Industrial excess heat utilisation for residential heating

Vom Fachbereich Bau- und Umweltingenieurwissenschaften der
Technischen Universität Darmstadt

zur Erlangung des Grades eines
Doktors der Ingenieurwissenschaften (Dr.-Ing.)

Dissertation

von

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aus Pforzheim

Darmstadt 2022

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Korreferent: Prof. Dr.-Ing. Clemens Rohde

Fritz, Markus: Industrial excess heat utilisation for residential heating
Darmstadt, Technische Universität Darmstadt,
Jahr der Veröffentlichung der Dissertation auf TUprints: 2023
URN: urn:nbn:de:tuda-tuprints-231689
Tag der mündlichen Prüfung: 21.12.2022

Danksagung

Die Erstellung dieser Dissertation war für mich eine lange Reise mit unterschiedlich ausgeprägten Höhen und Tiefen. Ich möchte mich bei allen bedanken, welche mich auf diesem Weg begleitet haben um die Höhen zu genießen und die Tiefen zu überwinden.

Zuerst möchte ich mich bei meiner Erstreferentin Prof. Dr. Liselotte Schebek bedanken. Vielen Dank, dass Sie sich auf diese Reise mit einem externen Doktoranden eingelassen haben und mich immer mit hilfreichen Hinweisen unterstützt haben. Vielen Dank an Prof. Dr. Clemens Rohde, welcher mich ursprünglich zum Fraunhofer ISI gebrachte hat, mich in sein Team aufgenommen hat und nun als Korreferent diese Dissertation betreut hat. Danke für die vielen Freiheiten während der Erstellung der Dissertation, die vielen spannenden Projekte und den notwendigen Pragmatismus.

Des Weiteren möchte ich Patrick Plötz danken, dass du mich auf dieser Reise als Mentor begleitet hast. Vielen Dank für deine tatkräftige Unterstützung und vor allem auch Danke für die Erinnerung, dass man die Höhen genießen und die Feste so feiern muss wie sie fallen. Vielen Dank auch an Ali Aydemir, dass du mich als inoffizieller fachlicher Mentor stets unterstützt hat, immer gute Ideen für Probleme hattest und mich des Öfteren mit deinen teils abstrusen Geschichten abgelenkt hast.

Natürlich geht auch ein riesen Dank an alle Kolleginnen und Kollegen vom ISI, dem Geschäftsfeld Energieeffizienz, meinen studentischen Hilfskräften und dem TPK Team. Ihr alle sorgt dafür, dass ich (fast) jeden Tag gerne ans ISI komme. Vielen Dank für eure ganze Unterstützung, eure Ideen und das kollegiale Miteinander, was eine ganz besondere Motivation versprüht.
Ganz besonderen Dank an Aline Scherrer, die in den ersten Jahren meinen ganzen Quatsch im Büro ertragen hat. Der restlichen Banksy Crew, mit der ich viele schöne Stunden verbringen durfte. Miriam Schöfer, die mich bei der finalen Formatierung dieses Dokuments unterstützt hat. Julius Wesche, der so verrückt war und mit mir das Projekt enPower gestartet hat. Und natürlich Danke an meinen Teams-Buddy-Fachexperten Konstantin Krauß, der mir viele Sitzungen (ich sage nicht welche) und Home-Office Stunden versüßt hat.

Vielen Dank auch an meine restlichen Freunde und meine Familie. Ihr habt mir immer wieder gezeigt wie schön das Leben auch abseits des Instituts und der Dissertation ist.

Abschließend einen riesigen Dank an Caro. Ich kann nicht mal ansatzweise ausdrücken wie dankbar ich dir für deine Unterstützung und deine Geduld mit mir bin.

Wie jede Reise kommt nun auch diese Reise zu Ende. Retrospektiv habe ich eine Menge über mich und auch über die Wahrnehmung von Rückschlägen gelernt. Oftmals sind diese nicht so schlimm wie sie im ersten Moment scheinen. Wie Qui-Gon Jinn schon sagte: "Du darfst niemals vergessen: Deine Wahrnehmung bestimmt deine Realität!"

Contents

Preamble to the cumulative dissertation

This cumulative dissertation consists of five scientific publications, constituting chapters 2-6. Three of these publications have been published in international peer-reviewed journals. These are:

Fritz, Markus; Plötz, Patrick; Schebek, Liselotte (2022): A Technical and Economical Comparison of Excess Heat Transport Technologies. In: Renewable and Sustainable Energy Reviews (168). DOI: 10.1016/j.rser.2022.112899.

Fritz, Markus; Ali Aydemir; Schebek, Liselotte (2022): How much excess heat might be used in buildings? - A spatial analysis at municipal level in Germany. In: Energies. DOI: 10.3390/en15176245.

Fritz, Markus; Savin, Margaux; Aydemir, Ali (2022**):** Usage of excess heat for district heating - analysis of enabling factors and barriers. In: Journal of cleaner production (363). DOI: 10.1016/j.jclepro.2022.132370.

The fourth publication has been published as a peer-reviewed publication in the Proceedings of the eceee Summer Study 2019:

Fritz, Markus; Aydemir, Ali (2019): Don't waste the water, use wastewater - excess heat distribution for private households through sewer networks: ECEEE (eceee Summer Study 2019. Proceedings).

The fifth publication has been published as a working paper in the sustainability and innovation series:

Fritz, Markus; Werner, Dorian (2022): Industrial excess heat and residential heating - Potentials and costs based on different heat transport technologies. Working Paper Sustainability and Innovation No. S 11/2022. Karlsruhe: Fraunhofer ISI

Below is the complete publication list with all publications that were published during the dissertation period:

<u>Journal articles:</u>

Fritz, Markus; Plötz, Patrick; Schebek, Liselotte (2022): A Technical and Economical Comparison of Excess Heat Transport Technologies. In: Renewable and Sustainable Energy Reviews (168). DOI: 10.1016/j.rser.2022.112899.

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Rohde, Clemens; Alsheimer, Sven; Arens, Marlene; Aydemir, Ali; Billerbeck, Anna; Dütschke, Elisabeth; **Fritz, Markus**; Hirzel, Simon; Jochem, Eberhard; Marscheider-Weidemann, Frank et al. (2021): Rationelle Energieverwendung. In: BWK. Das Energie-Fachmagazin. Online available: https://publica.fraunhofer.de/entities/publication/b5ac6058-7ff5-4460-90c5-0f67875a66dd/details

Oberle, Stella; Stute, Judith; **Fritz, Markus**; Klobasa, Marian; Wietschel, Martin (2020): Sector coupling technologies in gas, electricity, and heat networks. Competition or synergy? In: Zeitschrift für Technikfolgenabschätzung in Theorie und Praxis : TATuP. DOI: 10.14512/tatup.29.2.24

Niederste-Hollenberg, Jutta; Schirmer, Gitta; Borger, Julia; Winkler, Jenny; Zheng, Lin; **Fritz, Markus**; Hillenbrand, Thomas; Kolisch, Gerd (2020): Die Potenziale der Energieeinsparung in der Abwasserwirtschaft. In: Ökologisches Wirtschaften. DOI: 10.14512/OEW350347

Rohde, Clemens; Arens, Marlene; Billerbeck, Anna; **Fritz, Markus**; Hirzel, Simon; Jochem, Eberhard; Marscheider-Weidemann, Frank; Reuter, Matthias; Schlomann, Barbara; Steinbach, Jan et al. (2020): Rationelle Energieverwendung 2019. In: BWK. Das Energie-Fachmagazin. DOI: 10.37544/1618-193X-2020-08-09-148

Aydemir, Ali; **Fritz, Markus** (2020): Estimating excess heat from exhaust gases: why corrosion matters. In: Energ. Ecol. Environ. 5 (5), S. 330–343. DOI: 10.1007/s40974-020-00171-5.

Fritz, Markus; Plötz, Patrick; Funke, Simon Á. (2019): The impact of ambitious fuel economy standards on the market uptake of electric vehicles and specific CO2 emissions. In Energy Policy. DOI: 10.1016/j.enpol.2019.111006

Rohde, Clemens; Reuter, Matthias; Brugger, Heike; Hirzel, Simon; Hettesheimer, Tim; Plötz, Patrick; **Fritz, Markus**; Thielmann, Axel; Steinbach, Jan (2019): Rationelle Energieverwendung. Eine Literaturanalyse des Jahres 2018. In: BWK. Das Energie-Fachmagazin. Online available: https://publica.fraunhofer.de/entities/publication/ea02e19c-63e4-4834-9c69-d880f81e3b37/details

Conference papers/ working papers

Fritz, Markus; Werner, Dorian (2022): Industrial excess heat and residential heating - Potentials and costs based on different heat transport technologies. Working Paper Sustainability and In-novation No. S 11/2022. Karlsruhe: Fraunhofer ISI

Billerbeck, Anna; **Fritz, Markus**; Aydemir, Ali; Manz, Pia (2022): Strategic heating and cooling planning to shape our future cities: ECEEE (eceee Summer Study 2022. Proceedings). DOI: 10.24406/publica-300

Fritz, Markus; Aydemir, Ali (2020): The energy of exergy - analysis of different olefin production routes. ECEEE (Industrial Efficiency 2020 - Decarbonise Industry! eceee Industrial Summer Study 2020. Proceedings). Online available: https://publica.fraunhofer.de/entities/publication/6e66107f-0817-407c-bfb2-e9613e83ded3/details

Reports:

Aydemir, Ali; Fritz, Markus; Billerbeck, Anna (2022): Strategic H&C planning success factors. DOI: 10.24406/publica-182. Online available: https://actionheat.eu/resources/strategic-hc-planning-success-factors

Bieker, Susanne; Fritz, Markus; Hohmann, Claudia; Aydemir, Ali; Schratz, Udo; Müller, Philipp; Glöckner, Andreas and Körkemeyer, Karsten (2021): InnoA2-Up. Umsetzungsplanung für Pilotanlagen zur innovativen Abwärmenutzung und -verteilung über die Kanalisation. Endbericht. Online available: https://publica.fraunhofer.de/entities/publication/4a961c52-8b5d-4049-a800-414902fc5c8c/details

Steinbach, Jan; Popovski, Eftim; Henrich, Jasmin; Christ, Catrice; Ortner, Sara; Pehnt, Martin; Blömer, Sebastian; Auberger, Andreas; Fritz, Markus; Billerbeck, Anna; Langreder, Nora; Thamling, Nils; Sahnoun, Malek; Rau, Dominik (2021): Umfassende Bewertung des Potenzials für eine effiziente Wärme- und Kältenutzung für Deutschland. Online available: https://irees.de/wp-content/uploads/2021/03/Comprehensive-Assessment-Heating-and-Cooling_Germany_2020.pdf

Niederste-Hollenberg, Jutta; Winkler, Jenny; Fritz, Markus; Zheng, Lin; Hillenbrand, Thomas; Kolisch, Gerd; Schirmer, Gitta; Borger, Julia; Doderer, Hannes; Dörrfuß, Ilka (2021): Klimaschutz- und Energieeffizienzpotenziale in der Abwasserwirtschaft - aktueller Stand und Perspektiven. Online available: https://publica.fraunhofer.de/entities/publication/7474ff69-4935-4ca6-8e4c-5bba309cb56c/details

Radgen, Peter; Leisin, Matthias; Flatau, Roman; Aydemir, Ali; Fritz, Markus; Neusel, Lisa; Arens, Marlene (2020): Exergie und Wirtschaft. Online available: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/cc_26-2020_exergie_und_wirtschaft_0.pdf

Aydemir, Ali; Bieker, Susanne; Fritz, Markus; Müller, Philipp; Glöckner, Andreas (2020): Wirtschaftlichkeitsbewertung und Sensitivitätsuntersuchung zum "Erläuterungsbericht Entwurfsplanung Gebiet 1 von ECO.S Energieconsulting Stodtmeister". Online available: https://publica.fraunhofer.de/entities/publication/99a656c5-b0ca-47c9-a5f3-51bef91dc047/details

Eichhammer, Wolfgang; Fritz, Markus; Pehnt, Martin; Fritz, Sara; Nast, Michael; Steinbach, Jan; Henrich, Jasmin; Popovski, Eftim (2019): German sustainable heating solutions - Best practices and application in China. Online available: https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/German_Sustainable_Heating_Solutions_EN.pdf

1 Introduction

1.1 Energy consumption and heating in Germany

Germany aims to become climate neutral by 2045 (BMWK 2021). To achieve this goal, a climate neutral energy supply must be ensured, and a reduction in energy demand must be achieved to ensure the security of supply. The final energy demand for Germany was 2,317 TWh in 2020 (Umweltbundesamt 2022).

This final energy demand is divided among the industry, household, transport and tertiary sectors and different application areas, such as space heating, process heat and air-conditioning. The application area of heating is responsible for about 55% of the German final energy demand, corresponding to 1,283 TWh (AGEB 2021). In recent years, only minimal savings have been achieved in this area. From 2011 to 2020, the final energy demand for heating decreased by 4.4%. (AGEB 2021). In this application area, the industry and household sectors are of particular importance. In households, 84% of the final energy was used for residential heating (space heating and hot water) in 2020, corresponding to 564 TWh. In the industrial sector, approximately 67% of the final energy demand was used for the provision of process heat, corresponding to 1,583 TWh. However, large amounts of this process heat are released unused into the environment in the form of excess heat (Brückner 2016; Aydemir and Fritz 2020).

This industrial excess heat mainly occurs in low-temperature ranges (<200°C), often making it difficult to use for other industrial processes (Fritz et al. 2022a). Using it to provide residential heating, on the other hand, could be a relevant option for reducing greenhouse gas emissions. Yet industrial plants are often far from residential areas. Thus, excess heat must be transported to end-using households. Today, in the EU and Germany, district heating networks primarily enable the transport of excess heat (Fritz et al. 2022c; Hummel et al. 2014; Fang et al. 2013).

Current scenarios for the German energy system assume that 17–26% of residential heat demand in 2045 will be covered by district heating (Prognos et al. 2021; BCG 2021). These scenarios assume industrial excess heat will cover 11–12% of district heating generation in 2045. In 2018, this share was only 1.7% (Steinbach et al. 2021). This low percentage indicates that significant changes must be made in residential heating, district heating and excess heat usage to achieve climate goals.

Transporting excess heat from industrial plants to households is not only possible with district heating. The installation of district heating networks is capital intensive, and under certain circumstances, using other technologies can be technologically feasible and economical (Fritz et al. 2022b).

The use of excess heat is an important aspect of providing residential heating and reducing greenhouse gas emissions. The critical questions concerning excess heat use are what concrete contribution can excess heat make, which technologies are best suited for transporting excess heat to end-using households, and what is the cost of transporting excess heat.

1.2 Excess heat utilisation

1.2.1 Definitions

Industrial excess heat is heat generated during an industrial process that cannot be used in the production process (Fritz et al. 2022c; Pehnt et al. 2010; Viklund and Johansson 2014). Thus, the heat is a by-product of an industrial process and is currently unused but could be used in the future to increase energy efficiency and reduce greenhouse gas emissions. This industrial excess heat results from thermodynamic constraints and inefficiencies in plants and processes (Brückner 2016; Hirzel et al. 2013).

In this thesis, excess heat refers to the heat contained in the exhaust gas of individual production processes, mainly resulting from combustion processes (Brückner et al. 2015; Jouhara et al. 2018). Excess heat can also be diffuse heat generated by, for example, the radiant heat of hot products in production or by excess heat from electrically operated machines. Collecting and bundling this excess heat is a significant challenge, and its utilisation is more complicated, as the temperature level is often low and the amount is also low.

Excess heat can be differentiated according to temperature level and temporal availability. The temperature level determines which applications' industrial excess heat can be used. The definitions of low-temperature and high-temperature excess heat differ in the literature, although most studies refer to low-temperature excess heat at a temperature of less than 100–150 °C (Fritz et al. 2022a; Jouhara et al. 2018; Brückner et al. 2015; Manz et al. 2021). Excess heat with a temperature of > 500 °C is commonly referred to as high-temperature excess heat (Fritz et al. 2022a; Jouhara et al. 2018; Brückner et al. 2015; Manz et al. 2021). Temporal availability also determines the use of industrial excess heat. Depending on the industrial processes, the temporal availability of excess heat varies greatly. Processes that supply continuous excess heat throughout the year are particularly suitable for excess heat use. Continuous excess heat can especially be seen in areas of low-temperature excess heat (Fritz et al. 2022a).

There are several ways to make excess heat usable. Fritz et al. (2022c) provided a list of possible usage options:

1. The internal use of excess heat
2. The use of excess heat in other plants or processes
3. The conversion of excess heat into other forms of energy

Figure 1 shows these different options. The heat flows are illustrated in blue, the possible production processes in grey and the excess heat recovery processes in orange. In the first option, excess heat is used internally in the process in which it is generated. This type of usage is known as heat integration, which refers to processes in which internal excess heat is used to reduce heat demand (Aydemir and Fritz 2020). In the second option, the excess heat is fed and used in other processes or plants. This option can be completed either internally in the same plant or externally in another plant or in district heating networks. If it is used internally, it is called heat integration, as in the first option. The third option involves converting excess heat into other forms of energy. For example, excess heat can be converted into electricity via organic Rankine cycles or into cooling energy via adsorption systems.

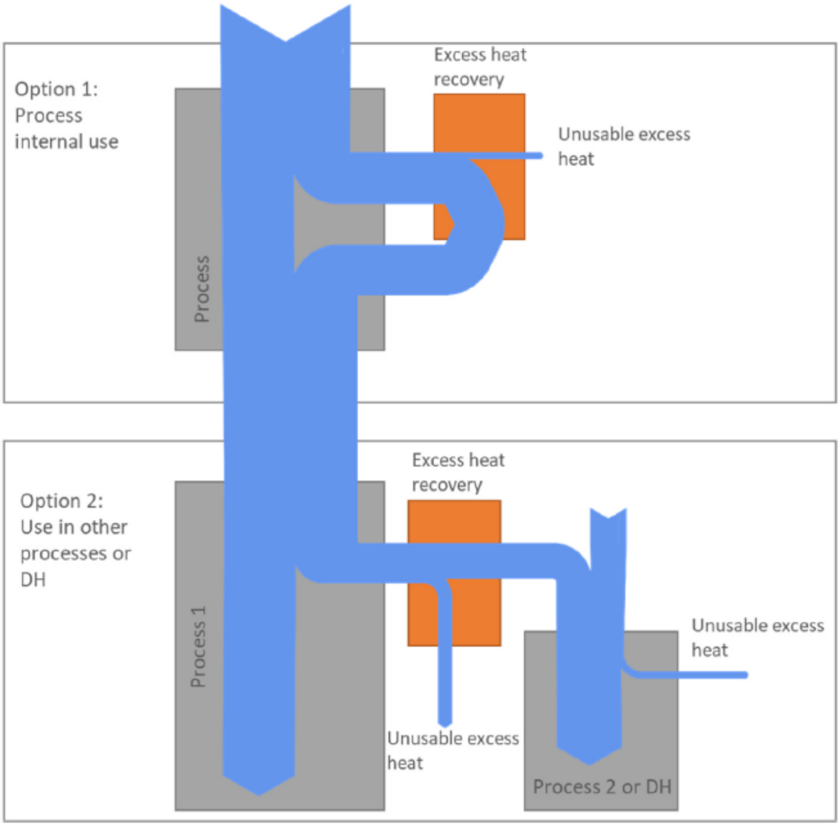


Figure 1 Excess heat utilisation options. Option 1 (top) internal use; Option 2 & 3 (bottom): Use in other processes or DH (Fritz et al. (2022c) based on Hirzel et al. (2013))

1.2.2 Status quo of excess heat utilisation for residential heating

The engineering analyses of excess heat and heat integration began at the latest in Germany in the 1930s (Bergmeier 2003). In those years, numerous journals explored the topic of heat economy. The aim of heat economy was to increase energy efficiency by using industrial excess heat. In the 1970s, the topic received attention again but in the context of the oil crises. Energy-intensive industrial companies in particular, such as those in the chemical and petrochemical industries, were seeking means of reducing energy consumption and increasing energy efficiency (Klemeš and Kravanja 2013). Accordingly, new methods and technologies were developed, which resulted in significant progress in the use of excess heat and heat integration. The oil crises also increased interest in district heating (Scholten and Timm 1978). In 1979, the first project in Germany was developed in which industrial excess heat was used for district heating (Fritz et al. 2022c). Excess heat from a hot rolling mill was integrated into the district heating network of the city of Dinslaken. In the following years, further installations for the external use of excess heat followed. In 2018, 2,383 GWh of excess heat was fed into district heating networks (Steinbach et al. 2021).

1.2.3 Existing literature

Several approaches have been applied to calculate excess heat potential. A distinction can be made between top-down and bottom-up analyses. In top-down analyses, the available excess heat is determined based on the sector-specific data of the individual industrial subsectors. The advantage of this method is its relatively easy application and the need for only limited information on industrial processes and production. For Germany, these top-down analyses indicate a potential of 130 TWh/a

(Pehnt et al. 2010) to 300 TWh/a (Groß and Tänzer 2010). This range contrasts with the results of bottom-up studies, which have primarily been conducted recently. In these studies, the excess heat potential is determined based on site-specific data, production quantities or information on the exhaust gas of individual industrial processes. The advantage of bottom-up analyses over top-down analyses is that the former is based on real values, meaning fewer assumptions must be made. The potential in bottom-up analyses ranges from 37 TWh/a (Steinbach et al. 2021) to 70 TWh/a (Brückner 2016). Generally, bottom-up analyses show a lower potential than top-down analyses. Table 1 summarises the literature on excess heat potential estimates for Germany.

Table 1 Summary of literature (Fritz et al. (2022a))

Study	Excess heat amount [TWh/a]...	Methodological approach	... based on	Spatial resolution	Subsectors differentiated	Analysing the role of excess heat for DH
Groß and Tänzer (2010)	*280-300*	*Top-down*	*Rough key figures*	*national*	*no*	*no*
Pehnt et al. (2010)	*130*	*Top-down*	*Key figures from a Norwegian study*	*national*	*yes*	*no*
Persson et al. (2014)	*157*	*Top-down*	*Key figures and public available empirical data*	*site-specific*	*yes*	*no*
Aydemir et al. (2020)	*94*	*Top-down and bottom-up*	*public available empirical data*	*national*	*no*	*yes*
Brückner (2016)	*60-70*	*Bottom-up*	*Key figures and comprehensive Empirical data*	*federal state*	*yes*	*no*
Steinbach et al. (2021)	*37.5*	*Bottom-up*	*Comprehensive Empirical data*	*municipal level*	*no*	*yes*
Blömer et al. (2019b)	*52-63*	*Bottom-up*	*Comprehensive Empirical data*	*site-specific analysis but no publication*	*no*	*yes*
Manz et al. (2021)	*43*	*Top-down and bottom-up*	*Public available Empirical data*	*site-specific*	*yes*	*yes*

A few studies have considered estimating the potential of excess heat to provide residential heating (Cooper et al. 2016; Hering et al. 2018) or considering spatial conditions and examining the distribution of excess heat via district heating networks (Hering et al. 2018; Blömer et al. 2019b). However, transporting industrial excess heat is not just possible with district heating networks. Under certain conditions, other technologies can be technologically and economically feasible (Fritz et al. 2022b). Few studies have explicitly investigated different technologies for transporting excess heat. One stream of literature has presented technologies for transporting excess heat and performed a technical comparison of them (Ma et al. 2009a; Vallade et al. 2012; Xu et al. 2019). In these studies, no economic comparisons were conducted. The results of this literature stream show that, from a technical perspective, technologies other than district heating can be helpful in heat transport. Under certain conditions, these technologies can also lead to lower heat loss and thus achieve higher efficiency. Another stream of literature has compared individual heat transport technologies economically with district heating (Gao et al. 2019; Chiu et al. 2016), finding that district heating is not always the most economical solution for heat transport. A third stream of literature has explicitly analysed the technical aspects of individual heat transport technologies but has not compared them to district heating (Deckert et al. 2014; Ma et al. 2017; Miró et al. 2016; Liu et al. 2002; Aydemir et al. 2019; Fritz and Aydemir 2019; Ammar et al. 2013; Gao et al. 2019; Kang et al. 2000; Lin et al. 2009)

Despite the many successful instances in which excess heat is used in district heating networks, there are barriers to implementation (Fritz et al. 2022c). On the one hand, there are technical barriers, including temporal imbalance, local discrepancy and quality mismatch. These technical barriers can be reduced through technological development and innovation. On the other hand, non-technical barriers have been insufficiently researched in the literature. These have so far been identified either by conducting workshops (Schmidt et al. 2020) or by broader analyses in individual countries (Blömer et al. 2019a; Moser and Lassacher 2020a; Päivärinne et al. 2015).

1.2.4 Research gap

Although some research has determined the excess heat potential for Germany and analysed different technologies for the transportation of excess heat, no study has identified the economic site-specific excess heat potential from industrial exhaust gases in Germany, its possible contribution to residential heating and the suitable technologies for its use. However, this is of great significance for strengthening the scientific understanding of what technologies can utilise excess heat, what contributions they can make and what costs they may entail. Existing studies have shown that other technologies for transporting excess heat can be technically and economically more advantageous than district heating under certain conditions. No study has conducted a site-specific economic analysis of excess heat potential considering different technologies. Only a few studies have addressed the barriers and enabling factors for implementing excess heat projects, and no study has analysed them based on hypothesis testing through interviews. Doing so is particularly important because the implementation of projects is highly dependent on individuals' decisions. Thus, analysing the respective barriers and facilitating factors based on interviews with relevant stakeholders is crucial.

In summary, no study on the potential of industrial excess heat in Germany has considered different technologies for its use and has addressed the barriers and enabling factors for implementing such projects.

1.3 Research question and outline of this thesis

This work aimed to determine the excess heat potential for residential heating based on different heat transport technologies, estimate the cost of excess heat transport and provide recommendations for the future dissemination of excess heat use. The focus is on which technologies suit transporting industrial excess heat, what potential the respective technologies have and how high the costs are for transporting the excess heat. Since the literature has not provided such an analysis, the overarching research question of this thesis is as follows:

"What is the economic site-specific excess heat potential from industrial exhaust gases in Germany and its contribution for residential heating, taking into account suitable technologies for its use and considering barriers and drivers for its use?"

To answer the research question, a bottom-up optimisation model is developed, that enables a site-specific modelling of the industrial excess heat potentials. The input data for the model are locally determined excess heat potentials and heat demands from the EU project Hotmaps, which are aggregated at the municipal level. Further input data include the technical and economic parameters of different heat transport technologies. Finally, an analysis of enabling factors for and barriers to using excess heat for residential heating is carried out. This method allows a comprehensive assessment of the excess heat potential for the provision of residential heating. Thus, the individual steps to answer the research question are as follows:

1. Determination of the excess heat potential in Germany at the municipal level
2. Identification of transport technologies for excess heat use
3. Analysis of the excess heat potential, taking into account different transport technologies
4. Analysis of enabling factors for and barriers to excess heat use

This work steps represent the chapters of this dissertation. Each of these chapters is based on a scientific publication. Figure 2 shows the individual work steps and their placement in the dissertation.

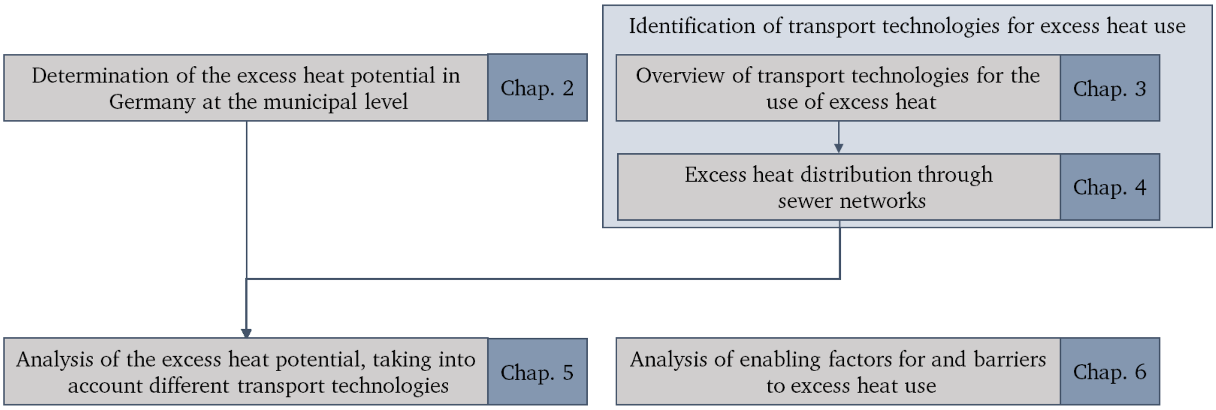


Figure 2 Work steps and thesis outline

This thesis focuses on Germany. The analysis of excess heat potential only includes excess heat in the form of exhaust gases. Therefore, diffuse excess heat flows or excess heat via wastewater are not considered. Yet the majority of excess heat is generated in energy-intensive industries and the manufacturing sector through the combustion of fossil fuels, meaning that this analysis considers most of the excess heat in Germany. The analysis is limited to selected technologies for transporting excess heat to end users. These technologies are selected based on quantitative and qualitative indicators and thus represent the most promising technologies for transporting excess heat. Due to data protection regulations, the results are evaluated at the municipal level, even though a more detailed evaluation is possible.

In the following paragraphs, an overview of the individual chapters of the dissertation is provided. Chapters 2–6 are based on scientific publications, and Chapter 7 contains the syntheses.

Chapter 2 contains the scientific publication “How Much Excess Heat Might Be Used in Buildings? A Spatial Analysis at the Municipal Level in Germany” (Fritz et al. 2022a). This chapter analyses the potentially available excess heat in Germany and compares it to the current residential heat demand. Furthermore, it includes an analysis of the excess heat potential in Germany according to different subsectors and temporal availability in the individual subsectors. Accordingly, the respective amounts of excess heat are calculated site-specifically based on data from more than 115,000 records of exhaust gas and fuel use at over 11,000 industrial sites. The calculation considers the presence of sulphur dioxide, which reduces the excess heat potential (Fritz et al. 2022a). Finally, the excess heat potential is was compared with the heat demand of households at the municipal level. This makes it possible to determine in which regions the use of excess heat is particularly advantageous.

Chapter 3 contains the scientific publication “A Technical and Economical Comparison of Excess Heat Transport Technologies” (Fritz et al. 2022b). This chapter presents an analysis of different transport technologies for the use of industrial excess heat. To complete this analysis, a technical and economic comparison of different technologies for transporting excess heat is was conducted. Thus, four heat transport technologies are identified based on the following indicators: future potential, data availability and current installations and pre-feasibility studies. These technologies are district heating, excess heat utilisation via sewage networks (ESN), absorption cycles and phase change materials (PCM). For technical comparison, an analysis of the lifetime, the temperature level that the technologies can provide, the heat capacity and the heat losses is carried out. Based on these findings, a classification of usable temperature levels and the usability of the technologies for different applications is undertaken. For economic comparison, the capital expenditures (CAPEX) and operational expenditures (OPEX) for each of the four technologies are calculated for approximately 450,000 combinations of transport distance and excess heat quantity. Based on these results, the most economical solution is identified for each of the approximately 450,000 combinations.

Chapter 4 contains the scientific publication “Don’t waste the water, use wastewater – excess heat distribution for private households through sewer networks” (Fritz and Aydemir 2019). This chapter presents a more detailed analysis of ESN. This technology offers a solution for excess heat utilisation without installing new district heating networks that can simplify and accelerate the process of excess heat utilisation. This technology feeds excess heat into existing wastewater and extracts it at another point along the flow path. An estimate of the potential use of this technology on a European level is made. For this purpose, data sets from over 950 industrial companies and over 26,000 wastewater treatment plants in Europe are used. The flow path to the nearest wastewater treatment plant is determined for each excess heat source, and the respective heat losses are quantified.

Chapter 5 contains the scientific publication “Industrial excess heat and residential heating: Potentials and costs based on different heat transport technologies” (Fritz and Werner 2022). It presents an analysis of the spatially resolved excess heat potential for the different technologies presented in Chapters 3 and 4. Thus, a bottom-up optimisation model is developed to calculate the most economical technology for using excess heat for 6,000 excess heat sources. For each source, up to 2,044 networks with different configurations of heat demand areas and technologies are calculated. Furthermore, a second optimisation is performed to identify for each excess heat source for the different technology and network configuration with which the largest amount of excess heat could be utilised. Finally, a sensitivity analysis of the transport distance is performed because the transport distance in the model is assumed to be the linear distance.

