, integrate these into the modelling as hourly load profiles to improve the analyses' accuracy.

Our analyses do not include an analysis of the total costs of providing heat to the end consumer. Our analysis only deals with the costs of transporting the heat. For the total costs, the costs for provision within the companies and the connection costs within the buildings must also be added. Furthermore, our analyses do not consider distribution costs within the respective demand areas. In further studies, the existing method should be extended, and the costs for the end users should be investigated. For this purpose, existing district heating networks are also of great importance, which should also be considered in methodological developments.

In Fritz et al. (2022b) the different technologies are investigated for a transport distance of 1,000 m to 30,000 m. Our analyses show that the median transport distance is less than 1,000 m, and almost all transport distances are less than 3,000 m. Future studies should repeat the analyses of Fritz et al. (2022b) and analyse the range smaller than 3,000 m to be able to make a conclusion about which technologies are advantageous in these transport ranges.

The results from sections 4.1 and 4.3 show that different results are obtained depending on the objective function. When optimising the maximum utilised excess heat, up to 20 %, more excess heat can be utilised compared to pure cost optimisation. However, the costs for transporting the excess heat increase significantly in this case. For this reason, an average value between these parameters should be found to be able to utilise a large amount of excess heat, as well as to be able to provide it at the lowest possible cost. Future research should therefore investigate how the modelling can be further optimised to be able to use as much excess heat as possible at the lowest possible cost.

The data source used for the excess heat sources from Fritz et al. (2022a) was adjusted in several steps and thus only reflects part of the excess heat. It can therefore be assumed that the total usable excess heat is greater. Also due to the limitation of the maximum sinks to be considered in our modelling, some of the existing excess heat is not fully utilised. In our modelling, the threshold of a maximum of 9 sinks is reached for 727 excess heat sources. Thus, for these 727 excess heat sources, the excess heat is not fully utilised, but only the part that can be absorbed by the 9 sinks. For this reason, the results of 12-17 TWh show a significantly lower potential than the 36 TWh presented in Fritz et al. (2022a). Future analyses should further develop the method in order to be able to calculate as many networks as possible so that excess heat is fully utilised and the computing time remains within reasonable limits.

The method used calculates a separate network for each excess heat source. This means that neighbouring excess heat sources are not taken into account. For the use of industrial excess heat, however, it makes sense to consider these sources together, at least for DH and Sorption, since the LCOTH decreases due to larger excess heat quantities. Furthermore, the method does not consider that there may be branches within the connection lines. Additional studies should further develop both the method for assessing several neighbouring excess heat sources and the routing.

6 Conclusion

We analysed over 6,000 excess heat sources and calculated the most economical technology for using excess heat based on a bottom-up optimisation model for each of these sources. For each source, up to 2,044 networks with different configurations of heat demand areas were calculated. In addition, we performed a second optimisation to identify for each source the technology and network configuration with which the largest amount of excess heat can be utilised. Our results show that up to 0.1 €/kWh of LCOTH, about 12-17 TWh excess heat can be utilised. For the cost optimisation, we see that DH is the most selected technology, as it has the lowest LCOTH for the respective network configurations. When optimising the amount of excess heat used, however, it becomes apparent that the technologies ESN and sorption are also used. This is mainly because the heat losses of these technologies are lower. However, it should be noted that the LCOTH are significantly higher. In summary, our results show that there is a large regional excess heat potential and that different technologies are advantageous depending on the aim of utilisation. The technologies for using industrial excess heat are available, but the next step must be market penetration and up-scaling.

7 List of figures

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