Chapter 6 contains the scientific publication “Usage of excess heat for district heating – analysis of enabling factors and barriers” (Fritz et al. 2022c). This chapter presents an analysis of the enabling factors for and the barriers to implementing projects for excess heat use in district heating networks. As previously mentioned, excess heat use can be a viable solution for decarbonising district heating networks. Nevertheless, many barriers to implementing such projects remain. In this chapter, the enabling factors and barriers for integrating excess heat into district heating networks are analysed based on a database of 45 realised projects in Germany, Austria and France. Based on a literature review, five hypotheses on enabling factors and barriers are formulated. These hypotheses are tested by literature research on individual projects and 13 expert interviews with representatives of excess heat-producing companies. Thus, in contrast to previous literature, both quantitative and qualitative data are used to test the hypotheses.

Chapter 7 contains the synthesis of the dissertation. It provides an overview of the contribution, an overarching discussion and the conclusion. It also offers recommendations for future research and policy making.

2 How Much Excess Heat Might Be Used in Buildings? A Spatial Analysis at the Municipal Level in Germany[1]

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.

[1] The chapter has been published as Fritz, Markus; Ali Aydemir; Schebek, Liselotte (2022): How much excess heat might be used in buildings? - A spatial analysis at municipal level in Germany. In: Energies. DOI: 10.3390/en15176245.

2.1 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 (eurostat 2022). Large amounts of this energy are released into the environment in the form of unused excess heat (Brückner 2016; Aydemir and Fritz 2020). 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 (Pehnt et al. 2010). 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 (Viklund and Johansson 2014).

However, there are different technical and non-technical barriers to using industrial excess heat (Fritz et al. 2022c). Technical barriers are temporal imbalance, local discrepancy and quality mismatch (Schmidt et al. 2020). 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 (Fritz et al. 2022c; Päivärinne et al. 2015; Blömer et al. 2019b), trust and trans-fer of information (Päivärinne et al. 2015), lack of know-how and capacity (Fritz et al. 2022c; Blömer et al. 2019b) and the binding character of contracts (Fritz et al. 2022c; Blömer et al. 2019b). However, some factors promote the implementation of projects for external excess heat utilisation (Fritz et al. 2022c). 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 (Viklund and Johansson 2014; Fritz et al. 2022c; Hirzel et al. 2013). 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.

2.1.1 Literature overview

The methodological spectrum to calculate the amount of excess heat ranges from estimation approaches based on key parameters (Pehnt et al. 2010; Manz et al. 2018; Groß and Tänzer 2010) to empirical works, such as that by Brueckner et al. (2017) 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 (Manz et al. 2021; Aydemir et al. 2020; Persson et al. 2014). For these analysis on excess heat potentials, a distinction can be made between bottom-up and top-down analyses. Bottom-up analyses (Brückner 2016; Manz et al. 2018; Hering et al. 2018; Steinbach et al. 2021) show a lower potential than top-down analyses (Pehnt et al. 2010; Groß and Tänzer 2010). Some works deal with the potential assessment of excess heat to cover the space heating demand (Hering et al. 2018; Cooper et al. 2016). In a few studies, spatial characteristics are taken into account, and the distribution via district heating networks or other technologies is examined (Blömer et al. 2019b; Hering et al. 2018). Potentials for the use of industrial excess heat have been analysed in the literature for individual countries (Brueckner et al. 2017; Steinbach et al. 2021; Cooper et al. 2016), for several countries (Manz et al. 2021; Miró et al.

2015) or on a global level (Forman et al. 2016). 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 (2010), 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. (2010) 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. (2014) 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. (2020) 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 (2016), 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. (2021) determine a theoretical excess heat potential of 37.5 TWh/a using a similar methodology. Blömer et al. (2019b) 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. (2021), 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 2 shows a summary of all the results from the literature.

In Hering et al. (2018), 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 (Manz et al. 2018; Pezzutto et al. 2019). 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 (Aydemir 2018; Aydemir and Rohde 2018; Chinese et al. 2018). 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. (2016), 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. (2018), 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 tobe built to use about 82% of the available heat. The same applies to the analyses in Steinbach et al. (2021), 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. (2019b), 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 2 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 (2010)]	280–300	Rough key figures	National	no	no
Pehnt et al. (2010)	130	Key figures from a Norwegian study	National	yes	no
Persson et al. (2014)	157	Key figures and publicly available empirical data	Site specific	yes	no
Aydemir et al. (2020)	94	Publicly available empirical data	National	no	yes
Brückner (2016)	60–70	Key figures and comprehensive empirical data	Federal state	yes	no
Steinbach et al. (2021)	37.5	Comprehensive empirical data	Municipal level	no	yes
Blömer et al. (2019b)	52–63	Comprehensive empirical data	Site specific analysis but no publication	no	yes
Manz et al. (2021)	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. (2014) 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 (Blömer et al. 2019b). Only one of the studies (Aydemir and Fritz 2020) 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.

2.1.2 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.

2.2 Data and methods

2.2.1 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 3.

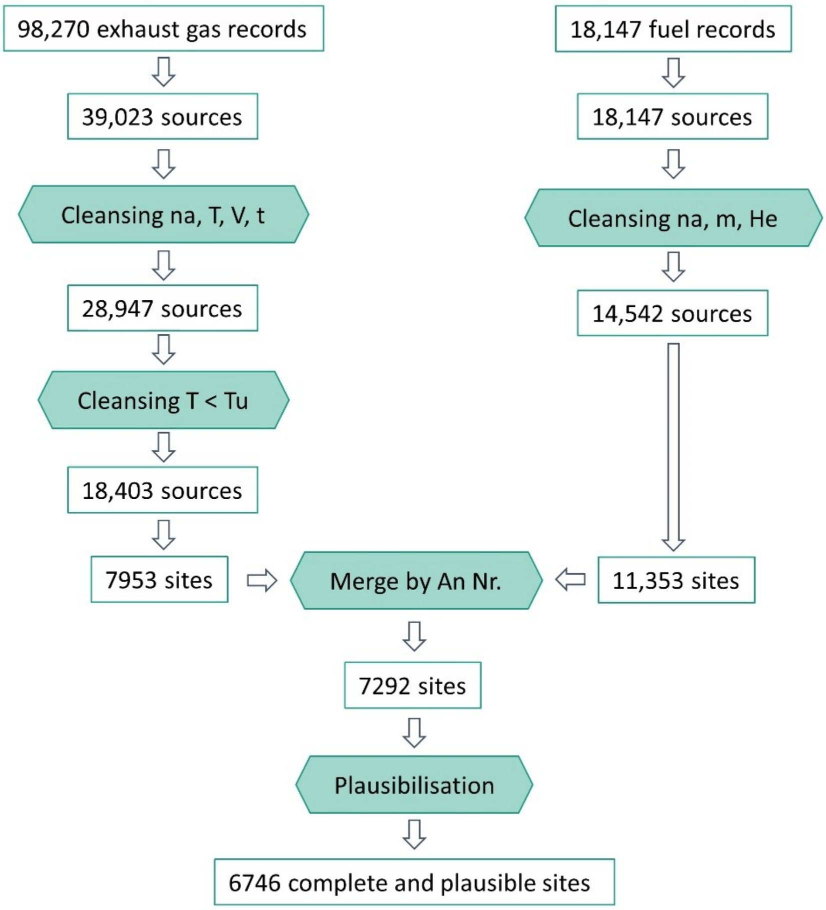


Figure 3 Method of data cleansing

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 (Pezzutto et al. 2019). 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.

2.2.2 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 Vs,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 (Langeheinecke et al. 2020). The weighted mean value of the exhaust gas temperature in our data set was 128 °C.

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

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. Tr 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).

$$Q_{s,j} = \sum_i Q_{s,j,i} \qquad (2)$$

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).

$$Q_s = \sum_j Q_{s,j} \quad (3)$$

where Q_s (kJ) describes the energy quantity of the exhaust gas of the corresponding pro-duction 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).

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

$EC_{s,j}$ (kJ) corresponds to the amount of energy that is brought into the source j by the fuel. Ms,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 (Johnson et al. 2008).

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.

2.3 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.

2.3.1 Results by subsector

Figure 4 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.

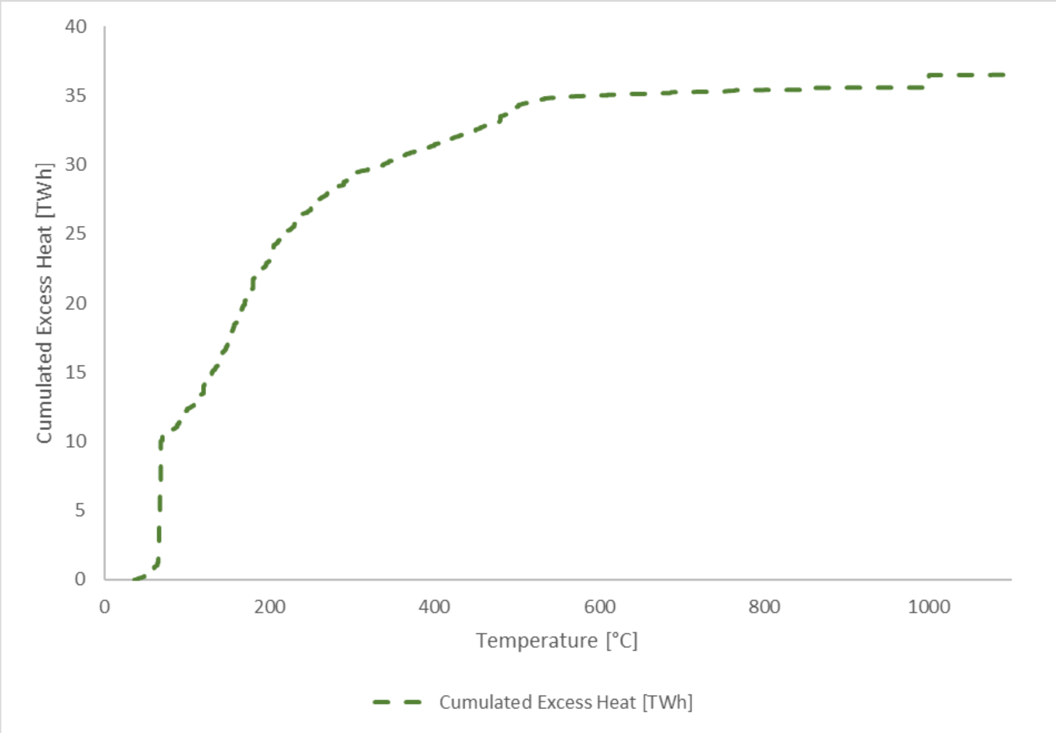


Figure 4 Cumulative excess heat by temperature level for the 6746 plausible sites in the data set.

Figure 5 shows the available excess heat by subsector. The representation corresponds to Figure 4 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.

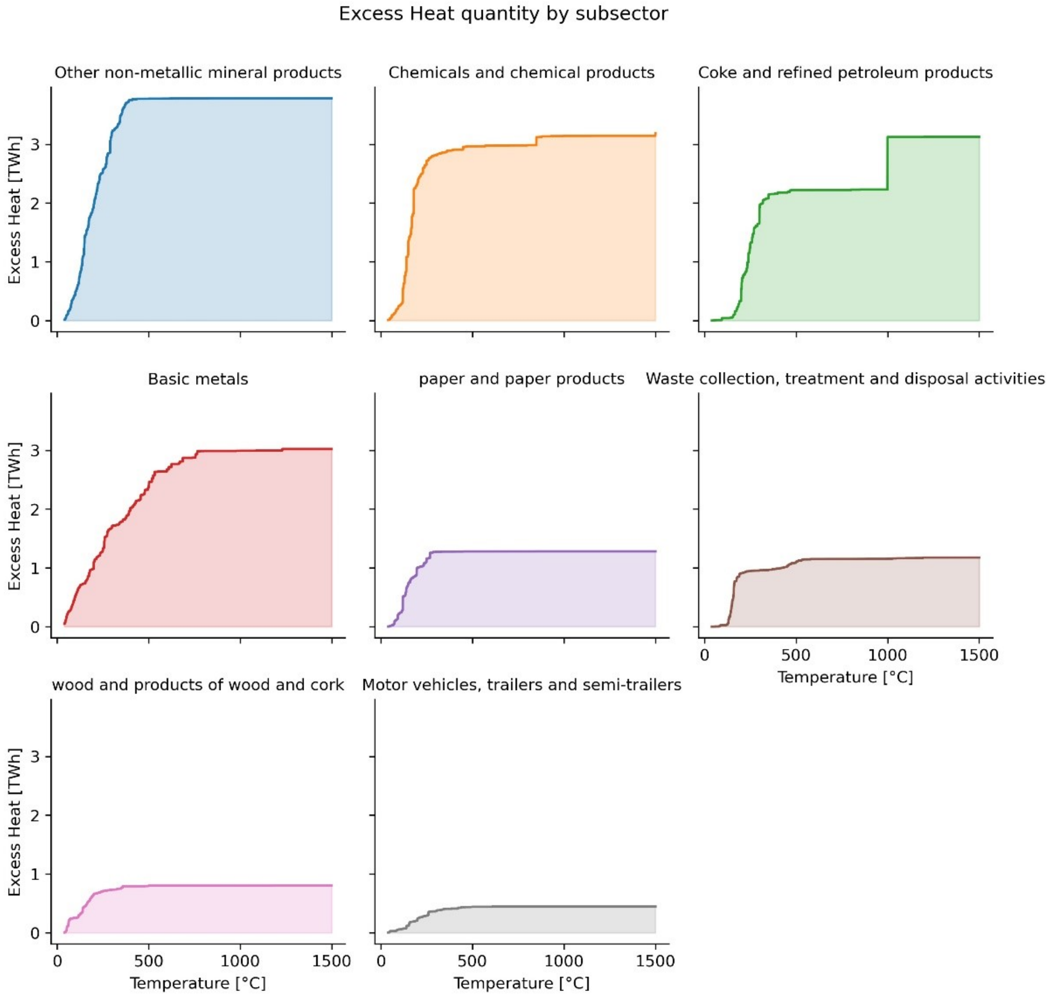


Figure 5 Excess heat quantity by temperature and subsector for the largest 8 subsectors (without the sub-sector of energy production).

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 6 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.

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 aswell 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.

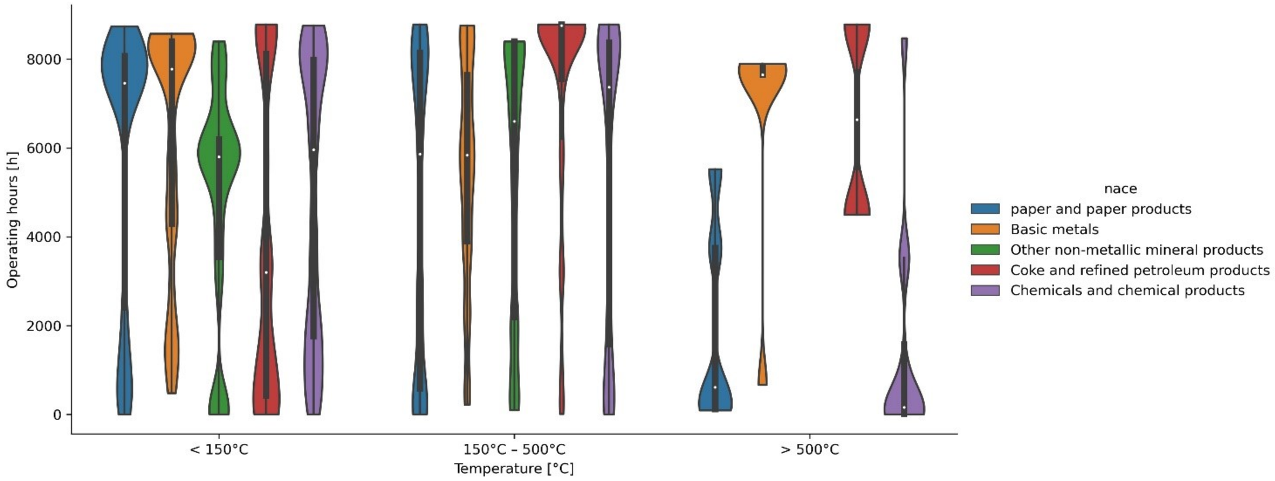


Figure 6 Operating hours by temperature level and subsector.

2.3.2 Spatial results

For the off-site use of excess heat, it is particularly relevant in which regions it accumulates. Figure 7 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 (statista 2020). 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.

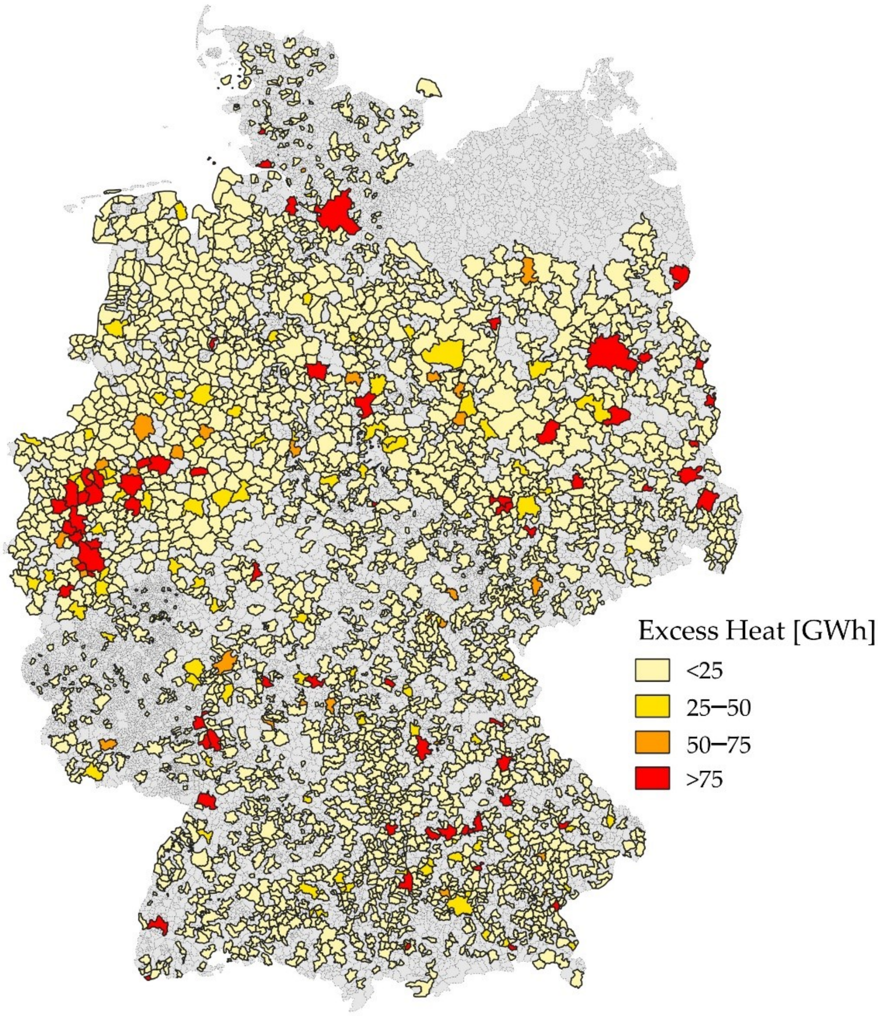


Figure 7 Available amounts of excess heat in GWh/a in Germany at the municipal level.

Figure 8 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.

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 7 do not coincide with the regions from Figure 8. 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.

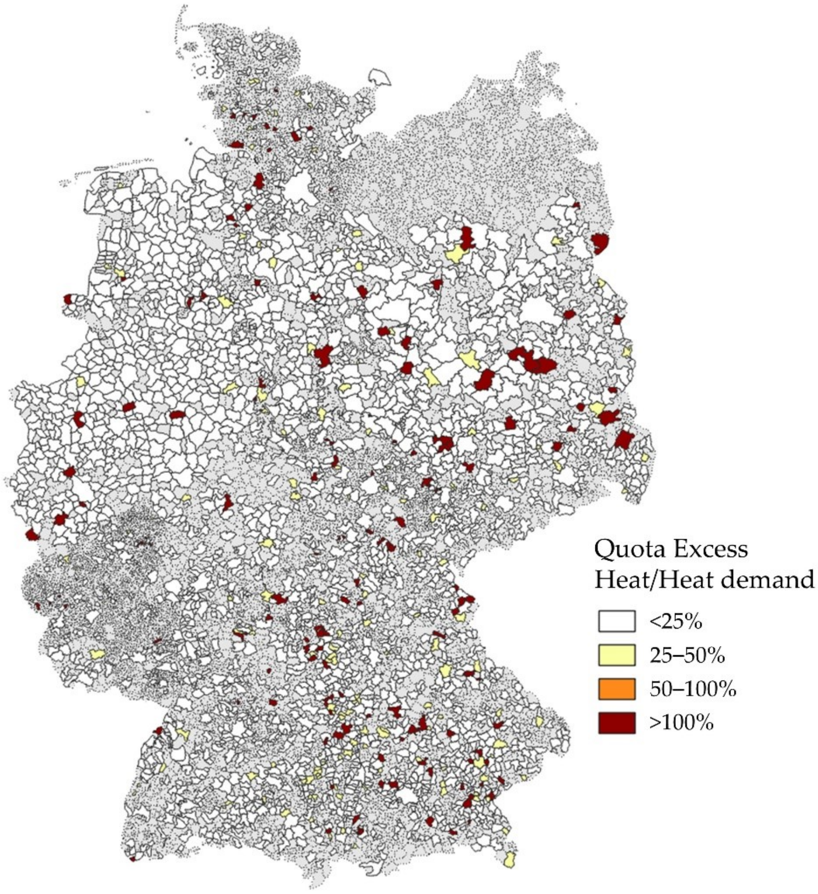


Figure 8 Spatial distribution of relative excess heat in comparison with heat demand.

2.4 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 (Fleiter et al. 2020; Herbst et al. 2021; Neuwirth et al. 2022). 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 possi-ble 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 (Neuwirth et al. 2022). 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 (Böhm et al. 2021).

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 (Langeheinecke et al. 2020). 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 (Hummel et al. 2014; Fang et al. 2013). 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. (2022c) 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 (Viklund and Johansson 2014). 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 (Viklund and Johansson 2014). At lower temperatures, the heat can be raised to the required temperature by means of a heat pump (Viklund and Johansson 2014).

2.5 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, Da-ta 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 Ba-den-Württemberg (LUBW); Bayerisches Landesamt für Umwelt (LfU); Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin; Landesamt für Umwelt Brandenburg (LfU); Die Sena-torin für Klimaschutz, Umwelt, Mobilität, Stadtentwicklung und Wohnungsbau Bremen; Behör-de für Umwelt, Klima, Energie und Agrarwirtschaft Hamburg; Hessisches Landesamt für Natur-schutz, 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.

2.6 Appendix

2.6.1 Appendix 2.A

Table 3 Available excess heat for different temperature levels.

Temperature (°C)	Available Excess Heat (TWh/a)	Percentage of Total
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

2.6.2 Appendix 2.B

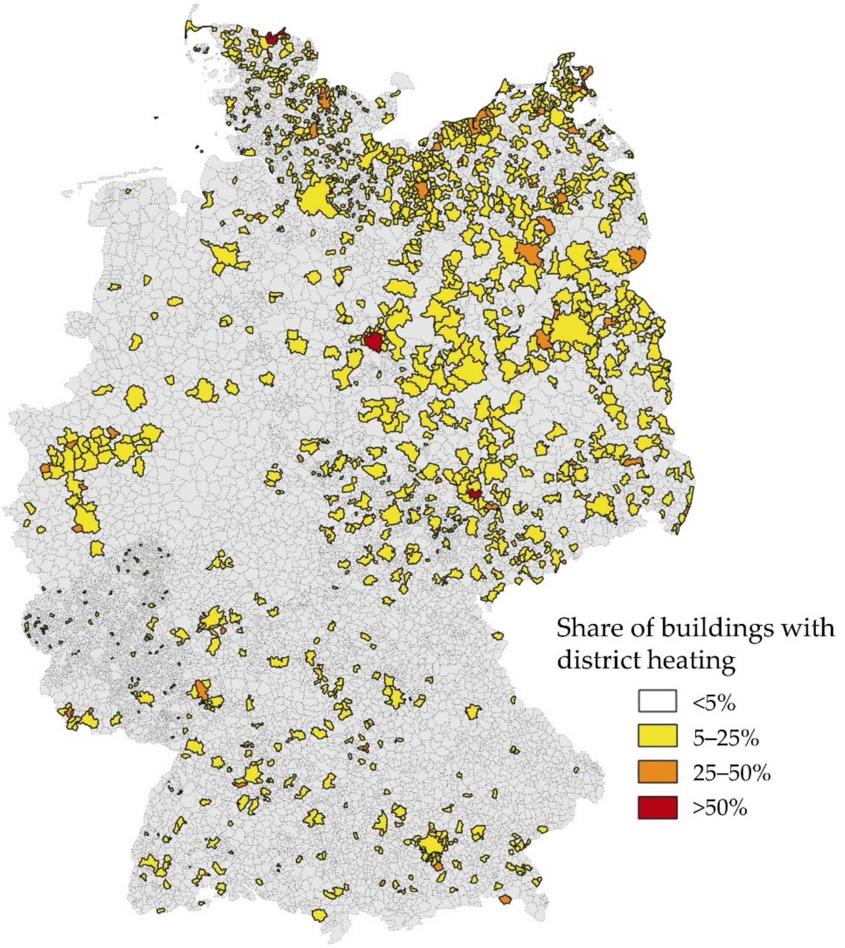


Figure 9 Spatial distribution of the share of buildings with district heating connection at the municipal level based on Statistische Ämter des Bundes und der Länder (2020).

3 A technical and economical comparison of excess heat transport technologies[2]

Abstract

The use of industrial excess heat to provide environmentally friendly and efficient heat for heating purposes can be part of the solution to achieve the climate goals of the European Union. CO_2 emissions from heating sector have to be dramatically reduced to reach ambitious CO_2 targets. In current installations in the EU, excess heat is transported to consumers primarily via district heating. However, the construction of district heating networks is capital-intensive and time-consuming. Depending on the framework conditions, other transport technologies may make more sense. In literature, there is no comprehensive overview that compares areas of application and technical framework conditions and notably carries out an economical comparison of technology. Here, we close this gap and conduct a qualitative and quantitative technical and an economical comparison of new and existing excess heat transport technologies. Based on comprehensive literature review, we screen available technologies and select four technologies for further analysis (district heating, sewer networks, absorption cycles and phase-change materials). We determine the most economical solution for approx. 450,000 combinations of transport distance and excess heat amount and also perform two sensitivity analyses. Our results show that the transport costs for DH are very high (>20 ct/kWh) for small amounts of excess heat (less than 1,000 MWh). In conclusion, district heating is an economic option for transporting heat, but for distances shorter than 6 km and low excess amounts lower than 1,000 MWh other technologies are more favorable.

Highlights:

- Analysis of four different technologies for off-site excess heat utilization
- Economic model for the evaluation of these technologies
- For small amounts of heat and short distances PCM is the most economical solution
- For large amounts of heat and long distances DH is the most economical solution

Abbreviations:

EU	European Union
DH	District heating
ESN	Excess heat distribution through sewer networks
PCM	Phase Change Materials
LCOTH	levelized costs of transported heat
CAPEX	capital expenditure
OPEX	operating expenditure costs

[2] The chapter has been published as Fritz, Markus; Plötz, Patrick; Schebek, Liselotte (2022): A Technical and Economical Comparison of Excess Heat Transport Technologies. In: Renewable and Sustainable Energy Reviews (168). DOI: 10.1016/j.rser.2022.112899.

Nomenclature:

Q	amount of excess heat (kJ)
L	Heat losses (kJ)
q	water flow (m^3/s)
D	pipe diameter (m)
d	transport distance (km)
p	specific installation costs for pipes (€/m)
t	lifetime (years)

3.1 Introduction

The industrial final energy demand accounts for a quarter of the European Union's (EU) final energy demand (cf. (European Environment Agency 2020)). Large amounts of this energy are released unused into the environment in form of excess heat (Brückner 2016; Aydemir and Fritz 2020). Thus, the use of industrial excess heat can be part of the solution to achieve the climate goals of the EU. Notably, the use of excess heat for the housing sector is an interesting option for climate mitigation: Private households account for one quarter of the European Union's final energy demand (European Commission 2018). Approximately 80 % of this is used to provide heat and hot water.

In Hering et al. (2018) it is shown for Germany that approx. 80% of the available excess heat has a temperature level of less than 300 °C. Brueckner et al. (2017) also show that approx. 69% of the available excess heat in Germany occurs in a temperature level of less than 200 °C. This low-temperature heat cannot be used in many production processes in industry (Aydemir 2018). Therefore, this heat is mainly suitable for the provision of residential heating and hot water.

However, industrial plants are often far away from residential areas and therefore the excess heat has to be transported to the end-using households. Today, in the EU mostly district heating networks enable the transport of heat and are analysed in several studies (Chiu et al. 2016; Colmenar-Santos et al. 2016; Fang et al. 2013; Hummel et al. 2014; Kavvadias and Quoilin 2018). However, transporting excess heat from industrial sites to households is also possible with other technologies. The installation of district heating networks is capital intensive and under certain circumstances the use of another technology can be technologically and economically more sensible.

Only a few studies explicitly analyse or compare different technologies for heat transport. Existing studies focus on the presentation and technical comparison of different technologies (Ma et al. 2009b; Vallade et al. 2012; Xu et al. 2019). Ma et al. (2009b) presents different technologies for transport of excess heat, but does not compare them economically. Xu et al. (2019) analysed various technologies and storage options for the use of excess heat, but also do not perform an economic analysis. These studies conclude that, from a technical perspective, technologies other than district heating for heat transport are also feasible and can achieve lower heat losses and thus higher efficiency. Other studies compare single heat transport technologies with heat networks, but do not study the other available technologies (Gao et al. 2019; Chiu et al. 2016). They show that district heating is not always the most cost-effective solution for heat transport. Another part of the literature specifically investigates technical aspects of individual heat transport technologies, such as phase-change materials (Deckert et al. 2014; Ma et al. 2017; Miró et al. 2016), methanol (Liu et al. 2002; Müller et al. 2014), sewer networks (Aydemir et al. 2019; Fritz and Aydemir 2019; Müller 2019) or liquid-gas absorption cycles (Ammar et al. 2013; Gao et al. 2019; Kang et al. 2000; Lin et al. 2009, 2011; Mazet et al. 2009). A comparison with other technologies is missing in this literature stream.

Overall, the current literature indicates that technologies other than district heating for transporting industrial excess heat to the end-using households may be technically feasible. However, in the literature there is no comprehensive overview that compares areas of application and technical framework conditions and notably carries out an economical comparison of these technologies.

The aim of the present paper is to close this gap in the literature and conduct a comparison of technical feasibility and economic performance of existing and up-coming excess heat transport technologies. Based on a comprehensive literature review, we identify seven different technologies: district heating (DH), excess heat distribution trough sewer networks (ESN), liquid-gas absorption cycles, methanol, phase-change materials (PCM), hydrogen absorbing alloys and solid-gas adsorption. We evaluate these seven technologies and the technologies methanol, hydrogen absorbing alloys and solid gas adsorption were excluded as they do not meet the minimum requirements for different indicators. For technological comparison, we use a qualitative and quantitative comparison to classify the technologies into different application areas. For economic assessment, we develop a uniform method for calculating the levelized costs of transported heat (LCOTH). In addition, we perform a sensitivity analysis to determine the impact of the interest rate and the heat losses. As a result, we determine the lowest LCOTH for different combinations of transport distance and amount of excess heat in a technology-neutral manner.

3.2 Technologies for thermal energy transport

The first part of this section presents the method and the results of the literature review for the selection of the technologies. The second part of this section presents the review, evaluation and selection of the technologies analysed in this paper. These technologies are then presented in more detail.

3.2.1 Literature research on individual technologies

In a first step, based on a literature screening, we search technologies for thermal energy transport. Here, the framework conditions were that the heat can be transported over long distances (>1 km) and that the required excess heat temperature is below 100 °C. For this purpose, we search the Scopus database for the terms: "({waste heat} OR {excess heat}) AND (industry OR industrial) AND (transport OR transportation OR transmission) AND NOT thermoelectric" in the abstracts and limited it to the research fields Engineering and Energy. This results in a total of 359 papers. Additionally we use the search term "(TITLE ({transportation of heat}) OR TITLE (heat AND (transportation OR transport) AND heating))" which resulted in 101 papers. From this research, 38 papers were identified that analyse the out-of-plant excess heat utilization in terms of single or multiple technologies. Based on these papers, 8 technologies were defined, which are basically suitable for the use of excess heat for buildings.
Figure 10 present these general possibilities for long distance heat transport of low temperature heat. The left side of Figure 10 shows the technologies of physical heat transport and the right side the technologies of thermochemical heat transport. Physical heat transport uses the sensible heat capacity of water or another material to transport heat. Thermochemical heat transport technologies use chemical reactions or latent heat capacities to transport heat . Within the category of thermochemical transport technologies a distinction is made between grid-bound and grid-free technologies. However, it is not excluded that grid-bound technologies can theoretically also be transported by road, rail or ship.

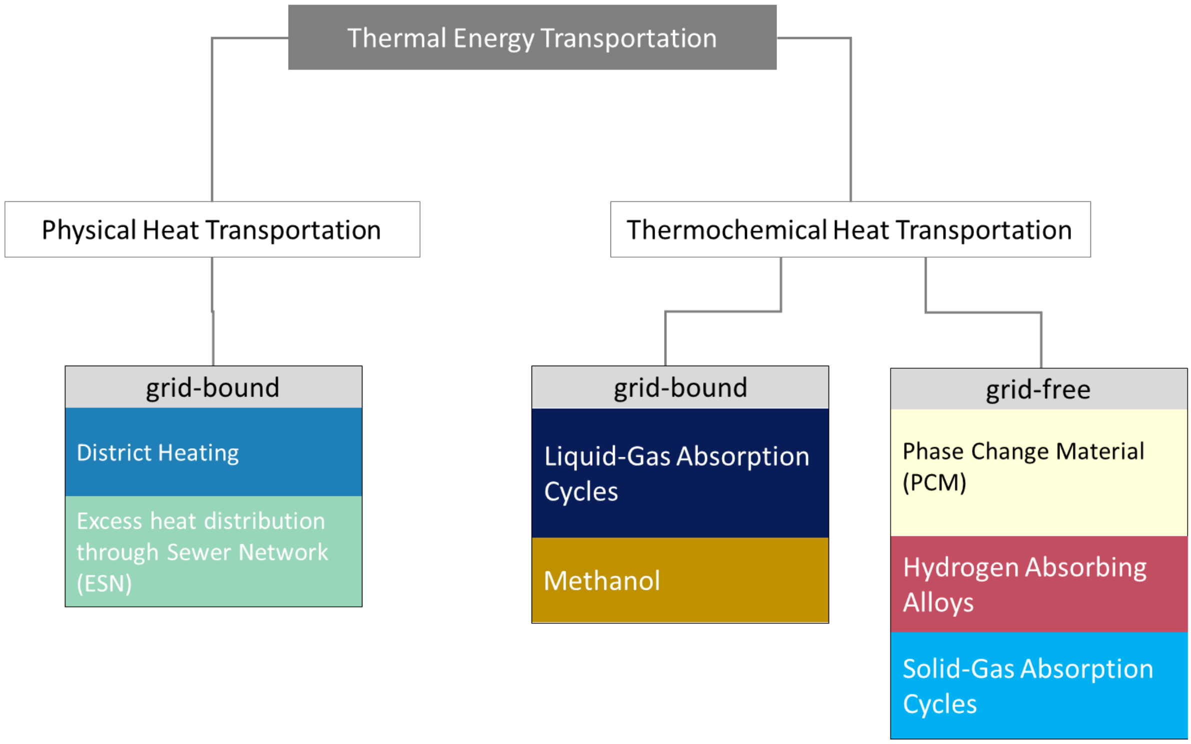


Figure 10 Overview of the identified heat transport technologies

Table 1 presents an overview of the literature. The classification of the literature is based on the considered technologies and whether a technical evaluation, an economic evaluation or a comparison with DH was carried out.

Table 4 Overview and scope of the literature

Study	**Technology considered**	**Technical evaluation**	**Economic evaluation**	**Technical oder economical comparison with DH**
Ma et al. (2009b)	Chemical reactions, PCM, hydrogen-absorbing alloys, Adsorption Cycles, Absorption Cycles	Yes	No	No
Xu et al. (2019)	Energy storages, absorption cycles	Yes	No	Yes
Vallade et al. (2012)	Sorption cycles	Yes	No	No
Chiu et al. (2016)	PCM	Yes	Yes	Yes
Gao et al. (2019)	Absorption cycles	Yes	Yes	Yes
Deckert et al. (2014)	PCM	Yes	Yes	No
Ma et al. (2017)	PCM	Yes	No	No
Castro Flores et al. (2017)	Thermal energy storages (+PCM)	Yes	Yes	No

Study	Technology considered	Technical evaluation	Economic evaluation	Technical oder economical comparison with DH
Zalba et al. (2003)	PCM	Yes	No	No
Miró et al. (2016)	Thermal energy storages (+PCM)	Yes	No	No
Liu et al. (2002)	Methanol	Yes	No	No
Müller et al. (2014)	Methanol	Yes	No	No
Fritz and Aydemir (2019)	ESN	No	No	No
Müller (2019)	ESN	Yes	No	No
Bieker et al. (2021)	ESN	Yes	Yes	No
Hasegawa et al. (1998)	Hydrogen absorbing alloys	Yes	Yes	No
Yu et al. (2008)	Solid-gas absorption	Yes	Yes	No
Ammar et al. (2013)	Absorption cycles	Yes	Yes	No
Kang et al. (2000)	Absorption cycles	Yes	No	No

Physical heat transport

District heating (DH) networks are the most common way to use industrial excess heat. Many recent studies show that DH networks will play an important role for space heating demand in the future (Lund et al. 2010; Rezaie and Rosen 2012; Lund et al. 2014; Werner 2017; Hummel et al. 2014). Heat is generated at a central heat generation site and delivered to one or more consumers. Transport takes place via pipelines and water is used as the heat transport medium.

The **excess heat distribution through sewer networks (ESN)** technology is quite an innovative approach. Different studies describe the potential of conventional wastewater heat utilization (Meggers and Leibundgut 2011; Wärff et al. 2020), which could be further increased by the use of excess heat. The ESN technology demonstrates the possibility of using wastewater as heat transport medium for excess heat. The excess heat is transported to buildings via the existing sewer networks and made usable by a heat pump. Thereby the temperature of the wastewater is raised by excess heat (Müller 2019; Bieker et al. 2021). The advantage of this technology is that no new infrastructure needs to be built and the heat transfer medium (wastewater) is already available.

Thermochemical heat transport

In **liquid-gas absorption cycles**, 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 chemical energy, which is stored in the solution, is transported via pipelines to the user. The advantage here is that the transport takes place at ambient temperature and therefore no thermal insulation of the pipes is necessary. The functional principle is based on a sorption heat pump. With the difference, that the generator and condenser are located at the source side and the evaporator and absorber at the user side.

In Liu et al. (2002) and Müller et al. (2014), the use of **methanol** to transport excess heat is described. Methanol can be used for the transport of heat by different decomposition and composition reactions. Müller et al. (2014) describe that the technology has a very low efficiency of 16% without consideration the transport losses.

Phase-change materials (PCMs) can store heat mainly in form of latent energy. This means that the energy is absorbed by a phase change from solid to liquid and the energy is released by a phase change from liquid to solid. In contrast to the sensitive heat transport technologies, heat transfer takes place at almost constant temperature. For this reason, PCMs are also well suited for additional heat storage in heat networks (Castro Flores et al. 2017; Thomson and Claudio 2019). To transport the heat, the PCMs, which are loaded with thermal energy, are transported in containers by road or rail to the respective location. At the place of use, the heat can be extracted from the PCMs, which results in the material becoming solid again.

Hydrogen absorbing alloys release heat during the absorption of hydrogen (Kang and Yabe 1996; Nasako et al. 1998). This process is reversible due to the addition of heat, which causes the hydrogen absorbing alloys to release the hydrogen again.

The technology of **solid-gas adsorption** is analysed in (Yu et al. 2008). The technical principle behind this technology is based on endothermic and exothermic adsorption processes and consists of 2 basic steps. In the first step, the adsorbent releases heat when adsorbing a reaction gas. In the second step, heat is supplied to the adsorbent, causing the adsorbent to release the reaction gas.

3.2.2 Review, evaluation and selection on individual technologies

Some of the presented technologies are considered more promising than others. In a second step, we conduct targeted research on the individual technologies. In doing so, we further narrow down the technologies based on the estimated future potential, current installations or pre-feasibility studies and the general data availability of the required indicators. Data availability means that data on operating costs, investment costs, lifetime, temperature level, heat capacity and data on heat losses are available.

DH is the most widely used technology to utilise excess heat for residential heating. In recent years, there are more and more installations, pre-feasibility studies, scientific studies and policies to promote the technology (Moser and Lassacher 2020b; Blömer et al. 2019b; Mathiesen et al. 2019). For ESN technology, a pre-feasibility study was conducted in 2019 and it shows that the technology is competitive with DH and other heat generation technologies (Aydemir et al. 2019; Müller 2019). For liquid-gas absorption technology, there are only few studies in recent years. However, Gao et al. (2019) shows that the technology can be economically and ecologically competitive with DH under certain circumstances. For the use of methanol as a heat transport medium, there are no studies in recent years. In contrast, almost all studies currently dealing with methanol assume a material use (Schorn et al. 2021; Sun and Aziz 2021; Ranjekar and Yadav 2021). For the technology PCM there are less studies in the last years, however a large number of installations and pre-feasibility studies exist (Miró et al. 2016). For the technologies hydrogen absorbing alloys and solid gas absorption, there are no significant studies since the beginning of the 2000s, which describe the use as a heat transport medium.

Current installations or pre-feasibility studies could not be identified for all technologies. DH has by far the largest number of currently installed projects (Fritz et al. 2022c; Moser and Lassacher 2020b; Schmidt et al. 2020). For the technology ESN a pre-feasibility study is available (Aydemir et al. 2019; Müller 2019). Miró et al. (2016) shows 13 known installations or pre-feasibility studies for PCM. For the remaining technologies, no recent installations or pre-feasibility studies for off-site use of excess heat could be researched. For these technologies, only laboratory tests or model calculations are known.

Data availability is also related to existing installations and pre-feasibility studies. Many of the indicators for the further calculations can be derived from these studies. Thus, all of the required indicators are available for DH, ESN and PCM. Likewise, all of the required data for the technology liquid gas absorption could be researched (Ammar et al. 2013; Gao et al. 2019; Kang et al. 2000; Mazet et al. 2009). For the technology methanol, all required data except for the heat losses could be researched (Müller et al. 2014; Ranjekar and Yadav 2021; Liu et al. 2002). For the technologies hydrogen absorbing alloys and solid-gas adsorption, data could be partially researched (Kang and Yabe 1996; Yu et al. 2008; Hasegawa et al. 1998). Data on the economic indicators and heat losses could not be researched.

Table 5 summarizes the results of the evaluation. It can be seen that 4 technologies (DH, ESN, Liquid-Gas Absorption and PCM) achieve a 0 or a + in the overall evaluation. For this reason, these 4 technologies will be considered in the further analysis.

Table 5 Review and evaluation of the technologies (+ = good, 0 = medium, - = poor)

	Future potential	Data availability	Current installations/ pre-feasibility studies	Overall evaluation
DH	+	+	+	+
ESN	0	+	0	0
Liquid-gas absorption	0	+	-	0
Methanol	-	+	-	-
PCM	0	+	+	+
Hydrogen absorbing alloys	-	-	-	-
Solid-gas adsorption	-	-	-	-

Technology details of the selected technologies

DH is the most common technology for using excess heat. The evolution of DH system technologies is explained in terms of generations (Lund et al. 2014). Over the generations, the temperature in the DH networks has decreased. In order to be able to feed renewable energies and low-temperature excess heat into heating networks, the temperature within the networks must be further reduced, which leads to the concept of 4th generation heating networks. The density of the fluid is 997 kg/m³, the sensible heat capacity is 4.2 kJ/(kg*K) and the assumed lifetime is 20 years (AGFW 2021).

With the **ESN,** excess heat can either be inserted directly via the wastewater that is produced anyway, or via additional heat exchangers in the sewer. Via the existing sewers, the wastewater is transported to the consumer at a higher temperature level and the heat can be extracted from the wastewater via heat exchangers in the sewer. This heat serves as a heat source for a heat pump (Aydemir et al. 2019). This increases significantly the coefficient of performance (COP) of the heat pump compared to conventional wastewater heat utilization. First analyses have shown that an odor nuisance can be excluded based on a moderate temperature increase (Müller 2019). Furthermore, negative influences on the operation of the wastewater treatment plant can also be excluded. After the heat exchange at the location of the heat user, the temperature level of the wastewater flow should correspond to the original temperature level. Figure 11 visualizes the technical concept of excess heat utilization by heat distribution via the sewer system. The industrial sites that provide the excess heat are shown on the right side. Households and potential consumers of the excess heat are shown in the middle and the wastewater treatment plant is shown on the left. The density of the fluid is 997 kg/m³, the sensible Heat Capacity is 4.2 kJ/(kg*K) and the assumed lifetime is 20 years (Aydemir et al. 2019).

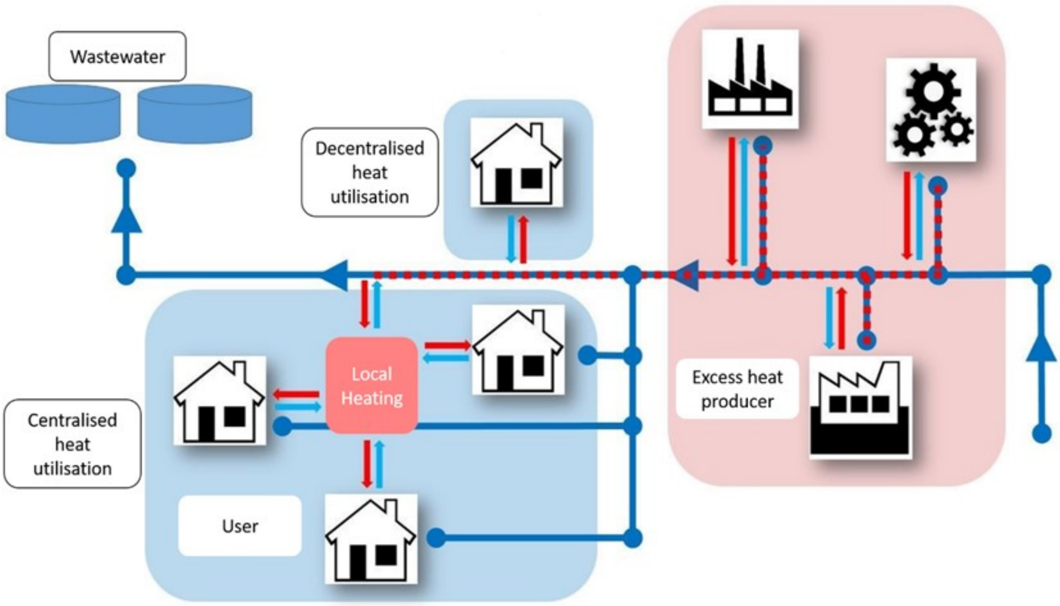


Figure 11 Schematic illustration of the ESN Technology (Müller 2019)

For the use of **absorption cycles**, different energy carriers can be used. In the literature, the lithium bromide-water cycle and the ammonia-water absorption cycle are mainly considered (Kang et al. 2000). The most promising working pair in terms of price and efficiency is the ammonia-water cycle. For this reason, it is used in the present paper for the comparison with the other technologies. The energy transport density for this technology is 127,75 kJ/kg (Gao et al. 2019) the temperature outlet is around 69 °C (Gao et al. 2019) and the assumed lifetime is 30 years (Pirouti et al. 2013).

The functionality of the ammonia-water absorption cycle is shown in Figure 12. The excess heat (1) is transferred to the cycle in the generator (2). The heat is used in the generator to split a strong ammonia-water solution (3) into a weak ammonia-water solution (4) and ammonia vapor (5). The weak ammonia water solution (4) is transported to the absorber (8) via a pipeline to the user side. Water contained in the ammonia vapor is removed, for example by rectification. The thus pure ammonia vapor is fed into the condenser (6), where the ammonia is liquefied. The liquid ammonia is transported via a pipeline to the user side into the evaporator (7). In the evaporator, the ammonia becomes gaseous again and absorbs heat, so that this process can be used for cooling. The ammonia vapor then flows from the evaporator (7) to the absorber (8), where it is absorbed by the weak ammonia water solution (4). During absorption, heat is released which can be used for heating purposes. The ammonia water solution (3), which is now strong again, flows through a third pipe from the absorber (8) on the user side to the source side in the generator (2).

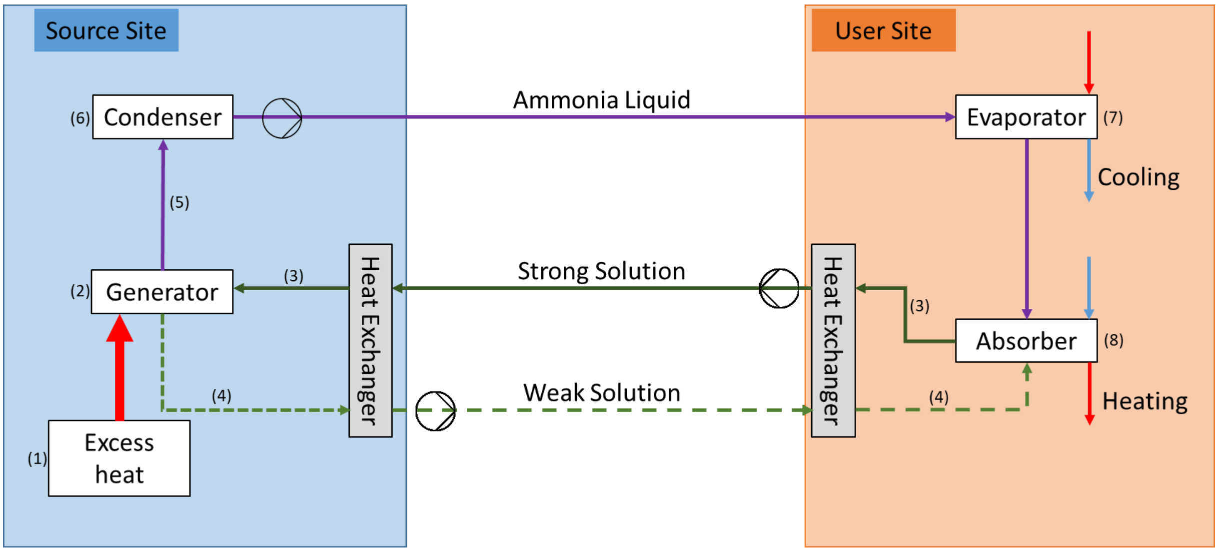


Figure 12 Principle of operation of the ammonia-water absorption cycle (based on Gao et al. 2019 and Ammar et al. 2013)

PCMs offer a higher thermal energy storage density than other latent heat storage materials. However, there are chemical storage systems that can have a higher thermal energy storage density. In comparison, however, chemical systems are more complicated, less robust and less reliable (Ma et al. 2017). A disadvantage of using PCMs is the relatively low thermal conductivity and the currently comparatively high price. There are many different PCMs (da Cunha and Aguiar 2020; Zalba et al. 2003). When selecting a suitable PCM, it is important that the temperatures of the heat source and heat sink are outside the phase change temperature to achieve complete melting/solidification. Sodium acetate trihydrate is mentioned in the literature in many studies and is considered a very promising PCM (Ma et al. 2009b; Miró et al. 2016). When using sodium acetate trihydrate, a thermal efficiency of about 90 % can be achieved. This means that 90% of the energy with which the storage is charged can be reused when it is discharged (Deckert et al. 2014). The latent heat density of sodium acetate trihydrate is 73.3 kWh/t, the density is 1450 kg/m³ and the melt temperature is 58 °C (Ma et al. 2017).

3.3 Methods

Excess heat can make an important contribution to decarbonise the heating sector. However, a major challenge is the transport of excess heat to the end-users. The research aim of this paper is to identify and compare different technologies for transporting excess heat. For this purpose, we identify relevant technologies and evaluate them technically and economically. The individual steps of the method are:

1. Literature research
2. Technical comparison
3. Economic assessment and comparison
4. Sensitivity analysis

The method and the results of the literature review are presented in chapter 3.2. In this chapter, steps 2 to 4 of the method are presented. Chapter 3.3.1 presents the second step of the method for the technical comparison. Chapter 3.3.2 describes the third step of the method for the economic evaluation and comparison of the transport technologies. Thereby, the assumptions and calculation methods are presented. Chapter 3.3.3 describes the fourth step of the method for conducting the sensitivity analysis. Finally, chapter 3.3.4 presents the data sources and assumptions for the economic analysis of the individual technologies.

3.3.1 Technical comparison

The aim of the technical comparison is to classify the technologies into different application areas. For this purpose, we perform a qualitative and quantitative comparison of different variables. We compare the lifetime, temperature level, heat capacity and heat losses for each technology. We make a classification of the usable temperature levels and thus rank the usability of the technologies according to different applications.

3.3.2 Economic assessment

For the economic assessment, we carry out an economic analysis and comparison of the technologies. For this purpose, we calculate the capital expenditure (CAPEX) and the operating expenditure costs (OPEX). The capital expenditure is calculated according to Konstantin and Konstantin (2018) as the annuity for one year with the following formula:

$$CAPEX = Invest * \frac{(1+i)^t * i}{(1+i)^t - 1} \tag{7}$$

where i is the interest rate, which we assume to be constant over all technologies at 2 %. t is the time period under consideration, which in the cases of our technology consideration corresponds to the lifetime of the individual technologies.

The OPEX of the individual technologies differ greatly in amount and basis of calculation and are explained individually in the respective subsections of the technologies below.
In the second step, the LCOTH are calculated. This is the sum of CAPEX and OPEX in relation to the amount of excess heat transported (Q) with consideration of losses (L). The calculation formula is:

$$LCOTH = \frac{CAPEX + OPEX}{Q - L} \quad (8)$$

In the third step, we compare the LCOTH of each technology. CAPEX and OPEX mainly depend on the amount of excess heat to be transported and the transport distance. For this reason, the respective CAPEX and OPEX of the technologies considered are calculated for approx. 450,000 different combinations of transport distance and amount of excess heat. In the following we call these different combinations reference cases. For each of the reference cases, it is thus possible to determine which technology provides the most cost-effective option for heat transport for this reference case.

3.3.3 Sensitivity analysis

In order to better evaluate the results and to check the robustness of the results, we also perform a sensitivity analysis. The sensitivity analysis covers the interest rate and the heat losses as parameters, as the interest rate may change significantly over the next few years and the heat losses have a large local dependence. We use the reference case with a transport distance of 12.5 km and an amount of excess heat of 2,250 MWh for the analysis. This reference case is at the boundary between 2 technologies in the economic analysis (cf. Figure 14).

3.3.4 Data sources and assumptions for economic assessment

District Heating (DH)

The investment for DH networks in general consists of costs for construction (civil engineering and installation), planning and material. The study of Dunkelberg et al. (2018) have analysed the cost structure for the investment of DH networks in dependence of the pipe diameters. This publication is used as main data source for assessment of DH networks.

For each of the reference cases, the required pipe diameter is calculated. Therefore, we calculate in a first step the required water flow to transport the heat. According to the variables from Table 6, the required flow of water can be calculated as follows: $q = \ (Q/(3600 * 8760\, s/a))/(20K * 971.8\, kg/m\text{^}3\ * 4.194\, kJ/(kg * K))$ where q in m³/s is the required flow of water and Q in kJ/a is the annually available excess heat amount. Assuming the average flow velocity from Table 6, the required pipe diameter is: $D = q/1.5\ (m/s)$. Thus, the specific costs can be determined according to Appendix 3.A. The total invest is: $Invest = d * p$ where d is the transport distance in km and p the specific costs in €/km.

Table 6 Input parameters for the calculation of pipe diameters for DH

Difference between flow and return temperature	20 K
Density at 80°C	971.8 kg/m³
Heat capacity at 80°C	4.194 kJ/(kg*K)
Flow velocity	1.5 m/s

The operating costs are assumed to be 2% of the invest per year according to AGFW (2021). Previous studies show that heat loss in heating networks is in the range of 5-16% (Nussbaumer and Thalmann 2014; Masatin et al. 2016; Nussbaumer et al. 2017; AGFW 2021). There are no indicators in the literature that reflect the heat losses in %/km as a function of diameter. For this reason, the assumption is made that the heat loss is 12% according to AGFW (2021).

So the LCOTH in €/kWh for this technology is calculated as formula (9):

$$LCOTH = \frac{CAPEX + Invest * 0.02}{Q * 0.88} \quad (9)$$

Excess heat distribution through sewer networks (ESN)

The investment for the use of ESN consists of the civil engineering costs, the installation costs, the planning costs and the material costs for the heat exchanger. The investment depends on the the size of the heat exchanger and the installation costs. For the civil engineering costs, it can be assumed that these remain relatively constant even with heat exchangers of different sizes. A detailed breakdown of these costs is available for a case study in Lünen, Germany (Aydemir et al. 2019). The civil engineering costs are estimated according to the results of the Case Study at 45,000 €. In the case study, the remaining costs (installation, planning and materials) were determined to be approximately 72,000 €. The heat transport of this installation is 3,000,000 kWh over the lifetime of the plant. Based on this, we deduce that the specific cost (without civil engineering) is 0.0242 €/kWh. So the total investment is: $Invest = 45{,}000\,€ + (Q * t) * (0.0242\,€ / kWh)$ where Q in kWh/a is the amount of excess heat available annually and t in years is the lifetime of the plant.

The results of the case study indicate that 1 % of the investment is incurred annually as maintenance costs. This includes the maintenance of the heat exchangers as well as the connecting pipes. In addition, this technology requires electricity to operate a heat pump to achieve the required temperature level. For this reason, additional costs are incurred for the required electricity. We assume that the heat pump achieves an average COP of 4.2 (Delta T of 45 Kelvin and a quality grade of 55 % (Danish Energy Agency 2021)). The average electricity price in Europe in 2019 was 0.213 €/kWh (eurostat 2021a). Assuming a cost increase rate of 0.8 %, this corresponds to an average additional cost of 0.0551 €/kWh of transported heat. Previous studies have shown that heat losses depend mainly on the material of the sewers and the soil properties (Fritz and Aydemir 2019). On average, heat losses amount to about 2 %/km. So the LCOTH in €/kWh for this technology is calculated as formula (10):

$$LCOTH = \frac{CAPEX + Invest * 0.01}{Q * 0.98^{d}} \quad (10)$$

where d is the transport distance in km. In our analyses, we assume that for each of the analysed variants, there is enough water in the sewer to transport the excess heat.

Absorption cycles

The investment for absorption cycles consists of the construction costs (civil engineering and installation), the planning costs and the material costs. For the construction costs and installation costs, we assume that these are identical to the costs of the heat networks based on Appendix 3.A for the respective diameter. We calculate the missing values in the range of small diameters with linear extrapolation. The pipes for the absorption cycle technology are made of carbon steel. The costs for these are based on manufacturer data (Haustechnikshop24.eu). An overview of this cost structure can be found in Appendix 3.B.

To calculate the invest, the required pipe diameters, which are needed to transport the excess heat, are calculated. According to Gao et al. (2019), the energy transport density is 127.75 kJ/kg, or 24.13 kWh/m³.

The flow velocity in the pipe transporting ammonia is 0.78 m/s (Gao et al. 2019). This means that the required pipe diameter is: $D = 2 * \sqrt{((Q/(3600 * \ 8760\ s/a))/(24.13\ kWh/m^3\ * 0.78 m/s * \pi))}$ where Q in kWh/a is the amount of excess heat available annually and D in meter is the pipe diameter. Based on the required diameter and the data from Appendix , the specific costs for the reference cases can be calculated. So the total investment for this technology is: $Invest = d * p$ where d is the distance in km and p the specific costs in €/km.

Since the general technology is similar to heat networks, we assume that the maintenance costs are also 2 % of the investment per year, as in the case of heat networks. Previous literature shows that the losses for sorption technology is much lower than the heat losses in heat networks. Moreover, Gao et al. (2019) results show that they are almost identical even for different distances. We assume that the average losses are half of the average losses of the heat networks and thus 6 %. So the LCOTH in €/kWh for this technology is calculated as formula (11):

$$LCOTH = \frac{CAPEX + Invest * 0.02}{Q * 0.94} \tag{11}$$

<u>**Phase change materials (PCMs)**</u>

The investment of the PCMs consists of the material costs of the PCM and the system costs. For the material costs, we calculate the amount of PCM that must be available to transport the amount of excess heat generated in one day. The latent heat density of sodium acetate trihydrate is 73.3 kWh/t (Ma et al. 2017). The costs of sodium acetate trihydrate is 1500 €/t (Alibaba.com). For the remaining system costs, we assume that they are about 110 €/$kWh_{storage}$. This represents the average value of all PCM systems considered in Castro Flores et al. (2017) minus the costs for the PCM. So the total investment for this technology is: $Invest = \ (Q/365)/(73.3\ kWh/t) * 1500€/t + Q/365 * 110\ €/kWh$ where Q in kWh/a is the amount of excess heat available annually.

For our comparison, we assume that the PCMs are transported by truck. The average cost of transport by truck is about 1.83 €/km (BMEnet GmbH 2020). We assume that a truck will load an average of 5 tons (Assuming a 12-ton truck with a possible maximum load of 7 tons). This means the specific costs are 0.366 €/(t*km). Thus, the transport cost (OPEX) for PCMs in one year is: $OPEX = Q/(73.3\ kWh/t) * d * 2 * 0.366\ \ €/(t * km)$ where Q in kWh/a is the amount of excess heat available annually and d in km is the transport distance between the source to the sink. The heat losses during the transport are assumed to be 10% according to Deckert et al. (2014). So the LCOTH in €/kWh for this technology is calculated as formula (12):

$$LCOTH = \frac{CAPEX + OPEX}{Q * 0.9} \tag{12}$$

3.4 Results

This section analyses the results of the technical and economical comparison. The first part presents the results of the technical comparison. The second part presents the results of the economic comparison. Therby, a comparison of the capital and operating expenditures is made and the absolute levelised costs of transported heat are analysed. In the last part of this section, the results of the sensitivity analysis are presented.

3.4.1 Technical comparison

We analyse the lifetime, the temperature level, the heat capacity and the heat losses for the various technologies and compared them with each other. Table 7 describes these technical properties of the technologies. The lifetimes of the technologies vary greatly. PCMs have the lowest lifetime of 12 years and absorption cycles the highest with a lifetime of 30 years. This shows that the use of PCMs can make sense, especially in the case of uncertain market developments in individual industries, since they are designed for a lifetime of 12 years. With regard to the temperature level, it can be seen that there are major differences between the technologies here. DH can be used for a wide temperature range. The Absorption Cycle and PCM technologies have temperature levels of 69 °C and 58 °C. Due to the characteristics of the chemical reaction, the temperature level is not flexible. The ESN technology has a temperature level of 15-30 °C, without the use of a heat pump. There are also large differences when considering heat capacity. PCMs have the highest heat capacity with 330 kJ/kg. This means that PCMs can be a viable solution when only limited space to use excess heat is available. The heat losses are also very heterogeneous for each technology. Heat losses in DH networks and ESNs are the highest, since energy is transported in form of sensible heat, which is partly released into the environment during transport. To evaluate the influence of heat losses, a sensitivity analysis was performed in section 3.4.5. A more detailed description of the individual indicators is presented in the following.

Table 7 Overview of the characteristics of the technology

	Lifetime [a]	Temperature level [°C]	Heat Capacity [kJ/kg]	Heat Losses through transport
DH	20	70 - 120	84	12 %
ESN	20	15 - 30	84	~ 2 %/km
Absorption Cycles	30	69	128	6 %
PCM	12	58	330	10 %

The results show that different technologies are suitable for different applications. Figure 13 shows an overview that classifies the technologies for different areas of application. The y-axis indicates the temperature level that the respective technology can provide. The x-axis shows the amount of excess heat that can be transported with the respective technology. It should be noted that the x-axis with the amount of excess heat is logarithmic.

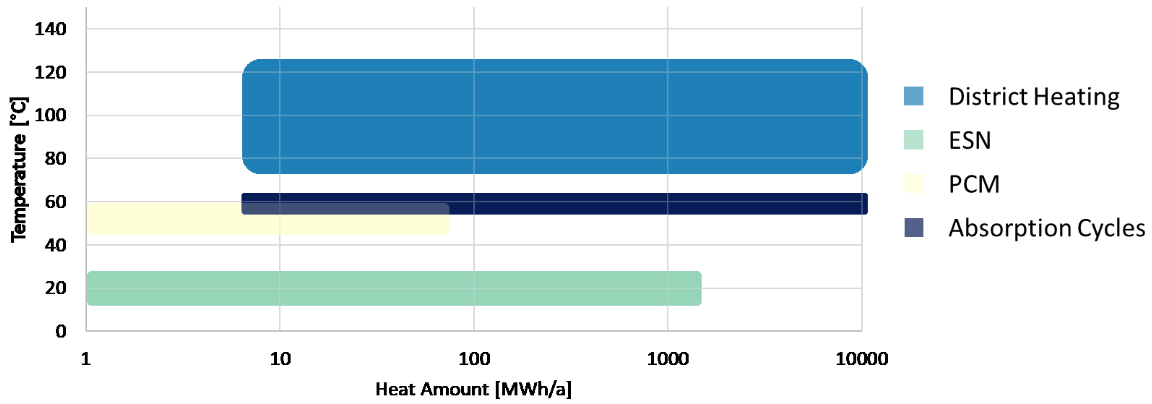


Figure 13 Technical Comparison of viable range of applications for the technologies in dependence of excess heat amount and temperature

From Figure 13, it can be seen that DH has a wide range of applications. DH is flexible in terms of temperature level. In addition, different heat amounts can be transported by varying the dimensions of the pipes. However, the technology is less suitable for smaller amounts of heat, as very small pipe diameters or very low flow rates would have to be used. As shown in Figure 13, the ESN technology is particularly useful in the area of low temperatures and relatively small heat amounts. The technology is very much dependent on the availability of wastewater, as this also determines the temperature in the sewer. The optimal dry-weather flow for heat transport is about 0.001365 l/(s*MWh) for a temperature rise in the sewer of 20 K. PCM technology is particularly useful for smaller excess heat amounts. It can be scaled up more easily, but the transport costs for large amounts of excess heat are very high. The choice of PCM determines the temperature level that can be provided. In our analyses, the PCM is sodium acetate trihydrate, which can provide a temperature of up to 58 °C. The technology of the absorption cycle is as flexible as the heat networks. By dimensioning the system and the pipes, it is theoretically possible to use it for many different heat amounts. However, as with PCMs, the temperature level depends on the choice of solution. In our case it is ammonia-water solution which can provide a temperature of up to 69 °C.

3.4.2 Economical comparison

We calculate the specific LCOTH for 450,000 combinations of transport distance and amount of excess heat (reference cases) for each technology as described in the method section. From the combinations we derive the diagram presented in Figure 14. The figure shows which technology has the lowest LCOTH for which combinations of transport distance (y axis) and amount of excess heat (x-axis). The results show that different technologies are appropriate for different distances and different amounts of excess heat.

In the case of smaller amounts of excess heat, the grid-bound technologies (DH and absorption cycle) have higher LCOTH because the construction of new infrastructures is very cost-intensive in relation to the amount of heat transported. For smaller heat quantities and shorter transport distances PCM has the lowest LCOTH. This is mainly due to the fact that the investment only consists of the investment in the PCMs and these costs are proportional to the amount of excess heat. Our analyses show that with an available amount of excess heat of more than 4 GWh, transport by DH has the lowest LCOTH. The Absorption Cycle technology has the lowest LCOTH only in a small range (1km transport distance and 350 - 370 MWh). Compared to DH, the material costs of carbon steel pipes for large diameters are significantly higher. As a result, despite the lower losses for larger excess heat quantities and thus larger pipe diameters, DH has significantly lower LCOTH. ESN technology has the lowest LCOTH for longer transport distances and smaller heat quantities. In contrast to DH, ESN offers the advantage that no new infrastructure has to be built. For larger heat quantities, however, the relatively high investment in large and expensive heat exchangers outweighs this. When interpreting the results, it should be noted that they are based on the assumptions described above. The boundaries of the individual technologies may shift slightly depending on the assumptions.

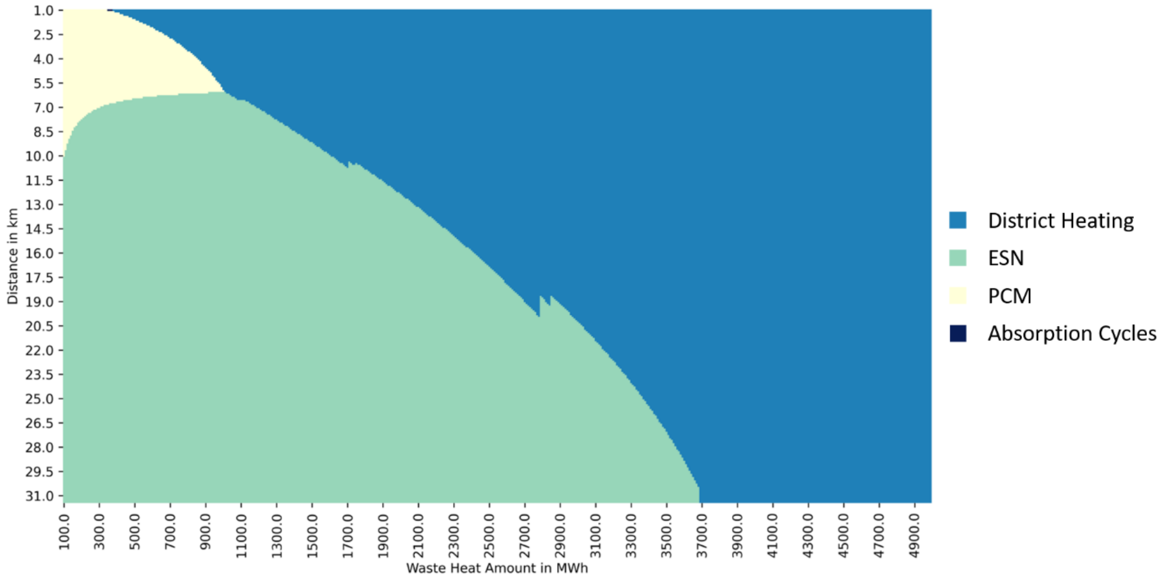


Figure 14 Phase Diagram for smallest LCOTH in dependence of excess heat amount (x-axis) and transport distance (y-axis)

3.4.3 Comparison of capital and operating expenditure

Figure 14 shows the technology with the lowest LCOTH for the respective reference cases. In order to be able to make a comprehensive evaluation of the respective technologies, we also analyse the CAPEX and OPEX of the respective technologies. Figure 15 shows a detailed representation of CAPEX and OPEX for the different technologies for 4 reference cases. These are (1) 5km transport distance and 500 MWh/a heat; (2) 5 km transport distance and 5000 MWh/a heat; (3) 30km transport distance and 500 MWh/a heat; (4) 30 km transport distance and 5000 MWh/a heat. In blue and shaded are respectively the OPEX and in orange and filled the CAPEX.

It can be seen that especially for the technologies where new infrastructure has to be built (DH and absorption), it is mainly the transport distance that determines the LCOTH. For large transport distances and small heat amounts, these technologies have higher LCOTH than the technologies where no additional pipelines need to be built. For ESN technology, for longer transport distances, both CAPEX and OPEX increase due to higher heat losses. In the case of PCMs, the specific CAPEX remains identical, since they are calculated linearly from the amount of excess heat. However, the OPEX increase significantly with longer transport distance. A complete table with the individual values can be found in Appendix 3.C.

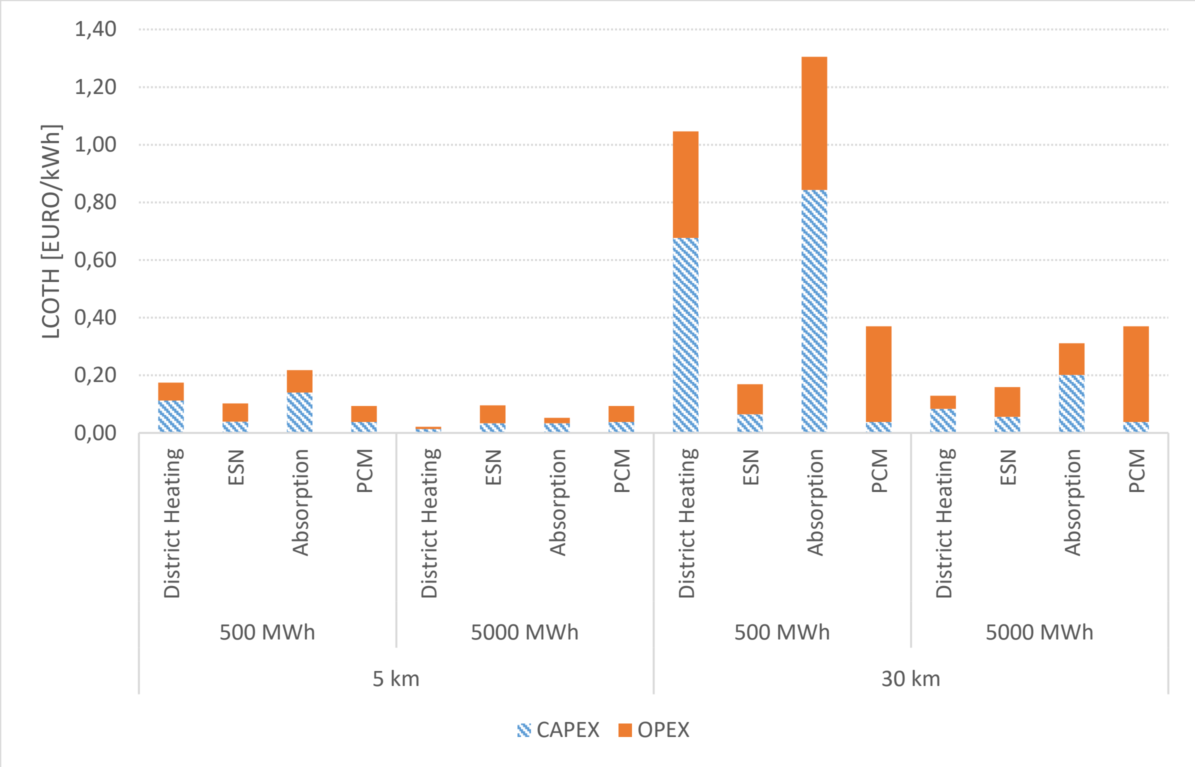


Figure 15 Comparison of CAPEX and OPEX for 4 reference cases

3.4.4 Absolute levelised costs of transported heat

In addition to identifying the technology with the lowest LCOTH for each reference case, we also calculate the lowest possible LCOTH for each reference case. Figure 16 describes the lowest LCOTH depending on the respective distance (y-axis) and amount of excess heat (y-axis). The darker the respective combination is shown, the higher the LCOTH. The LCOTH for the most economic heat transport technology range from 0.26 €/kWh to 0.004 €/kWh.

It can be seen that both the transport distance and the amount of available excess heat have an effect on the LCOTH. In general, the larger the amount of heat to be transported, the smaller the LCOTH. And the longer the transport distance, the larger the LCOTH. It follows that the greater the amount of heat to be transported, the longer the transport distance can be for the same LCOTH.

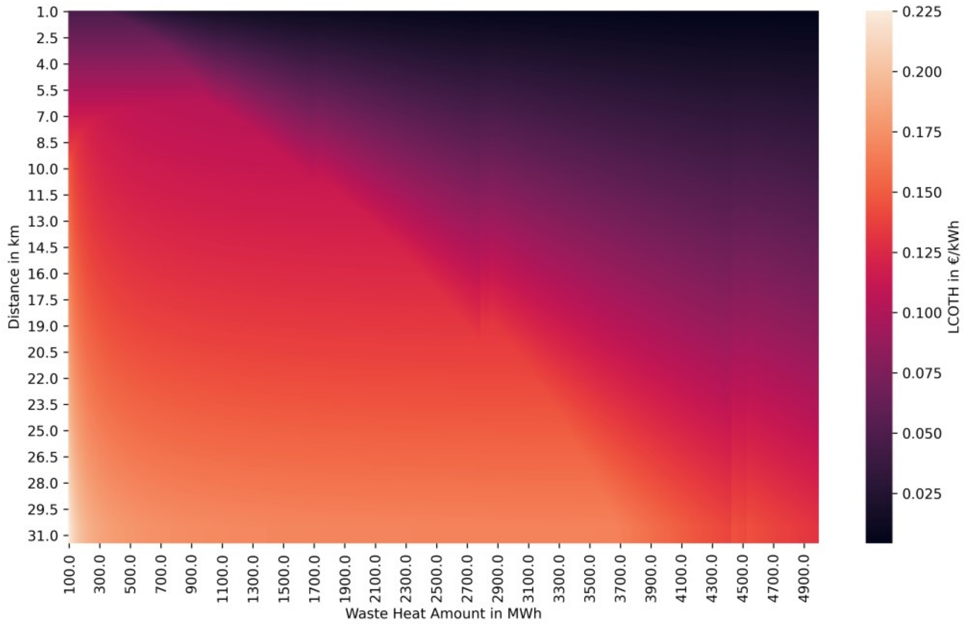


Figure 16 Absolute LCOTH for heat transport for different transport distances and excess heat quantities

Compared to conventional natural gas heating, the use of industrial excess heat can make sense in some cases. For this purpose, we calculate the specific costs for heat in a single-family house with a natural gas boiler for three different countries in which natural gas is primarily used for residential heating (Netherlands, Italy, Germany). For all cases we calculate an annual heat demand of 26,600 kWh/a (190 kWh/m²/a and 140 m²). We assume a natural gas boiler with 14 kW, which costs about 3,900 € (Danish Energy Agency 2021). For the gas prices we assume a cost increase of 4 % per year. The initial prices of the natural gas are for Germany 0.0620 €/kWh gas, for Italy 0.0897 €/kWh gas and for the Netherlands 0.101 €/kWh gas (eurostat 2021b). This results in heat costs of 0.099 €/kWh heat for Germany, 0.143 €/kWh heat for Italy and 0.161 €/kWh heat for the Netherlands. This shows that the economic viability of the systems depends very much on local conditions such as energy carrier prices and subsidies. Nevertheless, it can be said that for LCOTH higher than these thresholds, the use of excess heat is not an economical solution.

3.4.5 Sensitivity analysis and robustness checks

Our sensitivity analysis focus on the parameters interest rate and heat losses. We analyse the sensitivities at a transport distance of 12.5 km and an excess heat amount of 2,250 MWh. This point was chosen because it lies at the boundary of two technologies in Figure 14. Thus, the influence on the selection of the technologies can be seen. For other points the results may differ. Figure 17 shows the result of the sensitivity analysis of interest rate. The y-axis shows the LCOTH and the x-axis the respective percentage change of the interest rate and the absolute interest rate. It can be seen that especially DH and absorption cycle are sensitive to the change of interest rate. This results from the fact that for these technologies CAPEX has a higher share in LCOTH than OPEX and the interest rate only has an influence on CAPEX. In the case of the PCM and ESN technologies, it can be seen that they react less sensitively to the change in the interest rate, since the LCOTH of these technologies are largely determined by the OPEX.

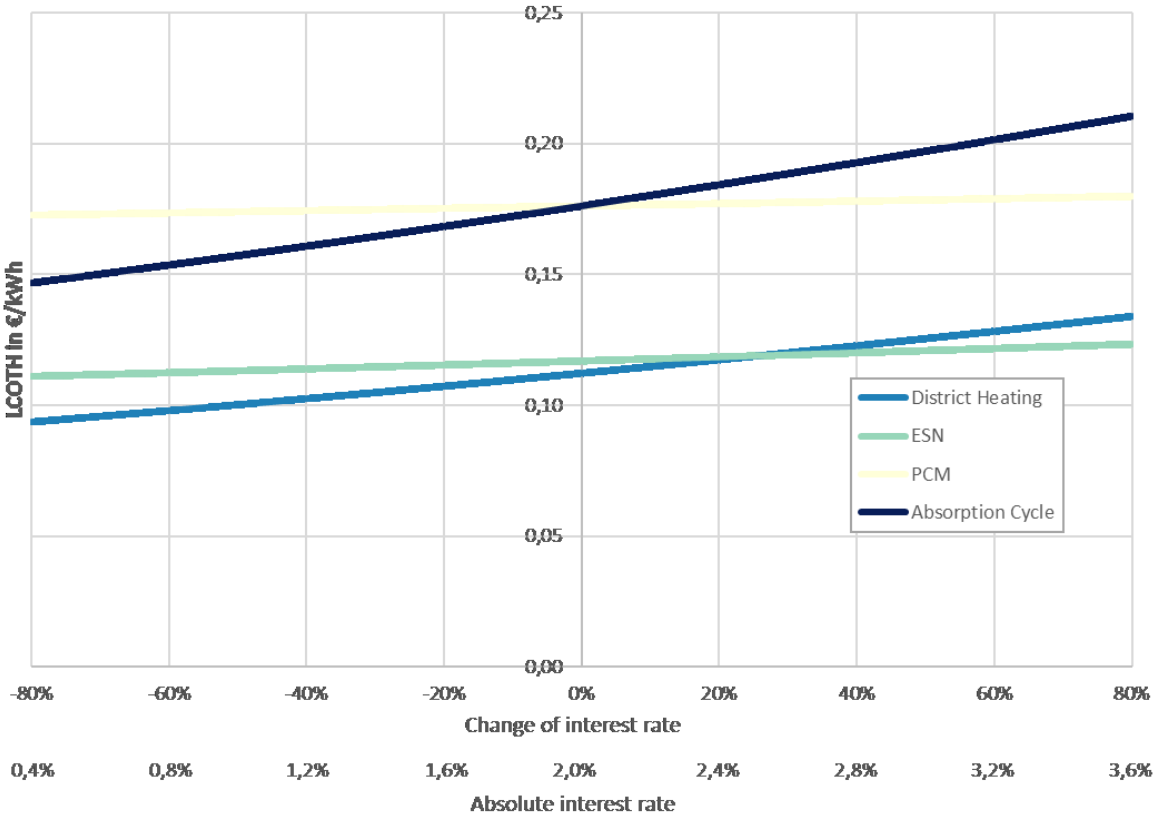


Figure 17 Sensitivity analysis of interest rate with an excess heat amount of 2,250 MWh and a transport distance of 12.5 km

Figure 18 shows the results of the sensitivity analysis of the heat losses. The y-axis shows the LCOTH and the x-axis the respective percentage change of heat losses. It can be seen that in contrast to the previous sensitivity analysis, the PCM and ESN technologies have higher sensitivity than the other technologies. For the selected combination of transport distance and excess heat amount, it can be seen that the ESN technology would be the best economic option if the heat losses would be about -30% compared to the initial assumptions. The same is applicable if the heat losses for the technology DH would be increased by +50% compared to the initial assumptions. Thus, the results show that heat losses can also have a decisive impact on the economic viability of the individual technologies.

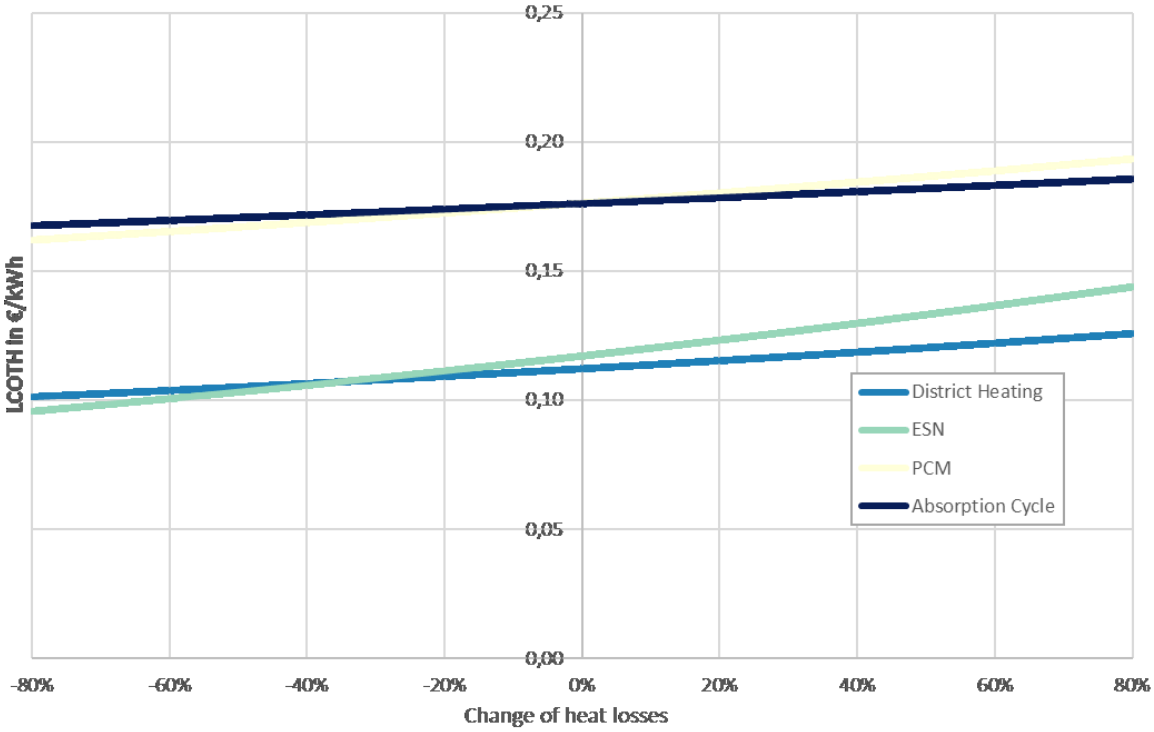


Figure 18 Sensitivity analysis of heat losses with an excess heat amount of 2,250 MWh and a transport distance of 12.5 km

3.5 Discussion

This section discusses the results and makes recommendations for further research. Our analysis is based on literature data and the highly transparent method presented in section 3.3. However, within our analysis, we make some assumptions that are discussed in the following.

Our analyses does not include an estimate of the total cost to provide heat for the end consumer. Our analysis deals exclusively with the costs for transporting the heat. For the total costs, the heat production costs of the excess heat, as well as the heat distribution within the buildings, must also be added. In further studies, the economic efficiency of the individual technologies for the end consumers should be investigated.

The technologies presented here differ fundamentally in their operation mode and can accordingly provide different temperatures. DH and absorption cycles can provide high temperatures, whereas PCM and ESN are limited in temperatures. For our analysed PCM, temperatures of about 60 °C are possible and for the use of ESN, a heat pump is necessary to increase the temperature. Depending on the desired temperature, this results in different COPs. In our analyses we assume a COP of 4.2, which means that approx. 65-75 °C can be provided. Our analyses refer to the climatic conditions in Central Europe. Depending on the climatic conditions, the framework conditions for individual technologies may change and the results may therefore differ for southern or northern countries (cf. (Mazzeo et al. 2021)). Future research should address this issue as it can provide a comprehensive overview of the usability of the technologies in different climatic conditions.

Furthermore, all results must be evaluated against the background that they were each calculated based on different lifetimes. For technologies with long lifetimes, the uncertainty of the assumptions increases in the later years. We address this by calculating the average annual CAPEX and average annual OPEX to obtain the average LCOTH. Nevertheless, there are still uncertainties regarding the price increase of the individual costs. This mainly affects the OPEX of the individual technologies. For the electricity costs to operate the heat pump, we assume a price increase of 0.8 % per year. Further studies could deal with this and especially analyse the price increase of the transport costs of PCM.

In our analyses, we assume that there is always enough wastewater available for the ESN technology. However, the amount of wastewater can fluctuate greatly (Bischof 1993). For this reason, the technology is particularly suitable in sewers where there is a high dry-weather flow. Another possibility is that the excess heat is not transferred into the wastewater by means of heat exchangers, but directly via the wastewater of the respective industrial plant. This can ensure that there is enough wastewater in the sewer to transport the heat. Another challenge is the accurate delivery of excess heat to the end users. When several consumers are connected to one sewer, the challenge can be that the temperature continues to decrease along the flow path. This would mean that a lower temperature is available to the end-users at the end of the flow path and thus the efficiency of the heat pump is lower. Further research should be done to investigate the feasibility of this technology in case studies.

When interpreting the results, it should be noted that the temperature difference between flow and return temperature is different for DH and ESN. For DH it is 20K and for ESN 45K. For this reason, we have carried out a third short sensitivity analysis with a temperature difference of 45K for DH. The results can be found in Appendix . The results show that only in the range of large transport distances (>15km) a noticeable shift of the phase boundaries is visible. For the range of small transport distances (<5km) the results are very robust.

In our analyses, we assume that PCM is transported by truck, since the expected distances are short. However, it is quite conceivable that PCMs could be transported by train or ship, which would reduce transport costs for longer distances. For DH, we make a general assumption of grid losses of 12 % based on AGFW (2021). This means that we overestimate the losses for shorter transport distances and underestimate the losses for longer transport distances. Other studies (Nussbaumer et al. 2017; Wetter et al. 2017; Horlacher and Helbig 2018) show that grid losses can vary greatly depending on the grid and can even be as high as 60 % for old grids. However, there are no references in the literature to heat losses in DH networks in %/m. For this reason, we compared several literature sources and use the general value of 12% based on AGFW (2021). To check the robustness of our results, we carry out a sensitivity analysis of the heat losses. The results of the sensitivity analysis show that if the heat losses of the DH change by 80%, the LCOTH only show a deviation of about 20%. Future research should analyse heat losses in more detail, which can improve our method for calculating LCOTH.

We assume average values according to (Dunkelberg et al. 2018) for the construction costs of heating networks. In reality, however, the construction costs of heating networks depend on the existing subsoil and the building density. This must be taken into account when analyzing real locations. For the construction costs for the sorption cycles, we use the construction costs of the heat networks as a basis, since no data are available in the literature for this. Further studies could analyse these aspects.

3.6 Conclusion

The results of this study make several contributions to the current literature. First, a comprehensive overview of excess heat transport technologies is provided. Second, technical and economic parameters are given for four selected technologies. Third, for the four technologies, an economic comparison is made for different combinations of transport distance and available amount of excess heat. This can provide an important decision-making basis for the selection of a technology for the transport of excess heat. Our results confirm, that DH is an economical option for transporting heat for many reference cases. However, the transport of heat for short transport distances and low excess heat quantities is more favorable with other technologies. For excess heat amounts lower than 1,500 MWh and transport distances of more than 10 km the ESN technology is the most economic application. For excess heat amounts lower than 700 MWh and transport distances lower than 7 km the PCM technology is the most economic application. Our results show that the transport costs for DH are very high for small amounts of excess heat (less than 1,000 MWh). For this reason, mainly projects with large amounts of excess heat have been implemented so far. In the future, however, the use of low-temperature excess heat with small available quantities will become more and more relevant, especially due to smaller excess heat utilization possibilities such as data centers. For this reason, it is important to continue research in these areas in the future to enable comprehensive excess heat utilization possibilities.

CRediT Author Statement

Markus Fritz: Conzeptualization, Methodology, Validation, Formal Analysis, Data curation, Writing - Original draft preparation, Visualization. **Patrick Plötz:** Supervision, Methodology, Writing - Review & Editing. **Liselotte Schebek:** Resources, Writing - Review & Editing

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

3.7 Appendix

3.7.1 Appendix 3.A

Pipe Diameter [m]	Total [€/m]	Civil engineering costs [€/m]	Planning costs [€/m]	Material costs [€/m]	Rest [€/m]
0.032	271	186	37	37	11
0.040	280	189	37	37	17
0.050	294	191	40	40	23
0.065	314	191	43	51	29
0.080	334	206	43	51	34
0.100	400	229	51	69	51
0.125	434	229	51	97	57
0.150	486	243	51	103	89
0.200	589	257	77	154	100
0.250	746	297	77	217	154
0.300	897	323	89	277	209

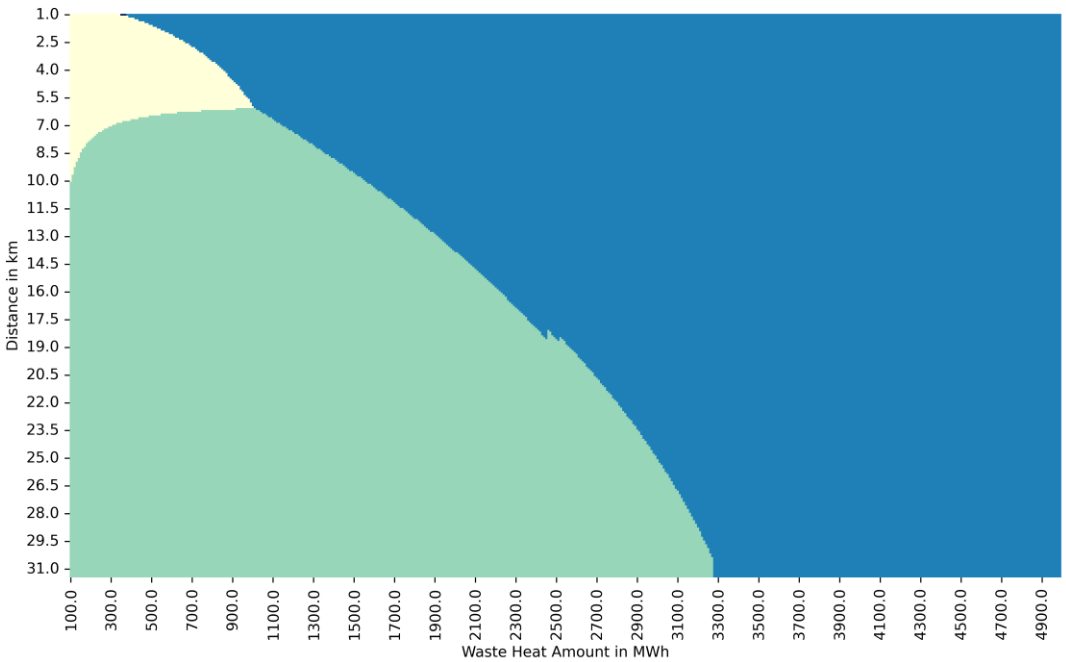
3.7.2 Appendix 3.B

Pipe Diameter [m]	Total [€/m]	Civil engineering costs [€/m]	Planning costs [€/m]	Material costs [€/m]	Rest [€/m]
0,200	1305	257	77	871	100
0,150	1023	243	51	640	89
0,125	862	229	51	525	57
0,100	660	229	51	329	51
0,080	527	206	43	244	34
0,065	457	191	43	194	29
0,050	407	191	40	153	23
0,040	362	189	37	119	17
0,032	317	186	37	82	11
0,025	278	179	34	55	10
0,015	244	174	32	30	8
0,012	230	170	30	23	7

3.7.3 Appendix 3.C

Distance	Amount	Technology	CAPEX	OPEX
5 km	500 MWh	District heating	0,11	0,06
		ESN	0,04	0,07
		Absorption	0,14	0,08
		PCM	0,04	0,06
	5000 MWh	District heating	0,01	0,01
		ESN	0,03	0,07
		Absorption	0,03	0,02
		PCM	0,04	0,06
30 km	500 MWh	District heating	0,68	0,37
		ESN	0,06	0,11
		Absorption	0,84	0,46
		PCM	0,04	0,33
	5000 MWh	District heating	0,08	0,05
		ESN	0,06	0,11
		Absorption	0,20	0,11
		PCM	0,04	0,33

3.7.4 Appendix 3.D



4 Don't waste the water, use wastewater - excess heat distribution for private households through sewer networks[3]

Abstract

Private households account for a quarter of the EU's final energy demand. Approximately 80 % of this is used to provide heat and hot water. 84 % of this heat is generated from fossil fuels. The provision of space heating by means of environmentally friendly district heating is regarded as an important lever for the decarbonisation of the building sector. In this respect, one of the EU's targets is to find heat sources for district heating networks that emit no or few GHGs. In this context, industrial excess heat is often discussed as possible supply option. However, if this heat is far away from district heating networks, then the construction of new infrastructure is capital intensive. This can lead to low economic efficiency. For this reason, the existing sewer network offers a solution with an existing infrastructure. Here excess heat can be transferred to the wastewater with heat exchangers, which leads to a rising wastewater temperature. The energy quantity of the wastewater is then taken at another point along the flow direction of the sewer and used as heat source for a heat pump. The heat pump can then be operated more efficiently with the warmer wastewater and the excess heat is thus used. However, the potential for transporting excess heat via sewer networks has not yet been assessed and we are therefore carrying out such an assessment. We use a data set of more than 950 industrial sites and more than 26,000 sewage treatment plants. For a given set of industrial sites with information about excess heat, we identify the nearest sewage treatment plant. After that, we determine the maximum distance and the flow direction of the wastewater and calculate the heat loss in the sewer network. Our results demonstrate that transferring heat via the sewer network offers high theoretical excess heat potentials. In conclusion, in the overall dataset the average heat loss in the sewer network is around 20 %, which is more or less in the range of heat losses in district heating. Further research is needed to quantify the economic and technical potential based on real case studies.

[3] The chapter has been published as Fritz, Markus; Aydemir, Ali (2019): Don't waste the water, use wastewater - excess heat distribution for private households through sewer networks: ECEEE (eceee Summer Study 2019. Proceedings).

4.1 Introduction

Private households account for a quarter of the EU's final energy demand (European Commission 2018). One of the EU's targets is to find heat sources for district heating networks that emit no or few GHGs. In this context, industrial excess heat is often discussed as possible supply option.

Industrial excess heat is generated by many industrial processes using process heat. From a technical point of view, excess heat can be described as unwanted heat generated by an industrial process . From a social point of view, it can be described as heat which is a by-product of industrial processes and currently not utilized, but which could be used for society and industry in the future (Viklund and Johansson 2014). In the past, numerous studies have quantified excess heat potentials that proceed in varying degrees of detail. Among them Brueckner et al. (2017) is to be emphasized, because the analysis was accomplished on basis of data, which were made available by enterprises in the context of the Federal Imission Control Act (Bundesimmissionsschutzverordnung). Therefore, the analysis is particularly extensive. The production sites evaluated in account for around 58 % of industrial fuel consumption in Germany. For the sites evaluated, this results in an excess heat volume of 35 TWh per year, which corresponds to about 13 % of the fuel consumption of the sites. With regard to excess heat potentials, the avoidance of excess heat and internal heat recovery should be given priority from an energy efficiency perspective. The solution examined here makes use of excess heat on an inter-company basis and is therefore usually only taken into consideration when internal measures have been exhausted. We regard any use that goes beyond heat integration within the company as inter-company use. This might also be a use in other sectors such as households or industry, trade and services. The significance of the option assessed here therefore depends in particular on the potential for inter-company excess heat utilisation in industry. Aydemir and Rohde (2018) quantify these potentials based on an excess heat estimate and a simplified cascade calculation for estimating intra-company heat recovery potentials. As a result, they determine that intra-company heat recovery potentials are despite the long history still highly relevant. Nevertheless, depending on the scenario, between a quarter and a half of the excess heat potential remains available for inter-company heat integration in their analysis.

Overall, current analyses thus show that, on the one hand, there is still considerable potential for excess heat in industry and, on the other hand, that it is unlikely that it can be completely recycled internally. It therefore makes sense to research additional options for inter-company use.

The technology transfers excess heat from industrial sites to the wastewater stream by means of heat exchangers. The temperature in the sewer is raised and the heat can be transported along the flow path. Downstream, the heat can then be used by established technologies such as heat exchangers and heat pumps. Even small temperature increases improve the coefficient of performance (COP) of the heat pump. Primary energy demand and greenhouse gas emissions are reduced by the efficient utilization of previously unused excess heat, while a high level of resource efficiency is achieved by the multiple use of existing infrastructure systems.

4.2 Data and Methods

4.2.1 Excess heat data and wastewater treatment plants

We use a total of 5,029 data records from industrial sites in Europe. The data were compiled within the framework of the hotmaps project and made available to the public (https://www.hotmaps-project.eu/). The methodology of data production is described in Manz et al. (2018). In principle, excess heat quantities for industrial sites are estimated based on emission data from the EU emissions trading system (EU ETS) and the European Pollutant Release and Transfer Register (E-PRTR) register. The data contain different variables for every year, of which the following ten are relevant for this paper: address, longitude, latitude, data source and the amount of excess heat in three different temperature ranges (<200 °C, 200-500 °C, >500 °C). Some of the data do not include information on the amount of excess heat from the individual sites. The other variables have no missing values at all. Figure 19 shows a histogram of all the remaining industrial sites with specific heat quantities according to the amount of available excess heat.

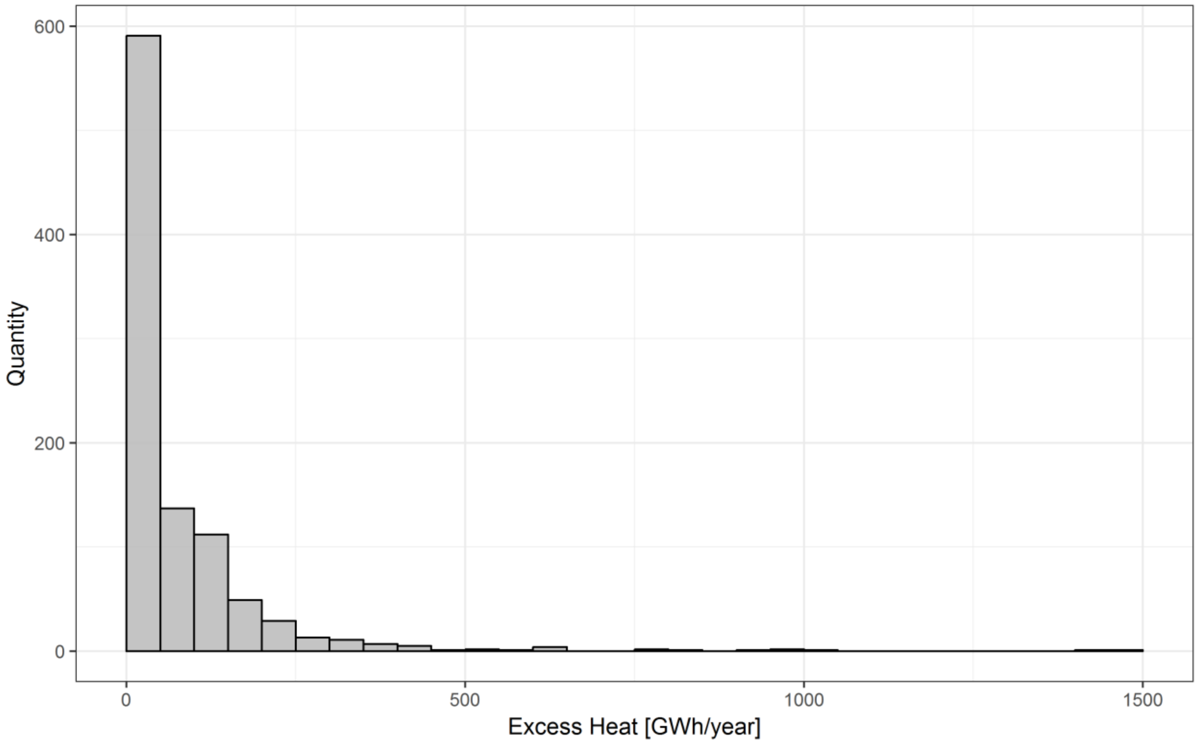


Figure 19 Quantity of available excess heat by different classes.

Figure 19 shows, that almost all industrial sites have an available excess heat of less than 500 GWh/year. More than 60 % of the industrial sites have an available excess heat less than 50 GWh/year.

The data on the wastewater treatment plants are based on the monitoring reports of the Urban Waste Water Treatment Directive (UWWTD). This directive was adopted in 1991 as Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. The UWWTD was adopted to protect the environment from negative effects of the collection, treatment and discharge of urban wastewater. It also covers certain industrial sectors. According to Article 15 of this Directive, Member States are obliged to monitor the requirements of the Directive and to make the information obtained available to the Commission. The data are edited by the Commission and published on the EEA website (https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-5). This data contain approx. 30,000 sewage treatment plants. This corresponds to about half of the municipal sewage treatment plants in Europe (Döing et al. 2006).

4.2.2 Methods

The research aim of this paper is to investigate whether the innovative approach of excess heat utilization through sewage networks might be a promising alternative compared to conventional excess heat utilization such as feeding district heating networks. In particular, we investigate the transport of heat in the sewer network and the heat loss during transport. To answer the research question, we combine a technical analysis with spatial analytical approaches. For this purpose, we determine the nearest wastewater treatment plant for 978 industrial sites and model an idealized sewer. We calculate the heat loss for four different sewer temperatures. In the following, the individual steps to answer the research question are described in more detail.

First, we identify the nearest sewage treatment plant for the industrial site. We used the havresine formula (Chopde and Nichat 2013) to calculate the distance from the heat sources to the wastewater treatment plants. This calculates the great-circle distance between two points based on the longitude and latitude of the two points. In order to identify the nearest wastewater treatment plant to the heat source, we implemented a sorting algorithm.

Second, for each industrial site we sum up the amount of excess heat from the individual temperature levels. For our calculation, the temperature level of the excess heat is not decisive, since the temperature in the sewer should rise to a maximum temperature and therefore the amount of energy is important. For the temperature of the sewer we use scenarios of (1) 30 °C, (2) 50 °C, (3) 70 °C, (4) 25 °C.
Third, we calculate the average amount of water required to dissipate the excess heat. We assume that the excess heat is generated constantly throughout the year. The wastewater temperature is assumed to be 15 °C (Wanner et al. 2004), which is to be increased to the four temperature levels of the four scenarios by excess heat. This results in a temperature difference $\triangle T$. The water flow is calculated according to formula (13):

$$F = \frac{CQ}{4.182\frac{kJ}{kg*K}*\Delta T_1*8760\frac{h}{year}*997\frac{kg}{m^3}} \quad (13)$$

With: F: flow rate [m^3/h]
Q: excess heat quantity [kJ/year]
$\triangle T_1$: temperature difference in the sewer [K]

Fourth, we calculate the sewer parameters based on the flow rate of the water. In this paper, we model a sewer that leads directly from the excess heat source to the sewage treatment plant and can dissipate the corresponding amount of water. In Germany, the flow velocity in wastewater pipes should be between 0.7 m/s and 2.5 m/s. We assume a flow velocity of 1.5 m/s for the calculation in this paper. For each excess heat source, we calculate the parameters of the sewer according to formula (14):

$$d = \sqrt{\frac{F}{1.5*3600\frac{m}{h}*\pi}}*2 \quad (14)$$

With: d: diameter of the sewer [m]
F: flow rate [m^3/h]

Thus, the required diameter d is given for each sewer. In the next step, we determine the wall thickness of the pipes based on manufacturer tables. As building material, we examine the material concrete more closely in this paper. The pipe parameters are determined based on a component list from a manufacturer of wastewater pipes (Berding Beton 2019). The coefficient of thermal conductivity for concrete is 2.1 (Ott 2019).

Fifth, we calculate the heat loss within the sewer. The design parameters of the sewer, the building material of the sewer and the temperature difference between the wastewater and its surrounding underground temperature are important for this. The annual average temperature in Germany from 2010 to 2018 at a depth of 1 m is used as the ambient temperature. This temperature is 11.7 °C (Potsdam-Institut für Klimafolgenforschung 2019). The temperature loss of the sewer is calculated according to the specifications of VDI 2055 according to the following formula:

$$L = \frac{2 * \pi * \lambda \ * \Delta T_2}{ln \frac{d_a}{d_i}} \tag{15}$$

With: L: temperature loss [W/m]

λ coefficient of thermal conductivity [W/mK]

ΔT_2: temperature difference wastewater and surrounding underground [K]

d_a: outer diameter [m]

d_i: inner diameter [m]

With the results of this calculation, the total energy loss can be calculated based on the length of the sewer.

4.3 Results

4.3.1 Heat loss in sewers

As a first step, we identified the nearest wastewater treatment plant for each industrial site. As described in the methods section, we calculated the distances to all wastewater treatment plants for each industrial site within a grid and were thus able to identify the nearest wastewater treatment plant for each excess heat source. Figure 20 shows the industrial sites on a map of Europe.

Figure 20 Available industrial sites in Europe.

Figure 20 shows that our data contain excess heat sources throughout Europe. There is an accumulation of available data mainly in Central Europe, but there are also data sources in Eastern Europe, Western Europe and the North.

Our distance calculation represents an overestimation of the flow path and thus also an overestimation of the heat loss, since the heat sink must lie between the industrial site and the wastewater treatment plant. Figure 21 shows the frequencies of the calculated distances.

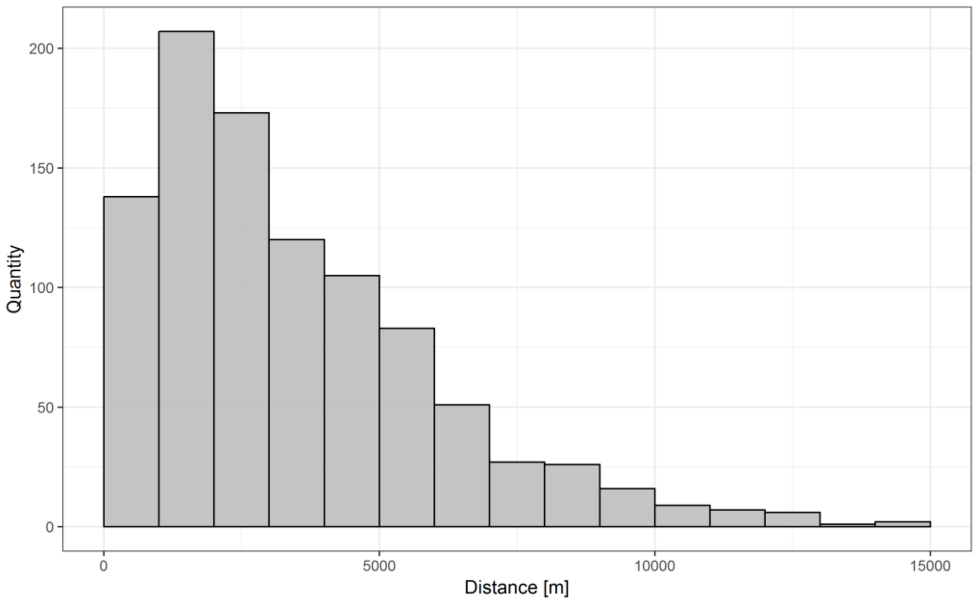


Figure 21 Quantity of maximum length of flow paths.

Figure 21 shows that short distances to the wastewater treatment plants are represented frequently. Over 75 % of the distances are less than 5 km. The most common distance is 1,000 to 2,000 meters with a frequency of 21 %. There are very few cases where the flow path is longer than 10,000 meters. However, since the distance to the nearest sewage treatment plant was calculated in our analysis, the result represents the maximum possible flow path. In reality, the flow paths might be shorter, as the heat sink must be located between the heat source and the wastewater treatment plant in order to use the technology.
Figure 22 shows the total heat loss for all modeled sewers. The heat loss is shown for four different wastewater temperatures.

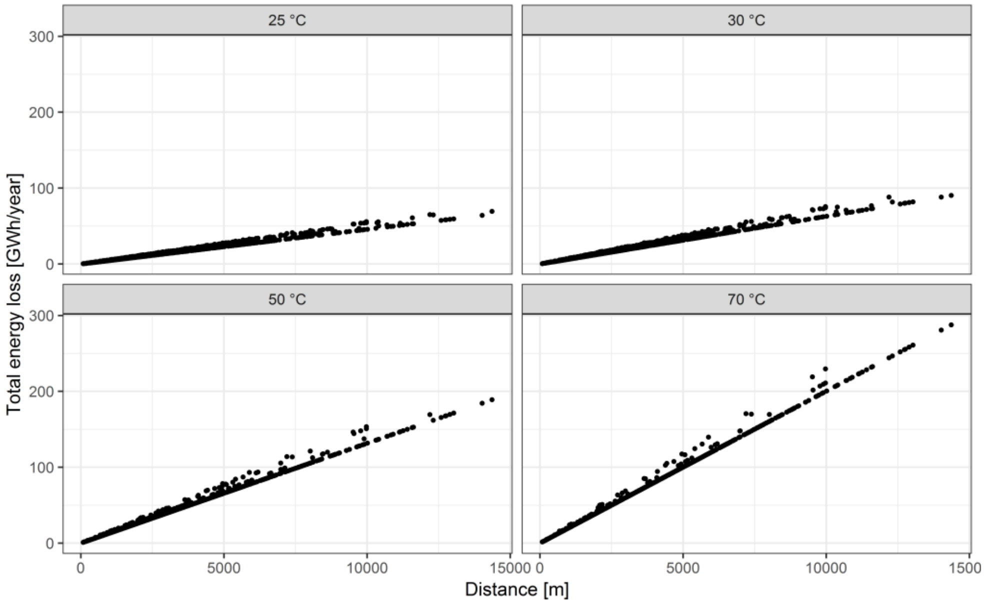


Figure 22 Total energy loss in GWh/year as a function of the flow path length and the temperature of the wastewater.

Figure 22 shows that the heat loss within the sewer increases with the length of the flow path. It can also be seen that at higher temperatures in the sewer the heat loss in the sewers is higher for same distances than at lower temperatures. Depending on the temperature in the sewer, this also changes the possible identified use cases. For higher temperatures, short distances are of particular interest.

4.3.2 Potential of usage

For a possible use of this technology not only the total heat loss is important, but also the percentage heat loss. In order to determine a possible utilization potential, it must be determined up to which heat loss a sewer connection is meaningful. In our study, we consider all possible cases in which the percentage heat loss is less than 25 % as a possible usage option as heat losses in district heating networks are ranging usually between 10 and 20 %. Table 8 lists the number of possible uses depending on the wastewater temperature and the associated total amount of excess heat.

Table 8 Potential use cases of the technology in the given data set

Temperature	Potential use cases	Percentage of potential use	Quantity of excess heat
25 °C	410	42 %	61.5 TWh
30 °C	321	33 %	55 TWh
50 °C	179	18 %	39.8 TWh
70 °C	117	12 %	31.5 TWh

The results from Table 8 show that at lower temperatures the proportion of possible uses decreases faster than at higher temperatures. At a temperature of 30 °C, 321 out of 978 sewers have a heat loss of less than 25 %. This means that at this temperature a possible use would be conceivable in 33 % of cases. The average heat loss in the sewer at a temperature of 30 °C is 21.4 %.

The results also show that there is an almost linear correlation between the number of potential uses and the total amount of usable excess heat. This means that not only a few industrial sites with large amounts of excess heat characterize the results.

Our analyses show that the percentage of energy losses at different temperature levels depends on the length of the sewer, the amount of excess heat available and the sewer parameters. It cannot be generally said that lower temperatures are recommended for long distances or higher temperatures for high excess heat quantities. The configuration parameters for the use of the technology should be reviewed individually for each use.

4.4 Conclusion and discussion

In our analysis we show that at a wastewater temperature of 30 °C for 321 of the 978 cases investigated, it might make sense to use the existing sewer infrastructure. This corresponds to a share of approx. 33%. We justify this with the fact that the heat losses based on an idealized estimate for these cases are below 25%. This is in the area of district heating networks. The weighted average heat loss for all modeled sewers at a temperature of 30 °C is 21.4%.

Further research is needed to develop a more accurate formula for calculating heat loss within the sewers. Overall, the analysis shows that using the sewer network to transport excess heat is a promising alternative. Next analyses should therefore examine this technological option based on case studies with real sewer data in order to evaluate to what extent the impression is confirmed.

5 Industrial excess heat and residential heating - Potentials and costs based on different heat transport technologies[4]

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 trans-ported to the end-using households. In this paper, we determine the economic excess heat poten-tial for residential heating in Germany, considering different transport technologies. For this pur-pose, 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 net-works 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.

5.1 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 and 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 and Tänzer 2010; Pehnt et al. 2010) and bottom-up (Steinbach et al. 2021; Brückner 2016; Blömer et al. 2019b) 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 and 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

[4] The chapter has been published as Fritz, Markus; Werner, Dorian (2022): Industrial excess heat and residential heating - Potentials and costs based on different heat transport technologies. Working Paper Sustainability and In-novation No. S 11/2022. Karlsruhe: Fraunhofer ISI

is also possible with other technologies (Ma et al. 2009a; 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. 2009a; 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.

5.2 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 and 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 and 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.

5.3 Data and methods

5.3.1 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:

$$Q = V * O * 1.3 \left(\frac{kg}{m^3}\right) * 1.04 \left(\frac{kJ}{kg * K}\right) * (T - T_r) \qquad (16)$$

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[5]. 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.

5.3.2 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).
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
5. 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.

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

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 and Konstantin (2018) as the annuity for one year:

$$CAPEX = Invest * \frac{(1+i)^t * i}{(1+i)^t - 1} \tag{17}$$

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):

$$LCOTH = \frac{CAPEX + OPEX}{Q - L} \tag{18}$$

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 23 shows the individual steps of the method.

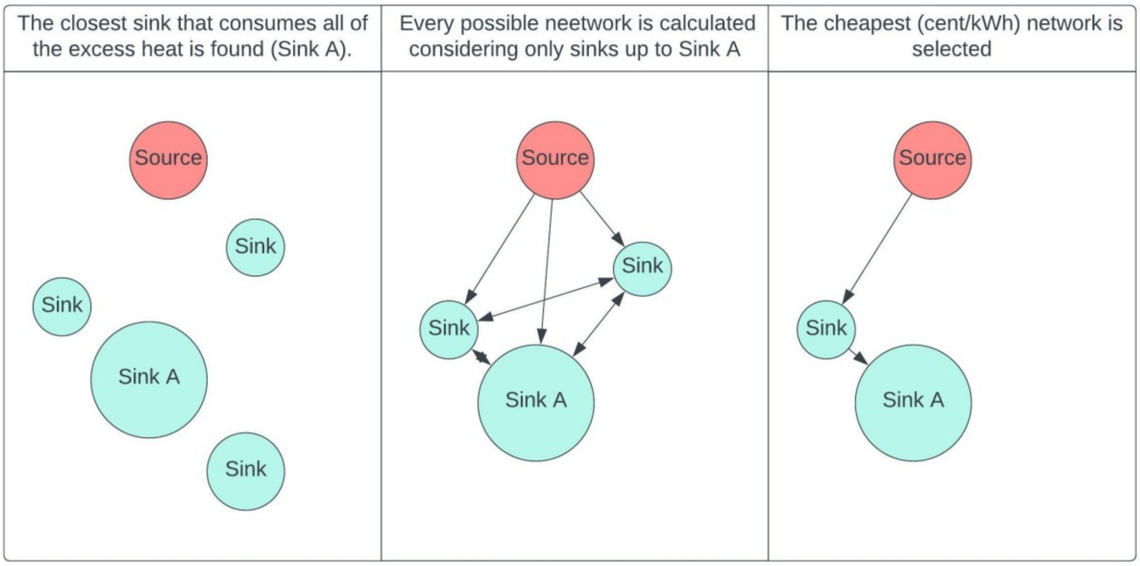


Figure 23 Step 1 (left), steps 2 and 3 (middle) and step 4 (right) of the model

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 5.4.2.

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 5.4.3.

5.4 Results

5.4.1 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 24 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.

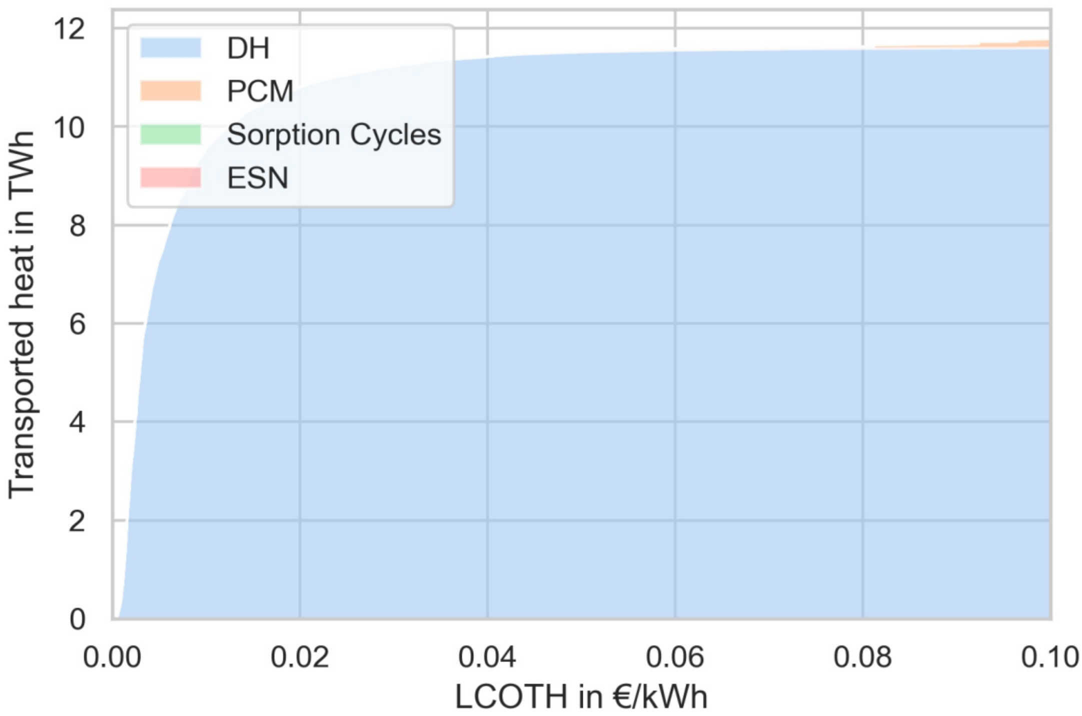


Figure 24 Cumulative LCOTH for cost optimisation

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 25 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.

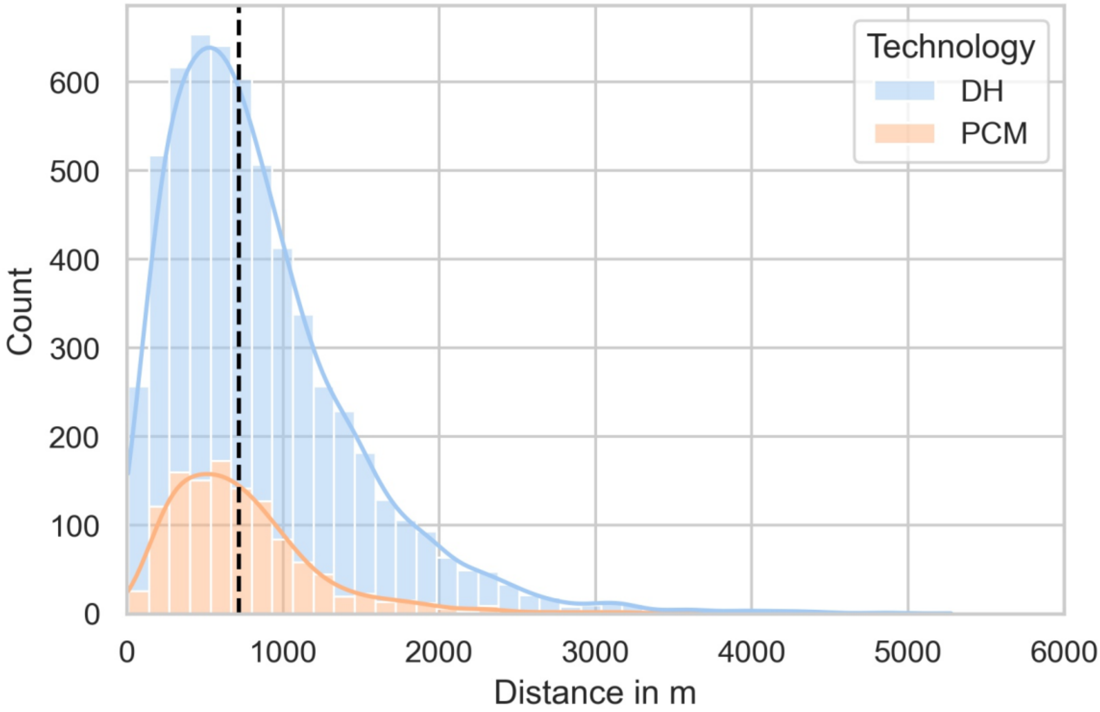


Figure 25 Histogram of the transport distance by technologies

Figure 26 shows a histogram of the LCOTH resulting from the modelling. The blue bars show net-works 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.

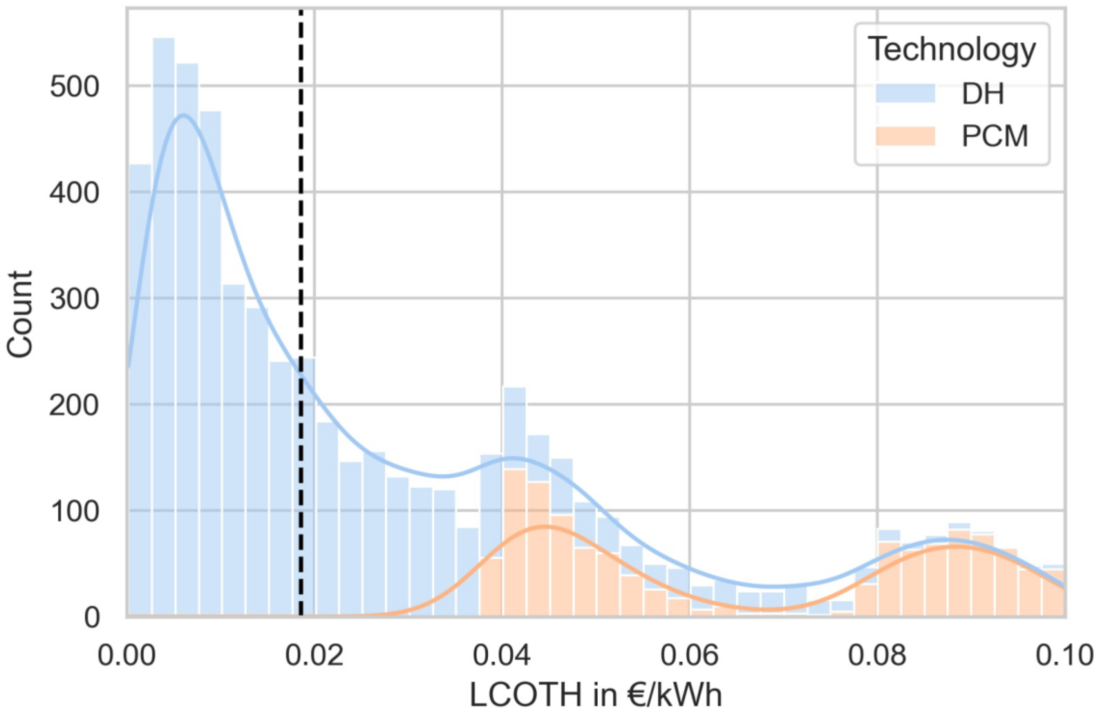


Figure 26 Histogram of the LCOTH by technologies

Figure 27 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 de-termined 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 rela-tively high, and excess heat can only be transported with LCOTH higher than 0.09 €/kWh.

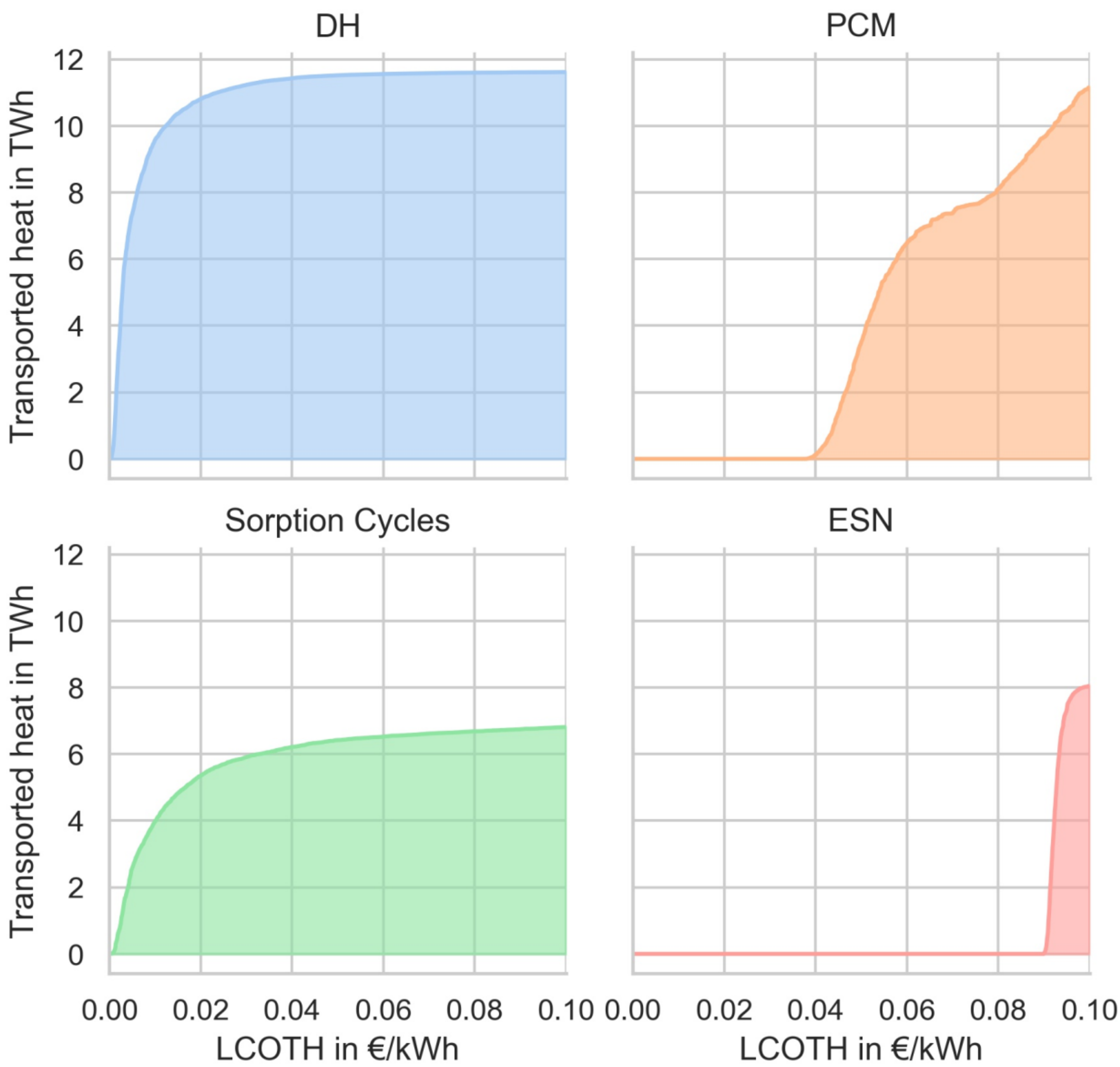


Figure 27 Cumulative LCOTH for cost optimisation for each technology

5.4.2 Sensitivity analysis

In the results of the previous section, the linear distance is used to determine the transport dis-tances. 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 5.4.1 are carried out again, and scaling factors of 1.5 and 2 are used for the transport distance. Figure 28 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.

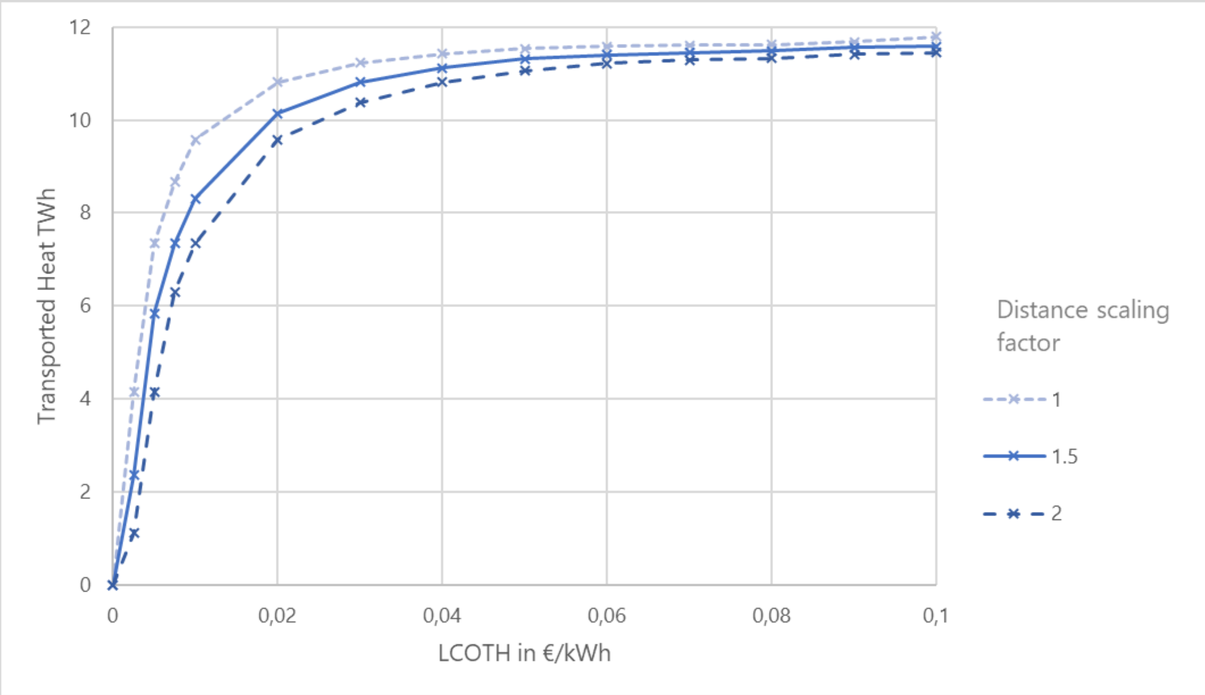


Figure 28 Sensitivity analysis of the transport distance

5.4.3 Heat amount optimisation

In contrast to the results from section 5.4.1, 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 29 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 24). 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.

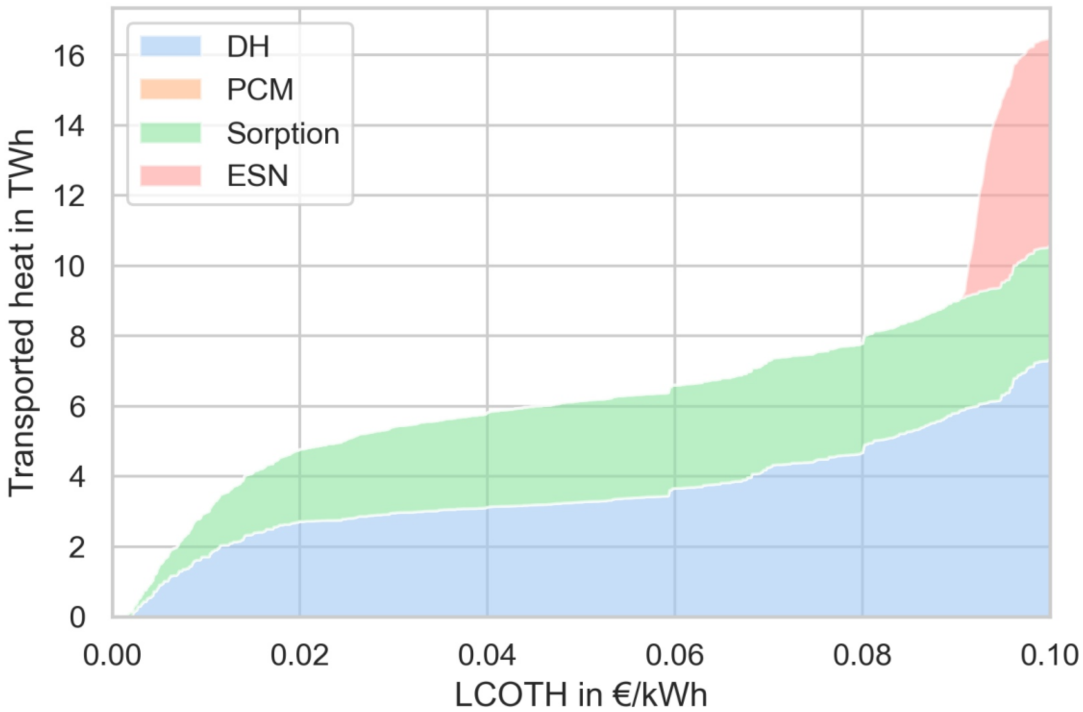


Figure 29 Cumulative LCOTH for optimising the maximum amount of excess heat used

Figure 30 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 26, 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.

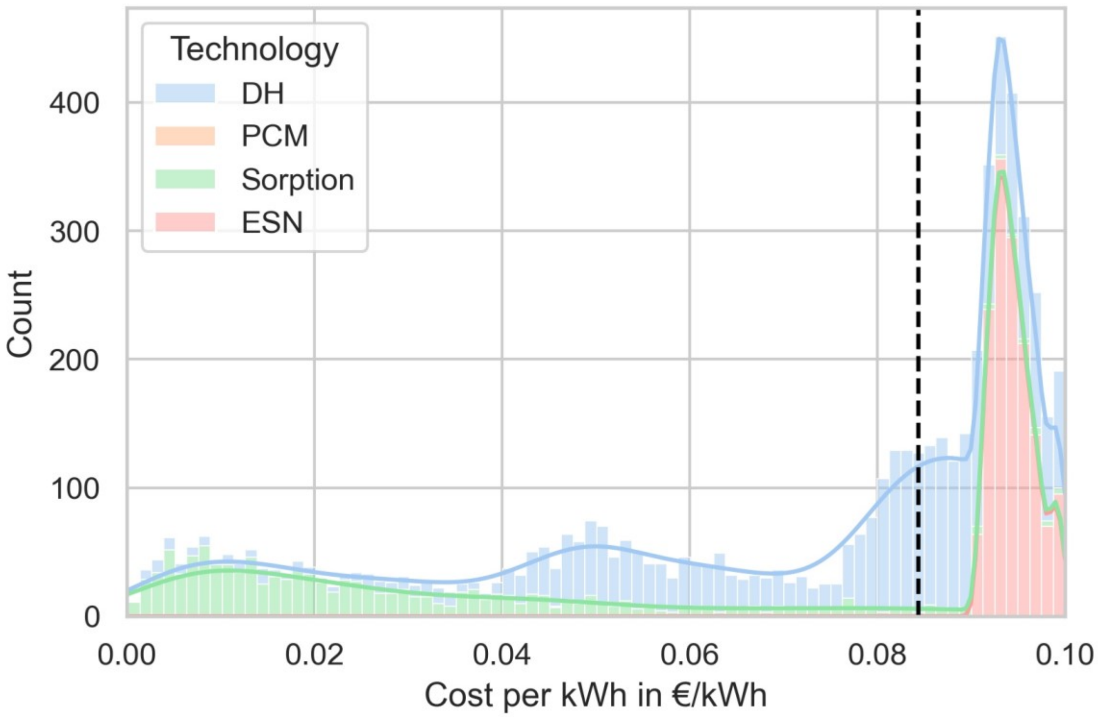


Figure 30 Histogram of the LCOTH for optimising the maximum amount of excess heat used

5.5 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.

5.6 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.

6 Usage of excess heat for district heating - analysis of enabling factors and barriers[6]

Abstract

The use of industrial excess heat can be an important factor for the expansion and decarbonization of district heating networks. However, the enabling factors and barriers to implement excess heat recovery projects for district heating are still uncertain. Here, drivers and barriers for the integration of excess heat into district heating networks are analysed and a public available database of 45 implemented projects in Germany, Austria and France is created. 5 hypotheses of enabling factors and barriers were formulated and tested through 13 expert interviews with excess heat producers. Unlike the current literature, expert interviews are combined with a literature review to test the hypotheses. Thus, both quantitative and qualitative data are used to verify or refute the hypotheses. The results demonstrate that projects are often implemented only thanks to individuals and that the communication and exchange between the necessary stakeholders is often insufficient. It is also evident here that relevant stakeholders are often unaware of excess heat recovery opportunities. Furthermore, the results show that financial aspects are often not the main reasons for excess heat recovery for district heating, but play an important role in the decision-making. In conclusion, there are many barriers that can be overcome through meaningful policy design or better information and support.

[6] The chapter has been published as Fritz, Markus; Savin, Margaux; Aydemir, Ali (2022): Usage of excess heat for district heating - analysis of enabling factors and barriers. In: Journal of cleaner production (363). DOI: 10.1016/j.jclepro.2022.132370.

6.1 Introduction

Heating and cooling accounts for about half of Europe's total energy demand, with 75% of this still dependent on fossil fuels (European Commission 2018). Thus, rapid and significant change is needed to reach the EU 2050 climate targets. District heating (DH) is a promising option in this context. Firstly, DH still harbours a high economic potential in Europe (Mathiesen et al. 2019; Rezaie and Rosen 2012). Secondly, DH networks have the potential to reduce the carbon footprint of many consumers at once by changing the supply technologies and energy sources of the networks (Lund et al. 2010; Werner 2017). It can already be observed in the EU that countries with a high share of DH also use a higher share of renewable energies for heat supply (Mathiesen et al. 2019). In addition, excess heat can be integrated into DH networks (Fang et al. 2013; Hummel et al. 2014). On the one hand, this reduces the CO_2 footprint of the networks and, on the other hand, offers the potential to reduce heating costs (Aydemir et al. 2020). Integrating excess heat into DH networks can therefore be a relevant driver for the expansion and decarbonisation of DH networks. Recent studies show that there is a large potential for utilising industrial and non-industrial excess heat in Europe (Forman et al. 2016; Manz et al. 2021; Schmidt et al. 2020). At the same time, there are still large amounts of excess heat that remain unused. In many cases, this is due to the fact that, in addition to technical feasibility, there are barriers preventing the integration of excess heat into DH networks.

This paper is structured as follows. The remainder of section 6.1 describes the existing literature, the identified research gap and our contribution. Section 6.2 describes the method and data used. Section 6.3 presents the results of the identified case studies. Section 6.4 describes the formulated hypotheses and the results of testing them. Section 6.5 discusses the findings, and the paper finishes with policy implications and conclusions in section 6.6.

6.1.1 Existing literature

Industrial excess heat results from inefficiencies in plants and processes as well as from thermodynamic constraints (Brückner 2016; Hirzel et al. 2013). Inefficiencies include the lack of insulation to reduce heat losses. Thermodynamic constraints result from process characteristics, e.g. when minimum temperatures must be maintained in melting furnaces, which in turn result in excess heat. First, the excess heat can be used internally in the plant or process from which it originates: In this case, the excess heat is recovered and reused (cf. Option 1 in Figure 31). Second, it can be used by feeding it into other plants or processes. This can be done either internally (e.g. within a factory) or externally (e.g. when fed into district heating networks) (cf. Option 2 in Figure 31). Third, the exergy contained in the excess heat can be converted into other forms of energy, e.g. for the generation of electricity or cooling. Figure 31 shows these different options for excess heat utilisation. The heat flows are shown in blue, possible production processes in grey, and the excess heat recovery in orange. The top part of the figure describes the use of excess heat within the process (option 1) and the bottom part describes its use in other processes or in DH networks (option 2).

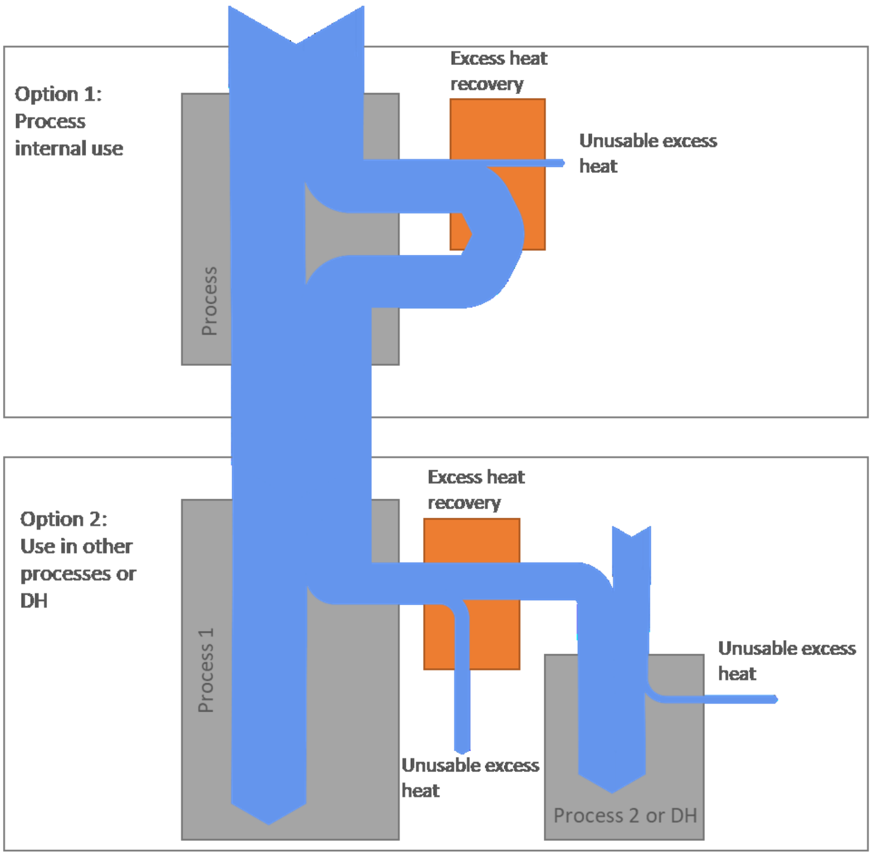


Figure 31 Excess heat utilisation options. Option 1 (top): Process internal use; Option 2 (bottom): Use in other processes or DH

Bergmeier (2003) reviewed the history of excess heat and found that the topic was already dealt with in technical journals in the 1920s. In the late 1990s and at the beginning of the new millennium, articles investigated the excess heat potential, not only in individual case studies, but for larger geographical regions (Aydemir and Fritz 2020; Bianchi et al. 2019). More recent studies take an increasingly differentiated approach in determining the potential and attempt, for example, to quantify not only the theoretical energy potential, but also the technical, economic or exploitable potential. For example Aydemir and Fritz (2020) investigated how the theoretical potential changes when corrosive components in exhaust gas streams are taken into account. Aydemir and Rohde (2018) investigated how the theoretical potential changes when considering options for internal excess heat utilisation in industry. In addition, the potentials are increasingly georeferenced, as in Manz et al. (2018), e.g. to explore the potential uses for DH. There are already numerous examples for the integration of excess heat into DH networks (Petersen 2017), but potentials remain untapped (Aydemir et al. 2020; Persson et al. 2014), which is also due to the following three technical barriers.

The first technical barrier to using excess heat recovery (EHR) for DH is the temporal imbalance between heat source and sink (Dahash et al. 2019; Fito et al. 2020; Schmidt et al. 2020; Xu et al. 2019). Excess heat may be produced constantly throughout the day or year, but the heat is mainly needed in winter and in the evening or at night. One solution to this is to use seasonal heat storage (Dahash et al. 2019; Fito et al. 2020). Another solution is the use of thermal-driven chillers in summer to use the excess heat (Schmidt et al. 2020).
The second technical barrier is the local discrepancy (Ma et al. 2009a; Schmidt et al. 2020; Xu et al. 2019). Excess heat may be generated by companies in industrial areas, which are not usually sited close to densely populated areas, where heat is needed. In addition, the DH network may be not connected to the industrial site or have the capacity needed to transport the excess heat. However, it is technically

possible to install long DH networks or to expand or convert existing DH networks in order to be able to transport the excess heat (Ma et al. 2009a; Schmidt et al. 2020; Xu et al. 2019).
The third technical barrier is quality mismatch (Fito et al. 2020; Schmidt et al. 2020; Sun et al. 2014). The available excess heat may not have the required temperature or the amount of energy required. Possible solutions to this are to lower the temperature of DH networks to use low exergy networks or to increase the excess heat temperature using heat pumps (Fito et al. 2020; Schmidt et al. 2020; Sun et al. 2014).

These technical barriers can be effectively addressed through technology development. However, there are also other non-technical barriers and recent research has also focused on other enabling factors for and barriers to the use of excess heat in DH. The literature on these other factors is divided into 3 streams.

The first stream of literature analyses facilitating factors and barriers based on stakeholder interviews. Päivärinne et al. (2015) analysed enabling factors and barriers to the collaborations between DH companies and industrial companies for excess heat supply in Sweden. Lygnerud et al. (2019) conducted a stakeholder analysis as well as interviews in the context of 4 case studies. The biggest barrier mentioned in (Päivärinne et al. 2015) and (Lygnerud et al. 2019) is the financial aspect. This shows that economic efficiency plays an important role and that uneconomic projects are rarely implemented. Päivärinne et al. (2015) additionally shows that trust and the transfer of information are the main enabling factors for project implementation. The other barriers identified by Lygnerud et al. (2019) include the low technical maturity, incentives for renewables and combined heat and power, the absence of a legal framework and standardized contracts, diverging views regarding the heat value and the low temperature of urban excess heat. One advantage of stakeholder interviews is that many individual opinions can be collected in a neutral environment. A disadvantage, however, is that the selection of interview partners is often not transparent and they are often regionally limited.

The second stream of literature describes the barriers based on the results of stakeholder workshops. Blömer et al. (2019b) identified barriers to the use of excess heat in Germany when determining the potential for grid-based excess heat usage. Schmidt et al. (2020) conducted an in-depth literature review in combination with expert reviews. Blömer et al. (2019b) found that a lack of capacity and know-how, the legally binding nature of contracts, low transparency and favourable competing prices compared to fossil fuels are the biggest barriers. Schmidt et al. (2020) identified technical, economic, legal and societal enabling factors and barriers. The advantage of stakeholder workshops is that opinions from relevant stakeholders can be obtained in a targeted manner. A disadvantage, however, is that such workshops are often dominated by individuals with very strong opinions and others do not get a chance to speak.

The third stream of literature analyses the enabling factors and barriers based on implemented projects. Moser and Lassacher (2020b) tested three hypotheses based on a quantitative database of case studies implemented in Austria. One hypothesis is related to barriers to the usage of excess heat and states that projects will only be implemented if they are highly profitable. However, due to the lack of data, they were not able to verify or refute this hypothesis. The advantage of this method is that it is not reliant on individual persons. A disadvantage, however, is that enabling factors and drivers at the social level are difficult to derive from implemented projects.

The literature review shows that there is a great potential of excess heat, which is often not used. This is partly due to technical barriers, but also to non-technical barriers. In the literature, barriers and enabling factors have been identified by either conducting workshops (Schmidt et al. 2020) or carrying out wider analyses for individual countries (Blömer et al. 2019b; Moser and Lassacher 2020b; Päivärinne et al. 2015). In summary, many studies highlight that there are barriers to using excess heat in DH networks, but only one study has explicitly analysed the barriers across several countries. So far, no study has compiled a database of case studies, conducted interviews with key stakeholders and analysed enabling factors.

6.1.2 Our contribution

This paper aims to identify and analyse enabling factors for and barriers to the implementation of industrial EHR projects in DH and to create a database of existing EHR for DH projects in France, Germany and Austria. For this purpose, a literature review was conducted on implemented case studies to establish a database and then hypotheses formulated based on a literature review of enabling factors and barriers and the case study database. Finally, the hypotheses were tested in expert interviews with excess heat producers. Previous work investigating enabling factors for and barriers to the use of excess heat in DH has been based either on in-depth literature reviews or on workshops and therefore differs from our research in several aspects. First, a database of 45 real case studies was compiled and the complete database of identified case studies was published so that it can be used for further analysis. Second, hypotheses were formulated based on a literature review of enabling factors and barriers as well as on the results of our case study database. Third, expert interviews were combined with a literature review to test the hypotheses. Thus, both quantitative and qualitative data were used to test the hypotheses. To the best of the authors' knowledge, this has not been done in the literature before.

6.2 Methods

Industrial excess heat utilization in DH networks can help to increase the efficiency of these systems and reduce CO_2 emissions. This paper aims to find out which enabling factors and barriers exist to using industrial excess heat in DH networks. Case studies in Germany, Austria, and France were analysed, in which industrial excess heat is fed into DH networks. The case study approach was used to gain a detailed understanding of the enabling factors and barriers. Our analysis is based on the following four steps:

1. Desk research of existing case studies.
2. Compilation and evaluation of a case study database.
3. Formulation of hypotheses based on the literature on enabling factors and barriers, and the case study database.
4. Testing the hypotheses based on interviews and the database.

The **first step** prepared an overview of implemented case studies of industrial excess heat utilization in DH networks in Germany, Austria and France. Common search engines were used as well as databases like LexisNexis. Locally implemented case studies are often found in the local press and rarely in scientific publications. The search was conducted in German, French and English. Only projects that were actually implemented before 20.10.2020 were considered. Projects in the conception or implementation phase were therefore excluded from the analysis. In total, 45 case studies were identified.

In the **second step**, a more detailed analysis of the identified case studies was performed. A database of these projects was created and general, technical and governance information was compiled for each case study. This information was used to form the three different parts of the database. Each part was filled with quantitative and qualitative information on identified variables. The detailed analysis of the case studies included screening of press releases, newspaper articles such as interviews, corporate publications, city council homepages etc. Furthermore, wherever possible, existing data gaps were filled with the help of selective requests to the actors involved. A complete overview of the variables included in the database and a description of the data can be found in section 6.3.

In the **third step**, 5 hypotheses on industrial excess heat utilization in DH networks were formulated. According to Allen (2017), specific, testable and predictable statements were formulated as hypotheses. These hypotheses were based on a further in-depth literature review of enabling factors and barriers and the results from the case study database. The hypotheses are explained in more detail in section 6.4.

The **fourth step** was to test the formulated hypotheses based on the supplementary interviews with stakeholders of the case studies. A total of 13 interviews were conducted. The interviews served on the one hand (as described in the second step) to complete the database and, on the other hand, to test the formulated hypotheses. The interviews were conducted as semi-structured interviews to obtain answers to all questions from all industry representatives. Individual interviews are better suited to identifying the opinions of individuals and all the interviewed persons can be given the opportunity to comment in detail on all the hypotheses that have been formulated. The interviews were conducted in the respective national language by phone or as online video meetings and lasted between 30 and 60 minutes. Participants received the interview questions in advance so that they could prepare their answers or gather the information and input necessary to the discussion.

6.3 Technical results of the identified case studies

This section presents the data and the database derived from them. The desk research presented in section 2 identified 45 case studies from Germany, Austria, and France in which industrial excess heat is fed into a DH network. The geographical distribution of the case studies is: 14 in Germany, 27 in Austria and 4 in France. Figure 32 shows the local distribution of the identified industrial sites in each of the three countries. It can be seen that the identified case studies are heterogeneously distributed in the three countries investigated.

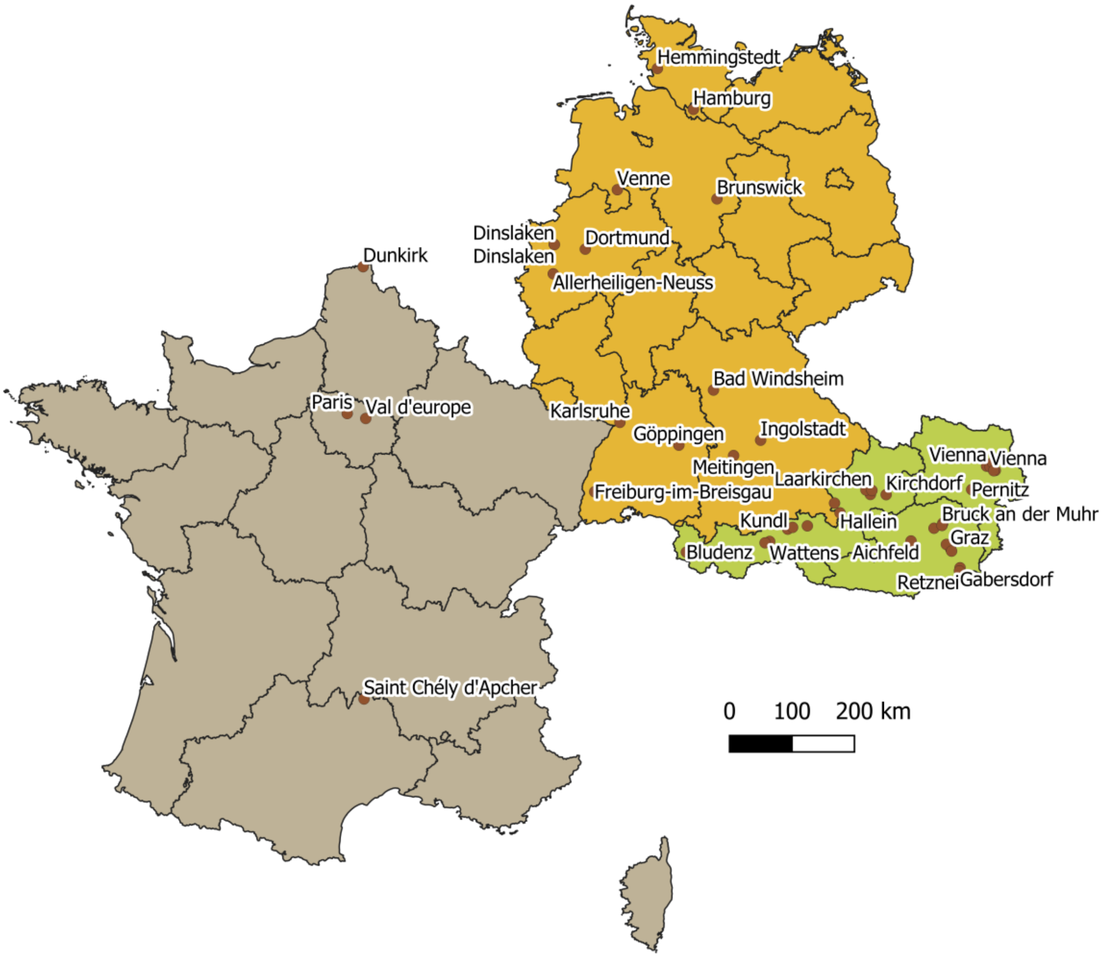


Figure 32 Location of the identified case studies.

Our database comprises the following parts: general information, technical information, and governance information. The investigated variables within the three parts were determined based on the availability of data in the literature, their comparability, and their relevance in highlighting the specific features of each case study. Data for each variable were gathered for all the identified case studies. Where possible, existing blanks were filled while conducting the interviews. Nevertheless, it should be noted that the database is not complete and many variables could not be determined for all case studies. An overview of all the data collected can be found in Table 9.

The full database contains more information than was used for the analyses in this paper. In the following, the variables highlighted in Table 9 are discussed in more detail, as they provide a basic description of the technical characteristics of the case studies. Table 10 shows the share of missing records for these variables. In particular, the respective share of industrial excess heat supply in DH networks was not available for about 66% of the case studies. This is due to the fact that it was not often possible to determine the total amount of heat delivered (excess heat and other producers) to the DH network in the case studies. The amount of excess heat fed into the DH network, on the other hand, could be determined for all but one case study. The full database can be found in Appendix 6A.

Table 9 Parts and variables of the database.

Part	**Variable**								
General information	Country	City	Year of implementation	Internal excess heat recovery	Company name	Sector	Company size	Total costs of the project	Business scenario
Technical information	Capacity	Amount of excess heat	CO_2 saved	Heat consumers	Existing or new DH system	Size of DH network	Share of excess heat supply in DH network	Distance company - DH network	
Governance information	Project initiators	Award for project							

Table 10 Share of missing records in the database.

	Year of implementation	Sector	Amount of excess heat	Sector	Existing or new DH system	Share of excess heat supply
Share of missing records	12.5 %	None missing	2.3 %	None missing	22.2 %	60.7 %

In total, the identified companies provide excess heat amounting to 2,863 GWh/yr. The available capacity is 475 MW. It should be noted, however, that information on capacity is only available for 29 of the 45 case studies. The breakdown of the companies by sector clearly shows that refineries, the metal industry, the wood and paper industry, and the chemical industry are the largest providers of excess heat in the data set. The refineries in Vienna (ID 18) and Karlsruhe (ID 1) provide 1,220 GWh/yr. of excess heat alone (cf. Figure 33). The "other" sector includes data centres, cement industry, tobacco industry, textile industry, and pharmaceutical industry. The cities belonging to the IDs can be identified from the database.

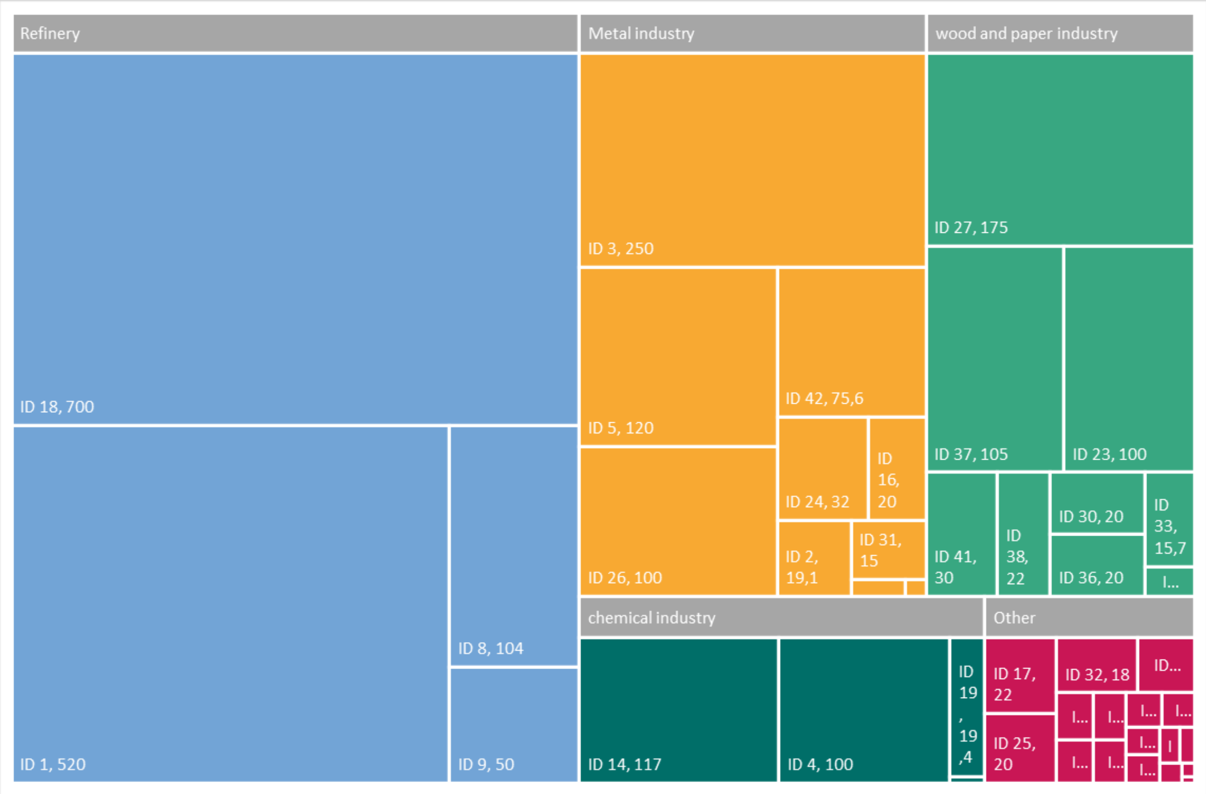


Figure 33 Amount of excess heat recovered by sector in GWh/yr.

Figure 34 shows the cumulative progress of the implementations over time and the amount of heat supplied. When looking at the development over time, it becomes clear that new projects have emerged almost every year (green bars) since the first project was implemented in 1978. Especially in the years from 2010 onwards, the increase is significantly greater. In the years 1979 to 2009 (30 years), a total of 15 projects were implemented. In the period from 2010 to 2019 (9 years), a total of 30 projects were implemented. It can also be seen that the amount of excess heat supplied (red line) has increased continuously over the years, but especially over the last 10 years. The steps in the figure are mainly due to individual cases implying the recovery of a large amount of excess heat.

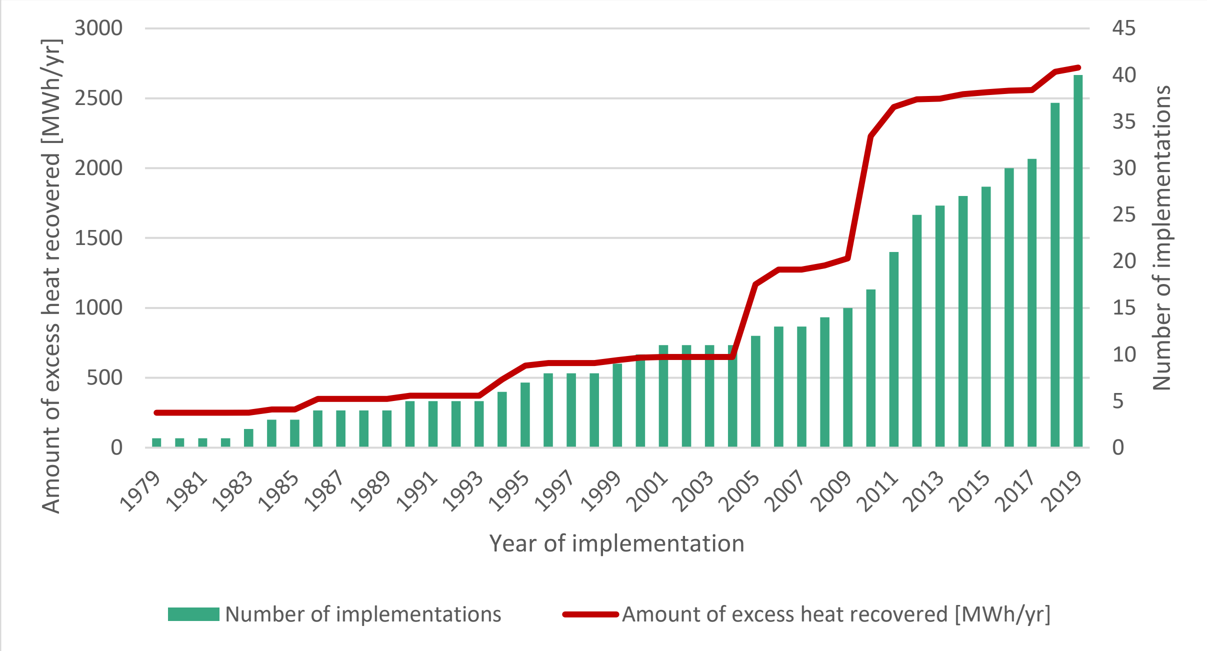


Figure 34 Amount of excess heat recovered and number of implementations over the years.

The amount excess heat provided to the DH network varies greatly in the case studies investigated. The results from the database show that there can be very low shares of excess heat in the DH networks (<10 %), but also very high shares (>90 %). Furthermore, the results suggest that the general use of excess heat for DH networks does not depend on the share of excess heat in the energy mix of the respective DH network. It should be noted, however, that this information could only be collected for 28 of the 45 case studies.

6.4 Formulation and testing of hypotheses

6.4.1 Formulation of hypotheses

Based on the findings from the case studies and a literature review, 5 hypothesis were formulated and then tested in qualitative interviews with industrial excess heat producers. In line with Allen (2017), specific, testable and predictable statements were formulated as hypotheses. This section explains how these hypotheses were derived and how they answer our research question. The hypotheses are:

1. Local actors are decisive for using EHR for DH.
2. EHR for DH requires the engagement of individuals.
3. Industrial excess heat producers are more likely to engage with EHR for DH if this does not induce costs or require investments on their part.
4. EHR for DH is more likely to be applied if a district heating network is already in place.
5. EHR for DH is seen by industrial actors as a long-term solution for the management of excess heat.

The **first hypothesis** is that local actors are decisive for using EHR in DH. This hypothesis is based on several findings from the literature. Colmenar-Santos et al. (2015) identified the lack of interest (as well as capacities) of local authorities to engage with large energy-related programs as a major barrier to the development of DH networks. Schmidt et al. (2020) showed that many stakeholders often need to be involved in the planning and implementation process, but there is often little contact between the companies and the DH network operators. Studies on transitions in the DH sector have emphasized that the technology is locally bound Hawkey and Webb (2012). The EU strategy on heating and cooling emphasises that supporting municipalities, cities or local governments is key in order to transition towards sustainable heating systems. It states that “the most effective way (…) is to empower and support local and regional authorities, in conjunction with all relevant stakeholders.” (European Commission 2016). More specifically, the German NAPE 2.0 stresses the need to improve the coordination and interplay between national and local funding mechanisms for EHR for DH systems (BMWi 2019). Research on existing policies aimed at fostering EHR for DH has shown that several policies focus on local actors to support the development of the technology (see French Programmations pluriannuelles de l'énergie (Ministère de la transition écologique 2021) and (Braun et al. 2019)). Assessing the relationship between local actors and EHR for DH projects is therefore important and should help decision-makers to improve or adapt strategies for more EH in DH networks.

The **second hypothesis** is that using EHR for DH requires the engagement of individuals. Such projects are often the initiative of single persons and contingent on the relationships between key individuals. This hypothesis was investigated by Päivärinne et al. (2015), but no firm conclusion could be drawn. Viklund (2015) showed that especially the support of management in companies is decisive for EHR for DH projects. In small and medium-sized enterprises (SMEs), energy efficiency measures are often the result of the strong engagement of enterprising individuals (Thollander et al. 2007). If this hypothesis is validated, it might reveal the lack of institutional networks for EHR for DH.

The **third hypothesis** addresses the issue of costs and investments. The hypothesis is that industrial excess heat producers are more likely to engage with EHR for DH if this does not induce costs or require investments on their part. Scholars have shown that financial resources are a critical factor when it comes to applying EHR for DH (Viklund 2015). EHR for DH projects often require large investments (Schmidt et al. 2020). Lygnerud et al. (2019) and Schmidt et al. (2020) showed that long payback periods and low profitability are a major barrier to the implementation of such projects. Lygnerud et al. (2019) showed that private industrial companies are profit-oriented which creates an intrinsic motivation for them to create “monetary value” out of excess heat. Moser and Lassacher (2020b) also investigated whether projects need to have a high economic return in order to be implemented, but could not answer this question due to a lack of data. However, recovering and selling excess heat are not part of the core business of such industries. As a consequence, they often lack information on the monetary benefits that might be associated with excess heat recovery strategies. Lygnerud et al. (2019) mentioned that the availability of company resources for excess heat recovery projects depends on the size and situation of the company. Payback periods for investments in EHR for DH projects are very long compared to the usual amortization periods considered by industrial actors. This confirms the results of Pehnt et al. (2010), who discussed barriers to excess heat recovery with stakeholders and experts. The lack of resources was mentioned as an important limiting factor, especially the lack of funding.

The **fourth hypothesis** is that EHR for DH is more likely to be applied if a DH network is already in place. Schmidt et al. (2020) assumed that the presence of an existing DH network may be a prerequisite for integrating excess heat and that the existence of an excess heat source could promote the development of new networks. Päivärinne et al. (2015) identified the absence of an existing DH network as a technical impediment for using EHR for DH systems. This hypothesis is important as it can help to evaluate whether DH and EHR are considered together in planning processes. Is the availability of EH an important variable when planning DH systems? Who searches for synergies between DH networks and EH availability and how? The outcome of testing this hypothesis has important technical implications. Technical barriers to the implementation of EHR for DH could be dismantled if integrating EHR were already considered at the development stage of the DH networks.

The **fifth hypothesis** addresses the excess heat producers’ motivation for applying the technology. The hypothesis is that EHR for DH is seen by industrial actors as a long-term solution for managing excess heat. Thollander et al. (2007) found that SMEs with a long-term energy strategy are more likely to implement energy efficiency measures. Schmidt et al. (2020), on the other hand, showed that long-term solutions are also desirable for DH network operators. They show that the lack of long-term guarantees is a barrier, and that DH network operators often have to install back-up systems in case the excess heat is reduced or the contracts are terminated. Especially with regard to the current transformation of industry (cf. Herbst et al. (2021)), it is of great importance to analyse the motivations for and against process changes.

6.4.2 Results of interviews and testing hypotheses

To test the formulated hypotheses, 13 expert interviews were conducted with the industrial companies identified in the database. The large majority of interviewees hold positions as technical or energy managers (9). Others are employed as process managers (2) or managing directors (2). Besides the chemical industry, all the industrial sectors from our database (agroindustry, cement industry, metal industry, refinery, wood and paper industry, and data centres) were represented. Overall, the sample is a fair representation of the industrial sectors involved with EHR for DH networks. The results of the expert interviews and the results of testing the hypotheses are presented in the following.
Figure 35 shows the results of the question about the internal motivating factors driving the implementation of EHR for DH networks. 13 out of 13 interviewees stated that "strengthening local ties" was an important internal motivating factor. This result indicates that the local context plays a decisive role in the decision-making of EH producers. The importance of local actors and relationships for EHR projects is discussed in more detail in section "Local actors are decisive for using EHR for DH".10 of the 13 industrial companies interviewed stated that EHR represents a "long-term solution for excess heat management", thereby highlighting another important driving factor for using EHR for DH. This result supports one of our hypotheses and is discussed in "EHR for DH is seen by industrial actors as a long-term solution for managing excess heat". Additionally, 9 of the 13 industrial companies interviewed said that reducing energy consumption and the resulting financial savings were a motivation for providing excess heat to DH networks.

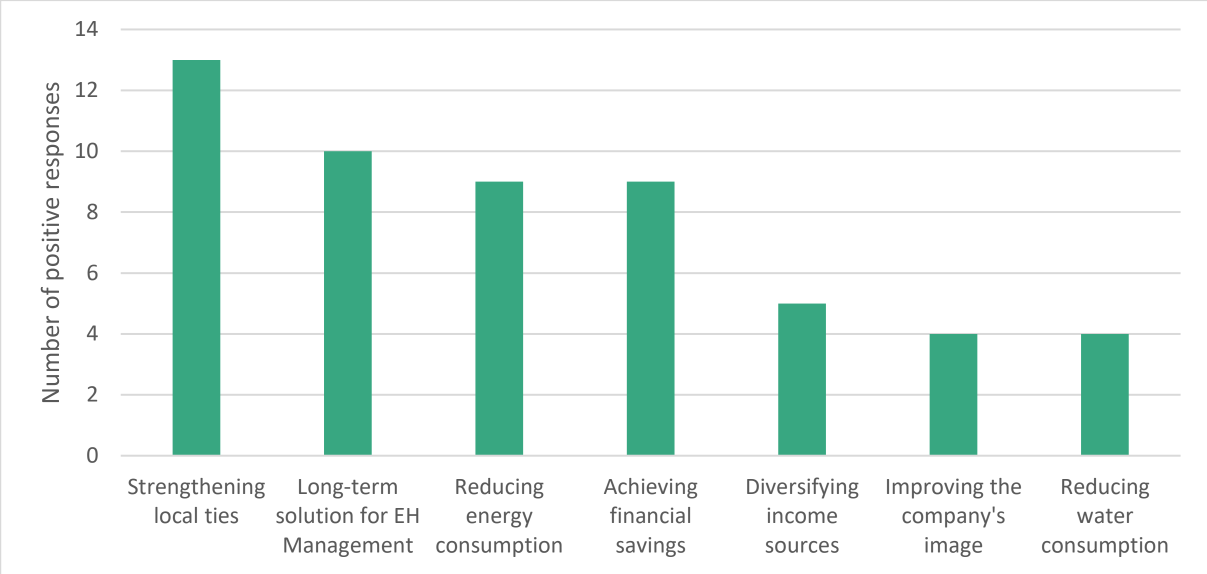


Figure 35: Internal motivations for industries to use EHR for DH (in number of positive responses) (n=13).

Local actors are decisive for using EHR for DH

Results from the interviews indicated that strengthening local ties is a major motivation for industrial excess heat producers to implement EHR for DH. 100% of the respondents agreed that they expected to improve the quality and number of their local partnerships. It was quite clear that the local context and dynamics with local stakeholders are considered when planning EHR for a DH project. More importantly, our results showed that industries definitely regard collaboration with economic and political actors as necessary for the successful implementation of EHR for DH. Even though politicians generally do not initiate technology application projects, 84% (n=13) of the companies explained that the support of political actors was important in setting up EHR for DH. As we can see in Figure 36, political actors at local level are more often involved than those at higher levels. Two main reasons were given for the importance of political support. Three companies explicitly stated that political stakeholders were important to facilitate or accelerate building processes. In particular, their support can make the construction of connection pipes between the companies and the DH system possible. These advantages were mostly due to support from those local stakeholders who are responsible for issuing construction permits in the countries examined. In several cases, political actors also facilitated access to subsidies. Such support with project financing was provided by both local and national actors. Following the same trend, a lack of political support is considered a barrier to EH for DH projects. It seems that applying the technology is hardly possible if local decision-makers (politicians) are opposed to it. Four out of thirteen companies highlighted that insufficient political support was an obstacle to the technology implementation.

Interviewees also highlighted that EHR for DH could not be implemented in a generally unfavourable context. For three companies, their attempts to implement EHR for DH in other plants of their group failed because of the lack of interest among local political and economic actors. This finding demonstrates that the lack of interest of local stakeholders such as political representatives and potential partners for EHR for DH can prevent technology implementation. Our first hypothesis can therefore be confirmed.

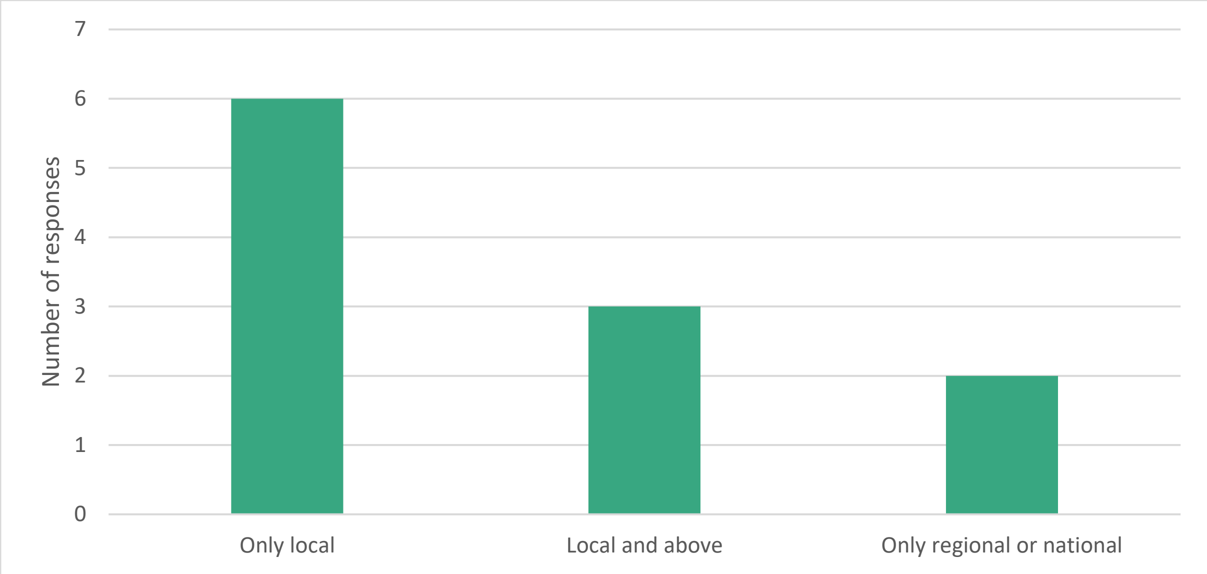


Figure 36: Intervention level of political actors involved in the development of EHR for DH projects (n=12).

EHR for DH requires the engagement of individuals

Individuals play a decisive role in EHR for DH. 53% (n=13) of interviewees stated that the technology would not have been implemented without the strong engagement of individuals in the company. Respondents mentioned that individuals played a major role in pushing the acceptance of EHR for DH within the company as well as in creating ties with cooperation partners such as DH providers, municipalities or external consultants. These "intrapreneurs" are not necessarily on the highest decision-making level in the companies. They share certain characteristics such as a "belief" in EHR for DH and its benefits as well as patience and persistence when pushing for technology implementation.
Individuals working at excess heat producers also contributed to the implementation of EHR for DH if they had knowledge relevant to the implementation. Companies that have employees able to plan EHR for DH projects or to manage and maintain the associated devices and technical components are more likely to adopt the technology. Our results showed that about half of the interviewed companies drew on human resources or in-house devices and instruments to gather the knowledge required for the implementation of EHR for DH. The large majority of responses regarding technological knowledge indicates that external and internal knowledge are generally combined and incorporated into the project development process. The second hypothesis regarding the engagement of individuals can therefore be confirmed.

Industrial excess heat producers are more likely to engage with EHR for DH if it does not induce costs or require investments on their part

The cost/revenue ratio of EHR for DH projects depends on technical aspects, as well as on the considered time frame. Three core technical variables are the distance between the DH network and the industrial site of EHR, the operating schedule of core processes as well as the temperature of the excess heat. In general, EHR for DH is costly and complex (Schmidt et al. 2020). The results leave no doubts about the high dependence of the technology on subsidies and on cost-sharing among project partners. Over the course of our data collection, we found that industrial companies use EHR for DH according to four business scenarios with different levels of engagement.

In business scenarios 1 and 2, a DH network might or might not already exist before EHR. In business scenarios 3 and 4, a DH network is constructed at the same time as the EHR project is implemented.

- Business scenario 1: The industrial company makes excess heat available to a DH operator and bears no or very limited project costs. The company might also enable the operator to do construction works on its property or to make technical adjustments to the existing company facilities. Maintenance works are usually handled by the company.
- Business scenario 2: The industrial company invests in the necessary technologies to decouple, recover and deliver excess heat such as a heat exchanger, a heat pump, a condenser etc. Costs for connecting the plant to the existing network might be carried or shared by the industrial heat producer as well.
- Business scenario 3: The industry invests in its own utilities in order to recover excess heat at its site and is co-creator of the DH network.
- Business scenario 4: The industry invests in its own utilities in order to recover excess heat at its site and is the sole creator of the DH network.

Ten companies pursuing business scenario 1 and six companies pursuing business scenario 2 were identified. Business scenarios 3 and 4 seem to occur less often with three and one identified cases, respectively (n=45, unknown=24). Business scenarios 3 and 4 require much larger financial investments on the part of the industrial companies. Therefore, these results indicate that industries are more likely to use EHR for DH if they bear very few or no costs. In line with this result, opportunities to implement EHR for DH might be missed because of too high investment requirements.

Interviewees stressed that their project would not have been implemented if it were not expected to be profitable at least in the medium to long term. Long payback periods and high investments were identified as barriers to EHR for DH by 53% of the interviewed companies. The generally high investments required coupled with low revenues from selling excess heat lead to long payback periods. Interviewees emphasized that financial returns were not a core objective of EHR as the payback periods are unusually long for private industrial companies. 42% of the companies expected payback periods shorter than 4 years. 25% expected payback periods between 4 and 7 years, and 33% expected payback periods longer than 7 years (cf. Figure 37). These long payback periods for projects recovering and delivering EH reinforce the attractiveness of business scenario 1, in which companies bear very little project costs. The three companies with the shortest expected payback periods followed this scenario. Two companies with the highest payback periods implemented their project according to business scenario 4. As mentioned above, only a few companies implemented their project with the objective to generate additional income. However, the relative economic viability of the project was important to nearly all the interviewees. Companies would not have applied the technology if the project implied financial losses in the long run and care was taken to get the shortest payback periods possible.

At least 57% of the projects listed in our database were subsidized by the EU, or the national or regional government. In some instances, several public donors funded the project. 5 out of the 13 interviewed companies had received funds for their investment. 4 of them would not have implemented the technology without the subsidy. The hypothesis that industrial excess heat producers are more likely to engage with EHR for DH if it does not induce costs or require investments on their part can therefore be confirmed.

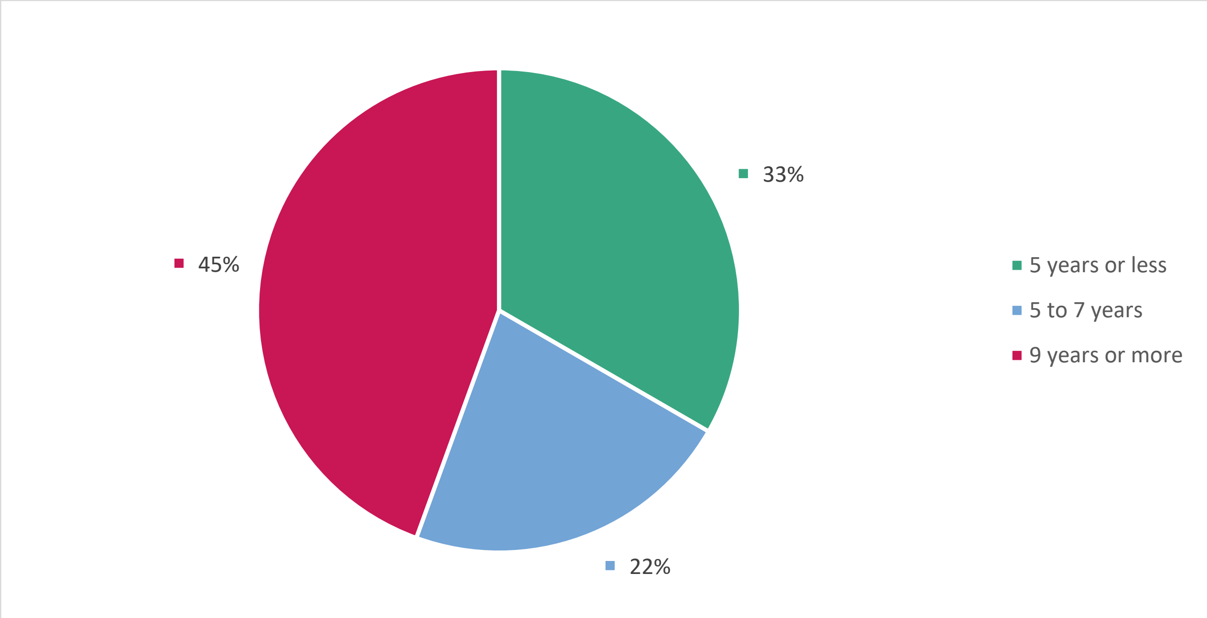


Figure 37: Payback periods expected by companies (in years) (n=9).

EHR for DH is more likely to be applied if a DH network is already in place

Figure 38 shows whether a DH network already existed before the use of industrial excess heat in the case studies identified. In 20 cases (44%), a new DH network was built simultaneously, and in 15 cases (33%), there was already an existing DH network before the EHR started. For 10 cases (22%), no information could be found. This means, that for one third of the examined cases, EHR for DH was applied with an existing DH network in place nearby. However, the construction or even a plan for a DH network can also trigger the recovery of EH for distribution. 38% (n=13) of respondents highlighted that the development or extension of a DH network near their company site sparked the first discussions and thoughts on whether to recover EH for external use or not. In the large majority of cases, establishing a DH network was embedded in a larger urban development project such as building a new residential area. In at least one third of the cases listed in the database, the DH network was developed at the same time as EHR for deliveries started. It cannot be ruled out that some DH networks were established because the excess heat potential was known, so causality between DH network construction and application of EHR for DH might be bidirectional. Nevertheless, the results certainly indicate that EHR for DH applications does not necessarily follow the establishment of a DH network.

Out of the 13 sites interviewed, 8 belonged to a larger company with other sites in Europe. 7 of them stated that they had recommended the recovery of excess heat for DH to other group entities. However, these attempts to replicate projects at other sites delivered mixed results: In two cases, a sister plant applied the technology shortly after hearing about the opportunity. In the five other cases, the technology has not yet been able to be applied. In addition to technical or political barriers, the lack of an existing DH network close to the plants contributed to some of these failed attempts to replicate EHR for DH projects. In summary, the absence of a DH network nearby can be a barrier for industrial companies to recover excess heat and deliver it to a DH network. However, and as mentioned above, it is still possible to plan EHR for DH even if a DH network does not already exist. DH networks can be planned and constructed at the same time as introducing EHR at the industrial site. Our fourth hypothesis can therefore not be confirmed.

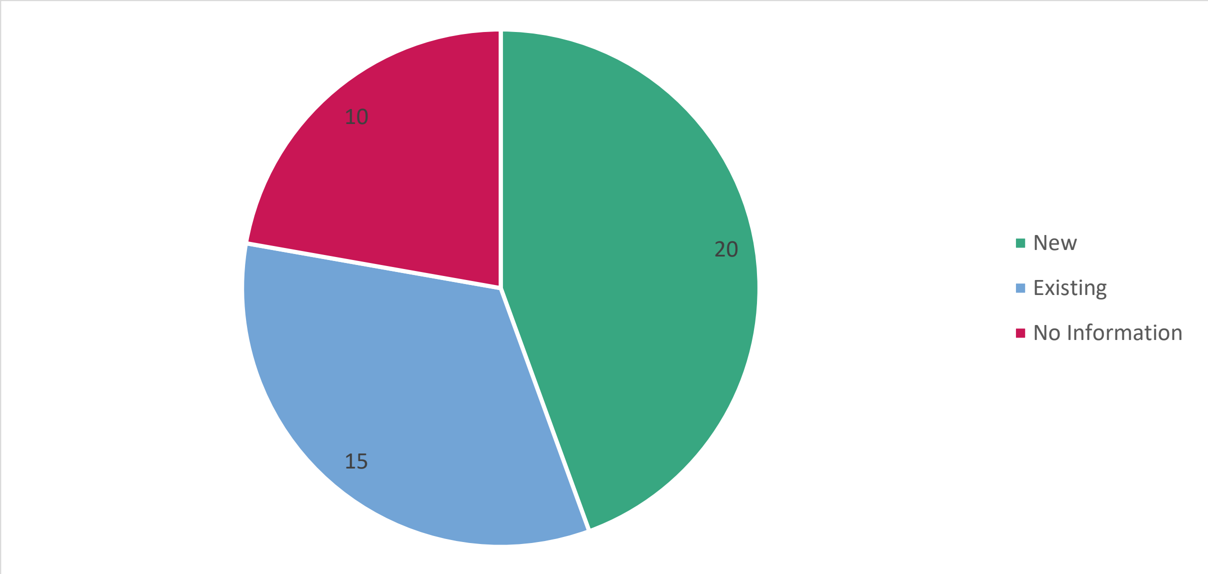


Figure 38: Share of technology applications according to the development stage of the DH when external EHR for DH recovery started (n=45).

EHR for DH is seen by industrial actors as a long-term solution for managing excess heat

Our analysis confirms the hypothesis that EHR for DH is considered by industrial actors as a long-term solution for managing the excess heat they produce. 77% of the responding industries understood EHR for DH as a long-term solution for EH management (cf. Figure 35). The long-term orientation of industrial actors engaging with EHR for DH is also reflected in the contractual arrangements framing the technology implementation. If a contract was signed with the DH utility, its duration was generally between 15 and 25 years.

How to manage their excess heat is an important topic for most energy-intensive industrial plants. Therefore, they welcomed the fact that EHR for DH offers a long-term solution to EH management. Indeed, producing excess heat can be costly, as the temperature and quality of excess heat that industries can release to the atmosphere are regulated. Having an outlet for excess heat reduces the amount of excess heat that has to be managed and disposed of and the amount of cooling required. Whenever industries use water for cooling the excess heat generated by their processes, delivering the heat to a DH network instead also saves water. Overall, implementing EHR for DH means long-term savings in terms of energy, water consumption, manpower and ultimately money. In specific cases, additional incentives for using EHR for DH were mentioned such as reducing noise levels at and around the industrial plant, or limiting the visible pollution from releasing EH to the atmosphere. In conclusion, the hypothesis can therefore be confirmed that industrial actors see EHR for DH as a long term solution.

6.5 Discussion and limitations

Our analysis is based on a literature research and data from qualitative interviews. A database was created with a total of 45 case studies on the use of industrial excess heat in DH networks. Due to the local character of using excess heat, a case-by-case approach is of great importance. The case studies were from Germany, Austria and France, so our findings are limited to these countries, but are in line with the results of previous studies in the literature which also examined other countries. It is therefore not expected that the identified enabling factors and barriers will differ greatly in other European countries. Nevertheless, national as well as regional regulations (including pricing strategies, technological standards, etc.) can have a major impact on using EHR for DH. For this reason, further research should investigate the relationship between the regulatory framework and the use of EHR for DH.

Five hypotheses were formulated based on desk research and the results from the database and tested in 13 interviews. Another possibility would be to identify further enabling factors and barriers based on the interviews. However, the sample size of our interviews is limited, which is why the focus was on the hypothesis testing method. Further research could also use structured questionnaires to explore enabling factors and barriers on a larger scale. The interview partners were evenly distributed across the sectors investigated. It should be noted that only industrial companies were interviewed that had already implemented projects and might be positively biased towards the technology. It is possible that industrial companies that have not yet had any experience with excess heat utilisation would perceive other enabling factors and barriers. Furthermore, representatives of French projects were not interviewed, so care should be taken when applying the conclusions drawn here to France.

"Windows of opportunity" are of great importance for using EHR for DH. The results of the interviews showed that the external framework conditions and regulation are often decisive for the use of excess heat. If a DH network is to be built or extended in the vicinity of the industrial company, or existing processes in the industrial plant are altered, this offers a good opportunity for EHR for DH. Projects are rarely implemented without such external "triggers". The analysis shows that EHR for DH is seen as a long-term solution for managing excess heat by industrial actors. However, European industry is currently undergoing major technological transformation in order to meet climate targets, and it is not yet clear in which direction the several industrial sectors will develop. In the current scenarios from literature, both electrified processes and processes based on synthetic gases are seen as possible developments (Fleiter et al. 2020; Herbst et al. 2021). Such long-term developments matter as different transformation options may in turn have different implications for excess heat management. Thus, the interaction between EHR for DH and industrial transformation could influence the perceptions of EHR for DH as a long-term solution for managing excess heat. Further research could analyse the influence of mega-trends in industry on the availability, quality and management of excess heat.

The existing database could also be expanded with case studies from other countries. Furthermore, additional interviews should be conducted with other relevant stakeholders such as DH network operators or local political representatives in order to obtain a more comprehensive overview of the motivations for and perspectives of EHR for DH. It should also be noted that the current transformation of industry is manifold. Many processes will be converted to renewable energies or electricity, which means that excess heat sources may be eliminated or new ones may be added such as data centres.

6.6 Policy implications and conclusions

Enabling factors and barriers to using excess heat for DH were analysed based on a literature review and stakeholder interviews. Our findings show that there are many barriers hindering the implementation of EHR for DH. From a policy perspective, our results demonstrate that the communication and exchanges between essential stakeholders are often insufficient, and that projects are often only initiated due to the engagement and determination of individuals. Therefore, EHR for DH should be supported by political actors in the future. Our results also indicate that the relevant stakeholders often do not know about the possibilities of EHR for DH. For this reason, the exchange between stakeholders should be facilitated, and best practice examples and guidelines should be made readily available. The barriers identified could be alleviated by creating or strengthening networks which bring together local political representatives, industries and DH network operators. In addition, sector-specific information regarding the feasibility and benefits of delivering EH to DH networks should be shared with industries. External actors such as chambers of industry and commerce, institutes of applied research, and local administrative bodies should be given the mandate to identify potential locations for EHR for DH and then to initiate dialogues and meetings between parties. Our results show that financial aspects are often not the main reasons for implementing EHR for DH, but they play an important role in decision-making. Projects must be profitable in the long term to be implemented. As a consequence, the lower the costs for the industrial company, the greater the willingness to deliver excess heat to a DH network. The high investments required and the long contract periods represent other major barriers. From a policy perspective, guidelines should be created here that make drafting contracts easier and give all the stakeholders involved more certainty in the process. The long-term management of excess heat and possible future process transformations should also be considered. In addition, the current regulations make it difficult for third parties to gain access to the DH network. It is currently very difficult for industrial companies to feed excess heat into a DH network if the DH network operator does not want this. For this reason, industrial companies should be offered energy audits that evaluate the use of their excess heat in a DH network. The decisive role played by local actors in EHR for DH, including DH operators, is confirmed by our results.

CRediT Author Statement

Markus Fritz: Conceptualization, Methodology, Validation, Data curation, Writing - Original draft preparation, Visualization. **Margaux Savin:** Formal Analysis, Investigation, Writing - Original draft support. **Ali Aydemir:** Validation, Writing - Review & Editing

Acknowledgements

We would like to thank all the interview partners for their time and insights into their companies. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6.7 Appendix 6A

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132370.

7 Synthesis

7.1 Contribution

This thesis aimed to determine the economic site-specific excess heat potential of industrial exhaust gases for residential heating based on different technologies and to provide recommendations for future dissemination. To answer the research questions, a method was developed that differed from existing publications in several respects. First, an intricately detailed spatial resolution was used. The data on excess heat-producing sites with site-specific accuracy were available, and the data on heat demand were available at a 100 × 100 m resolution. Second, the analysis considered several different transport technologies for utilising excess heat. In the literature, either different technologies have been investigated, or the excess heat potential has been determined based on single technologies. An analysis of the excess heat potential based on different technologies has not yet been performed. Third, the analysis of the excess heat potential considered the presence of sulphur dioxide in exhaust gas. In its presence, excess heat utilisation is much more complicated.

The results for the analysed data set indicated that the excess heat potential from industrial exhaust gases in Germany totalled about 37 TWh/a. The industrial subsector of “other non-metallic mineral products” held the most potential, with approximately 4 TWh/a. The spatial analysis results showed that in 61 municipalities, the annual amount of available excess heat is greater than the annual heat demand. Furthermore, the results of the technology comparison found that DH is, in many cases, an economical option for transporting heat. Nevertheless, heat transportation for short distances and low excess heat quantities is more favourable with other technologies. PCM is the economic technology for excess heat amounts lower than 700 MWh and transport distances lower than 7 km. The results of the bottom-up optimisation model indicated that for the cost optimisation, DH has the lowest LCOTH in about 75% of the cases. A cost threshold of 0.1 €/kWh of LCOTH resulted in a usable amount of excess heat of 12 TWh. When optimising the usable amount of excess heat, it became apparent that ESN and sorption technologies were also selected for having lower heat losses. In this case, the usable excess heat is about 17 TWh, but it should be noted that the LCOTH is much higher than the cost optimisation. In addition to technical and economic analyses, the results showed that actors play an essential role in implementing external excess heat projects. A project’s economic viability must be considered, but the expected profit is not decisive for its implementation. The existence of district heating networks is also not a mandatory prerequisite for project implementation, but long contract periods can be an enabling factor.

7.2 General discussion and recommendations for future research

This section includes an overarching discussion of the method used to answer the research question and the overarching assumptions. In addition, recommendations for future research are provided. The discussions and assumptions of the individual work steps can be found in Chapters 2–6.

A bottom-up optimisation model was developed to answer the main research question. The optimisation’s objective was to maximise excess heat usage under the consideration of a cost threshold or the minimisation of transport costs. A methodological alternative would involve adapting the objective of the optimisation to minimise greenhouse gas emissions or material consumption. Given the current political situation (the natural gas shortage in 2022), the aim to minimise heat losses and thus maximise excess heat use without considering a cost threshold would also be conceivable. The objective of using a cost threshold was chosen because the results from Chapter 6 indicated that the projects would not be implemented if they were not economically viable. The results also showed that the reasons for implementing the projects were often manifold. A simulation model would be more suitable for analysing the willingness to implement. One possible model is an agent-based model that maps the interactions and decisions of individual actors. Future research could perform this modelling and compare the results with the method presented here.

As described in Chapter 2, the results of the bottom-up analysis of the site-specific excess heat potential were used as input data for the model. Doing so has the advantage of providing real data on the flue gases' excess heat potential and the plants' respective operating hours. Other studies have used a top-down approach in which the respective excess heat quantities were determined based on the production volume. This approach has the advantage of requiring less data collection and allowing for excess heat that does not occur as exhaust gas to be considered. The disadvantage is that these values are often only estimates that do not correspond to reality and depend on the respective plant technologies.

Only the transport costs of the excess heat for the different transport technologies were calculated for the modelling. Thus, the investments in the buildings, the last metres of the distribution networks and the price of the excess heat were not considered. The results of the case study database from Chapter 6 indicated that the cost of excess heat can vary greatly depending on the company and that it is difficult to determine an all-inclusive price. Building on the transport costs determined in this thesis, future research should explicitly determine the costs for end consumers. To do so, all additional investments and the price of excess heat must be considered. Furthermore, the model used in this thesis did not perform an energy system optimisation. It was therefore not determind whether technologies other than excess heat could provide more economical residential heating, but an economic threshold was determined based on the current prices for fossil energy sources. If this value was exceeded, the excess heat from these sources was not used.

The modelling considered the transport costs up to the centre of residential areas, but not whether a heating network already existed in these areas. In reality, if a heating network already exists, the connection only has to occur up to a connection point, which reduces the transport distance and, subsequently, the transportation cost. Yet there is no comprehensive overview of existing heating networks in Germany in the literature. The AGFW database provides an overview of municipalities in Germany with a heating network, but the precise localisation of these networks with information on diameter, temperature and flow rate is unavailable. Future research should create a geo-referenced database of all existing district heating networks. This database could help future research not only in the specific field of excess heat but also in the broader field of heat transition.

Industrial excess heat amounts can change due to process or location changes. The energy system is undergoing a transition, and in many industries, there will be process changes that could reduce the amount of available excess heat. Industries may also relocate, as other locations provide better production conditions. The availability of areas for renewable energies or electrolysers could also be a decisive factor in the future. High energy prices in the year 2022 could lead to changes in industrial subsectors. It is conceivable that companies will further emphasise energy efficiency so that less energy is lost and less excess heat is available. This development occurred once before, during the oil crisis in the 1970s when nations were also attempting to reduce their energy consumption due to high energy prices (Klemeš and Kravanja 2013).

In Chapter 6, expert interviews were conducted to investigate enabling factors and barriers to using excess heat in district heating networks. Thirteen people working in companies that had already fed excess heat into district heating networks were interviewed. A survey would also have been possible to achieve a larger sample size, thus reaching more people, including those from companies that do not yet use excess heat. The disadvantage of a survey is that individual projects and solutions could not be addressed. Future research should investigate why companies decided not to use excess heat externally. Interviews could be conducted with companies that have decided against the external use of excess heat, or a broad survey could be performed via a questionnaire. A fascinating aspect of this survey is the opinions of companies on innovative technologies that are not district heating.

The results from Chapter 6 also align with those from the literature on barriers to general energy efficiency measures. The most frequently mentioned barriers are a lack of information, organisational problems and financial, political and technical challenges (Reddy 2013). As the analyses from Chapter 6 indicated, economic efficiency is an important prerequisite but often not the reason for implementing excess heat recovery projects. Often, the “window of opportunity” is a more significant driver for implementing excess heat recovery projects. Future work could investigate how companies can be supported to implement efficiency measures outside of the “window of opportunity.”

The method used to answer the research questions and the assumptions made were based on German conditions. In principle, the results are transferable to other countries, although some assumptions differ. The most significant adjustment would have to be made in the assumed prices for the individual technologies. The civil engineering costs of installing pipes are particularly relevant here, as local conditions impact them. The assumptions for individual technologies’ flow and return temperatures can also vary widely among other countries. Depending on the outdoor temperature, the heat losses for DH and ESN technologies can also differ significantly. In southern countries with higher temperatures, the losses will be lower; in northern countries with lower temperatures, the losses will be greater. Ultimately, though, the method is transferable to other countries with adjustments to prices and the indicators of the individual technologies.

7.3 Conclusions

The main goal of the thesis was to determine the industrial excess heat potential in Germany for residential heating. Different transport technologies for excess heat were considered, and the enabling factors and barriers to implementation were analysed.

The methodological conclusion is that bottom-up analyses are preferable to top-down analyses when calculating excess industrial heat. The results from Chapter 2 indicated that this excess heat potential varies widely, depending on the municipality. Many municipalities have considerable excess heat potential, but there are also municipalities without excess heat. Thus, industrial excess heat utilisation, like the entire heat transition, is a local task.

In conclusion, Germany has a significant excess heat potential of 37 TWh/a. In some municipalities, the annual excess heat potential exceeds the annual heat demand. Excess heat should be used more in these municipalities. It should be noted, though, that heat storage is necessary for full utilisation, as many industrial plants do not operate continuously throughout the year.

Currently, district heating is mainly used to transport heat. The results from Chapter 3 indicated that DH is technically feasible and the most economical of the technologies for many applications. Nonetheless, in some cases, other technologies can also be advantageous. The use of other technologies, such as phase change materials, is more economical, especially in areas with small excess heat quantities and short transport distances. Accordingly, the best solution for each industrial excess heat source should be examined on a site-specific basis.

The barriers to implementing projects for excess heat utilisation are similar to the general barriers to implementing energy efficiency measures. Often, these projects fail due to a lack of economic efficiency, too long amortisation periods or no “window of opportunity”. In contrast to other energy efficiency measures, communication and exchange among essential stakeholders are significant barriers to the external use of excess heat. Consequently, the interaction between stakeholders should be facilitated (peer-to-peer learning), and best practices, guidelines and targets should be readily available.

Even though industrial excess heat utilisation has been researched for several decades, only a few projects have been implemented in Germany, in which industrial excess heat is fed into district heating networks. Thus, this thesis must be understood as preliminary theoretical that provides essential insight into evaluating the potential for industrial excess heat utilisation. The technologies for utilising industrial excess heat are available; the next steps should be market penetration and upscaling.

7.4 Policy recommendations

The previous section provided an overview of promising research fields for utilising industrial excess heat for residential heating. This section suggests policy recommendations to support the utilisation of industrial excess heat for residential heating.

Actors in industrial companies often lack the necessary knowledge to implement projects using industrial excess heat. Therefore, additional training or consulting programmes should be implemented that address industrial excess heat utilisation. Direct implementation options and funding programmes should also be considered. If the external use of excess heat in heat networks is an option for companies, consulting companies should directly contact energy suppliers and share the results of the consultation.

The cooperation of individual stakeholders is a significant challenge. Thus, as noted in the previous paragraph, strengthening the exchange between stakeholders is crucial. Either companies or third parties can undertake this strengthening. Energy consultants, energy agencies or local climate protection managers can assume this role.

In the federal state of Baden-Württemberg in Germany, industrial companies are obliged to submit their energy consumption, heat energy demand and excess heat quantities upon request. Thus, the information is only transmitted if it is explicitly requested. For the long-term planning of the heat supply, the information on the excess heat generated by municipal industrial companies should be provided automatically. This regulation should also be extended throughout Germany to reduce municipalities' administrative efforts and to provide a more comprehensive database for excess heat use.

In the EU, hence in Germany, all companies not considered small or medium-sized must regularly perform energy audits (cf. Art 8 EED). The focus of these energy audits is to identify the internal savings potential of the companies. As an extension, an obligation could be introduced to audit the external use of excess heat.

The results from Chapter 6 showed that many companies believe there are too few "best-practice" examples for the successful external use of excess heat. Consequently, successful projects should be further promoted and advertised through funding and communication programmes.

8 Appendix

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Abbreviations

CAPEX	capital expenditure
COP	Coefficient of performance
DH	District heating
EED	Energy efficiency directive
EHR	Excess heat recovery
ESN	Excess heat distribution through sewer networks
EU	European Union
GHG	Greenhouse gas
LCOTH	levelized costs of transported heat
OPEX	operating expenditure costs
PCM	Phase Change Materials
UWWTD	Urban Waste Water Treatment Directive

References

AGEB (2021): Anwendungsbilanzen zur Energiebilanz Deutschland. Endenergieverbrauch nach Energieträgern und Anwendungszwecken. Available online at https://ag-energiebilanzen.de/wp-content/uploads/2020/10/ageb_20v_v1.pdf, checked on 7/12/2022.

AGFW (2021): Pauschalierte Kennwerte. Edited by AGFW. Available online at https://www.fw704.de/hauptmenue/kennwerte/pauschalierte-kennwerte/, checked on 30.01.21.

Alibaba.com: Sodium Acetate Trihydrate. Available online at https://german.alibaba.com/product-detail/sodium-acetate-trihydrate-acetic-acid-powder-sodium-salt-preservative-cas-no-127-09-3-60578753182.html, checked on 1/22/2021.

Allen, Mike (2017): Hypothesis Formulation. In Mike Allen (Ed.): The SAGE Encyclopedia of Communication Research Methods. 2455 Teller Road, Thousand Oaks California 91320: SAGE Publications, Inc. Available online at https://methods.sagepub.com/reference/the-sage-encyclopedia-of-communication-research-methods/i6391.xml.

Ammar, Yasmine; Chen, Yi; Joyce, Sharon; Wang, Yaodong; Roskilly, Antony P.; Swailes, David (2013): Evaluation of low grade heat transport in the process industry using absorption processes. In *Applied Thermal Engineering* 53 (2), pp. 217–225. DOI: 10.1016/j.applthermaleng.2012.04.056.

Aydemir, Ali (2018): Ermittlung von Energieeinsparpotenzialen durch überbetriebliche Wärmeintegration in Deutschland. Dissertation. Technische Universität Darmstadt.

Aydemir, Ali; Fleiter, T.; Schilling, D.; Fallahnejad, Mostafa (2020): 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: online* 30.

Aydemir, Ali; Fritz, Markus (2020): Estimating excess heat from exhaust gases: why corrosion matters. In *Energ. Ecol. Environ.* 5 (5), pp. 330–343. DOI: 10.1007/s40974-020-00171-5.

Aydemir, Ali; Hilgenfeldt, Verena; Hillenbrand, Thomas; Hohmann, Claudia, Menger-Krug, Eve; Niederste-Hollenberg, Jutta (2019): Innovative Abwärmenutzung durch Wärmeverteilung über die Kanalisation „InnoA2“. Teil ½.

Aydemir, Ali; Rohde, Clemens (2018): What about heat integration? Quantifying energy saving potentials for Germany. In *ECEEE Industrial Summer Study Proceedings; European Council for an Energy-Efficient Economy—ECEEE: Berlin, Germany*, pp. 197–205.

BCG (2021): Klimapfade 2.0. Ein Wirtschaftsprogramm für Klima und Zukunft. BDI. Available online at https://issuu.com/bdi-berlin/docs/211021_bdi_klimapfade_2.0_-_gesamtstudie_-_vorabve.

Berding Beton (2019): B-K-GM mit integrierter Dichtung, DIN EN 1916/DIN V 1201-Typ 2. Berding Beton. Available online at https://www.berdingbeton.de/produkte/produkte-oeffentlicher-, checked on 1/7/2019.

Bergmeier, Monika (2003): The history of waste energy recovery in Germany since 1920. In *Energy* 28 (13), pp. 1359–1374.

Bianchi, Giuseppe; Panayiotou, Gregoris P.; Aresti, Lazaros; Kalogirou, Soteris A.; Florides, Georgios A.; Tsamos, Kostantinos et al. (2019): Estimating the waste heat recovery in the European Union Industry. In *Energ. Ecol. Environ.* 4 (5), pp. 211–221. Available online at https://link.springer.com/article/10.1007/s40974-019-00132-7.

Bieker, Susanne; Fritz, Markus; Hohmann, Claudia; Aydemir, Ali; Schratz, Udo; Müller, Philipp et al. (2021): InnoA2-Up. Umsetzungsplanung für Pilotanlagen zur innovativen Abwärmenutzung und-verteilung über die Kanalisation. Endbericht.

Bischof, Wolfgang (1993): Abwassertechnik. 10. Aufl. Stuttgart: Teubner.

Blömer, Sebastian; Götz, Christian; Pehnt, Martin; Hering, Dominik; Ochse, Susanne; Hespeler, Sabrina et al. (2019a): 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. Heidelberg. Available online at https://www.ifeu.de/fileadmin/uploads/Schlussbericht_EnEffW%c3%a4rme-NENIA.pdf.

Blömer, Sebastian; Hering, Dominik; Thomassen, Peter; Jäger, Stefan; Götz, Christian; Pehnt, Martin et al. (2019b): 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, BMWi. Heidelberg, Leimen, Rostock. Available online at https://www.ifeu.de/fileadmin/uploads/Schlussbericht_EnEffW%C3%A4rme-NENIA.pdf.

BMEnet GmbH (2020): BME-Marktinformationen Frachten 3/2020. Straßengüterverkehr national und international. Available online at https://www.bme.de/marktinformationen-frachten-erschienen-preise-weiter-leicht-gesunken-3609/.

BMWi (2019): Energieeffizienzstrategie 2050. Available online at https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/energieeffiezienzstrategie-2050.pdf?__blob=publicationFile&v=12.

BMWK (2021): Deutsche Klimaschutzpolitik. Verbindlicher Klimaschutz durch das Bundes-Klimaschutzgesetz. Available online at https://www.bmwk.de/Redaktion/DE/Artikel/Industrie/klimaschutz-deutsche-klimaschutzpolitik.html#:~:text=Mit%20dem%20novellierten%20Gesetz%20wird,2045%20Treibhausgasneutralit%C3%A4t%20verbindlich%20erreicht%20werden.

Böhm, Hans; Moser, Simon; Puschnigg, Stefan; Zauner, Andreas (2021): Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials. In *International journal of hydrogen energy* 46 (63), pp. 31938–31951.

Braun, Marco; Bohlayer, Markus; Fleschutz, Markus; Steinbach, Jan (2019): Überbetriebliche Nutzungindustrieller Abwärme. Leitfaden für Kommunen. Available online at https://www.interflex4climate.de/images/PDF/Leitfaden.pdf.

Brückner, Sarah (2016): Industrielle Abwärme in Deutschland. Technische Universität München.

Brückner, Sarah; Liu, Selina; Miró, Laia; Radspieler, Michael; Cabeza, Luisa F.; Lävemann, Eberhard (2015): Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. In *Applied energy* 151, pp. 157–167.

Brueckner, Sarah; Arbter, Rene; Pehnt, Martin; Laevemann, Eberhard (2017): Industrial waste heat potential in Germany—a bottom-up analysis. In *Energy Efficiency* 10 (2), pp. 513–525.

Castro Flores, Jose Fiacro; Rossi Espagnet, Alberto; Chiu, Justin NingWei; Martin, Viktoria; Lacarrière, Bruno (2017): Techno-Economic Assessment of Active Latent Heat Thermal Energy Storage Systems with Low-Temperature District Heating. 5-18 Pages / International Journal of Sustainable Energy Planning and Management, Vol 13 (2017) / International Journal of Sustainable Energy Planning and Management, Vol 13 (2017). DOI: 10.5278/IJSEPM.2017.13.2.

Chinese, Damiana; Santin, Maurizio; Angelis, Alessandra de; Saro, Onorio; Biberbacher, Markus (2018): What to do with industrial waste heat considering a water-energy nexus perspective: ECEEE Industrial Summer Study in Berlin (Proceedings 2018).

Chiu, J.NW.; Castro Flores, J.; Martin, V.; Lacarrière, B. (2016): Industrial surplus heat transportation for use in district heating. In *Energy* 110, pp. 139–147. DOI: 10.1016/j.energy.2016.05.003.

Chopde, Nitin R.; Nichat, Mangesh (2013): Landmark based shortest path detection by using A* and Haversine formula. In *International Journal of Innovative Research in Computer and Communication Engineering* 1 (2), pp. 298–302.

Colmenar-Santos, Antonio; Rosales-Asensio, Enrique; Borge-Diez, David; Blanes-Peiró, Jorge-Juan (2016): District heating and cogeneration in the EU-28. Current situation, potential and proposed energy strategy for its generalisation 62, pp. 621–639.

Colmenar-Santos, Antonio; Rosales-Asensio, Enrique; Borge-Diez, David; Mur-Pérez, Francisco (2015): Cogeneration and district heating networks: Measures to remove institutional and financial barriers that restrict their joint use in the EU-28. In *Energy* 85, pp. 403–414.

Cooper, Samuel J. G.; Hammond, Geoffrey P.; Norman, Jonathan B. (2016): Potential for use of heat rejected from industry in district heating networks, GB perspective. In *Journal of the Energy Institute* 89 (1), pp. 57–69.

da Cunha, Sandra Raquel Leite; Aguiar, José Luís Barroso de (2020): Phase change materials and energy efficiency of buildings: A review of knowledge. In *Journal of Energy Storage* 27, p. 101083. DOI: 10.1016/j.est.2019.101083.

Dahash, Abdulrahman; Ochs, Fabian; Janetti, Michele Bianchi; Streicher, Wolfgang (2019): Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems. In *Applied energy* 239, pp. 296–315.

Danish Energy Agency (2021): Technology Data for Individual Heating Plants. Danish Energy Agency and Energinet. Available online at https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-individual-heating-plants.

Deckert, Marco; Scholz, Rainer; Binder, Samir; Hornung, Andreas (2014): Economic Efficiency of Mobile Latent Heat Storages. In *Energy Procedia* 46, pp. 171–177. DOI: 10.1016/j.egypro.2014.01.170.

Döing, Mark; Kabasci, Stephan; Krassowski, Joachim; Pastorelli, Guiseppe; Merrettig-Bruns, Ute; Larsen (2006): Marktstudie kommunale Kläranlagen in Europa: Anlagen - Marktvolumina - Hersteller - Trends.

Dunkelberg, Elisa; Gährs, Swantje; Weiß, Julika; Salecki, Steven (2018): Wirtschaftlichkeit von Mehrleiter-Wärmenetzen. Edited by IÖW. IÖW (Schriftenreihe des IÖW, 215/18). Available online at https://www.ioew.de/fileadmin/user_upload/BILDER_und_Downloaddateien/Publikationen/2018/IOEW-SR_215_Wirtschaftlichkeit_Mehrleiter-W%C3%A4rmenetze.pdf, checked on 1/30/2021.

European Commission (2016): EU strategy on heating and cooling. European Parliament resolution of 13 September 2016 on an EU Strategy on Heating and Cooling (2016/2058(INI)). In *Official Journal of the European Union*. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016IP0334&rid=5.

European Commission (2018): Heating and cooling. Edited by European Commission. Available online at https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling, checked on 1/14/2018.

European Environment Agency (2020): Final energy consumption by sector and fuel in Europe. Edited by EEA. Available online at https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-10/assessment, checked on 11/16/2020.

eurostat (2021a): Electricity price statistics. Edited by eurostat. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics.

eurostat (2021b): Natural gas price statistics. Edited by eurostat. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics.

eurostat (2022): Energy statistics - an overview. eurostat. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview, updated on February 2022, checked on 5/25/2022.

Fang, Hao; Xia, Jianjun; Zhu, Kan; Su, Yingbo; Jiang, Yi (2013): Industrial waste heat utilization for low temperature district heating. In *Energy policy* 62, pp. 236–246. DOI: 10.1016/j.enpol.2013.06.104.

Fito, Jaume; Hodencq, Sacha; Ramousse, Julien; Wurtz, Frederic; Stutz, Benoit; Debray, François; Vincent, Benjamin (2020): Energy-and exergy-based optimal designs of a low-temperature industrial waste heat recovery system in district heating. In *Energy Conversion and Management* 211, p. 112753.

Fleiter, Tobias; Rehfeldt, Matthias; Neuwirth, Marius; Herbst, Andrea (2020): Deep decarbonisation of the German industry via electricity or gas? A scenario-based comparison of pathways. Available online at https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2020/6-141-20_Fleiter.pdf.

Forman, Clemens; Muritala, Ibrahim Kolawole; Pardemann, Robert; Meyer, Bernd (2016): Estimating the global waste heat potential. In *Renewable and Sustainable Energy Reviews* 57, pp. 1568–1579.

Fritz, Markus; Aydemir, Ali (2019): Don't waste the water, use wastewater - excess heat distribution for private households through sewer networks: ECEEE (eceee Summer Study 2019. Proceedings).

Fritz, Markus; Aydemir, Ali; Schebek, Liselotte (2022a): How much excess heat might be used in buildings? - A spatial analysis at municipal level in Germany. In *Energies*. DOI: 10.3390/en15176245.

Fritz, Markus; Plötz, Patrick; Schebek, Liselotte (2022b): A Technical and Economical Comparison of Excess Heat Transport Technologies. In *Renewable and Sustainable Energy Reviews* (168). DOI: 10.1016/j.rser.2022.112899.

Fritz, Markus; Savin, Margaux; Aydemir, Ali (2022c): Usage of excess heat for district heating - analysis of enabling factors and barriers. In *Journal of cleaner production* (363). DOI: 10.1016/j.jclepro.2022.132370.

Fritz, Markus; Werner, Dorian (2022): Industrial excess heat and residential heating: Potentials and costs based on different heat transport technologies. In *Sustainability and Innovation* 11. Available online at https://www.isi.fraunhofer.de/content/dam/isi/dokumente/sustainability-innovation/2022/WP11-2022_Industrial_excess_heat_and_residential_heatings.pdf.

Gao, J. T.; Xu, Z. Y.; Chiu, J.N.W.; Su, Chang; Wang, R. Z. (2019): Feasibility and economic analysis of solution transportation absorption system for long-distance thermal transportation under low ambient temperature. In *Energy Conversion and Management* 196, pp. 793–806. DOI: 10.1016/j.enconman.2019.06.052.

Groß, B.; Tänzer, G. (2010): Industrielle Abwärme-Eine Potentialstudie für Deutschland. In *IZES-Institut für ZukunftsEnergieSysteme, Saarbrücken*.

Hasegawa, Hideo; Ishitani, Hisashi; Matsuhashi, Ryuji; Yoshioka, Michifumi (1998): Analysis on waste-heat transportation systems with different heat-energy carriers. In *Applied energy* 61 (1), pp. 1–12.

Haustechnikshop24.eu: C-Stahlrohre. Available online at https://www.haustechnikshop24.eu/installation/rohre-fittinge/c-stahlrohr/c-stahlrohr/rohr-1-00-m.html, checked on 1/24/2021.

Hawkey, David; Webb, Janette (2012): Multi-level governance of socio-technical innovation: the case of district heating in the UK. In Contribution to the Jean Monnet International Workshop, Copenhagen Business School. University of Edinburgh. Available online at https://www.pure.ed.ac.uk/ws/portalfiles/portal/6365363/MLG_of_SocTech_Innovation.pdf.

Herbst, Andrea; Fleiter, Tobias; Rehfeldt, Matthias; Neuwirth, Marius; Fahl, Ulrich; Kittel, Lena; Hufendiek, Kai (2021): Deutschland auf dem Weg zur Klimaneutralität 2045-Szenarien und Pfade im Modellvergleich. Industriewende. Available online at https://ariadneprojekt.de/media/2021/10/Ariadne_Szenarienreport_Oktober2021_Kapitel4_Industriewende.pdf.

Hering, Dominik; Richter, Stephan; Blömer, Sebastian, Pehnt, Martin (2018): Industrielle Abwärmenutzung in Deutschland. Potenziale zur Nutzung in Wärmenetzen. In *EuroHeat&Power* 47. Jg (10), pp. 14–19.

Hirzel, Simon; Sontag, Benjamin; Rohde, Clemens (2013): Industrielle Abwärmenutzung. Edited by Fraunhofer ISI. Available online at https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2013/Kurzstudie_Abwaermenutzung.pdf, updated on 2013.

Horlacher, Hans-Burkhard; Helbig, Ulf (2018): Rohrleitungen 2: Einsatz, Verlegung, Berechnung, Rehabilitation: Springer-Verlag.

Hummel, Marcus; Kranzl, Lukas; Villotti, Carmen (2014): Assessment of the economic viability of the integration of industrial waste heat into existing district heating grids: ECEEE (Proceedings 2014).

Johnson, Ilona; Choate, William T.; Davidson, Amber (2008): Waste heat recovery. Technology and opportunities in US industry. BCS, Inc., Laurel, MD (United States).

Jouhara, Hussam; Khordehgah, Navid; Almahmoud, Sulaiman; Delpech, Bertrand; Chauhan, Amisha; Tassou, Savvas A. (2018): Waste heat recovery technologies and applications. In *Thermal Science and Engineering Progress* 6, pp. 268–289.

Kang, Byung Ha; Yabe, Akira (1996): Performance analysis of a metal-hydride heat transformer for waste heat recovery. In *Applied Thermal Engineering* 16 (8-9), pp. 677–690.

Kang, Y.T; Akisawa, A.; Sambe, Y.; Kashiwagi, T. (2000): Absorption heat pump systems for solution transportation at ambient temperature — STA cycle. In *Energy* 25 (4), pp. 355–370. DOI: 10.1016/S0360-5442(99)00070-5.

Kavvadias, Konstantinos C.; Quoilin, Sylvain (2018): Exploiting waste heat potential by long distance heat transmission: Design considerations and techno-economic assessment. In *Applied energy* 216, pp. 452–465. DOI: 10.1016/j.apenergy.2018.02.080.

Klemeš, Jiří Jaromír; Kravanja, Zdravko (2013): Forty years of heat integration: pinch analysis (PA) and mathematical programming (MP). In *Current opinion in chemical engineering* 2 (4), pp. 461–474.

Konstantin, Panos; Konstantin, Margarete (2018): Power and Energy Systems Engineering Economics: Best Practice Manual: Springer.

Langeheinecke, Klaus; Kaufmann, André; Langeheinecke, Kay; Thieleke, Gerd (2020): Thermodynamik für Ingenieure: Springer.

Lin, P.; Wang, R. Z.; Xia, Z. Z.; Ma, Q. (2009): Experimental investigation on heat transportation over long distance by ammonia–water absorption cycle. In *Energy Conversion and Management* 50 (9), pp. 2331–2339. DOI: 10.1016/j.enconman.2009.05.016.

Lin, P.; Wang, R. Z.; Xia, Z. Z.; Ma, Q. (2011): Ammonia–water absorption cycle: a prospective way to transport low-grade heat energy over long distance. In *Int. J. Low-Carbon Tech.* 6 (2), pp. 125–133. DOI: 10.1093/ijlct/ctq053.

Liu, Qiusheng; Yabe, Akira; Kajiyama, Shiro; Fukuda, Katsuya (2002): A review of study on thermal energy transport system by synthesis and decomposition reactions of methanol. In *JSME International Journal Series B Fluids and Thermal Engineering* 45 (3), pp. 473–480.

Lund, H.; Möller, B.; Mathiesen, B. V.; Dyrelund, A. (2010): The role of district heating in future renewable energy systems. In *Energy* 35 (3), pp. 1381–1390. DOI: 10.1016/j.energy.2009.11.023.

Lund, Henrik; Werner, Sven; Wiltshire, Robin; Svendsen, Svend; Thorsen, Jan Eric; Hvelplund, Frede; Mathiesen, Brian Vad (2014): 4^{th} Generation District Heating (4GDH). In *Energy* 68, pp. 1–11. DOI: 10.1016/j.energy.2014.02.089.

Lygnerud, Kristina; Wheatcroft, Edward; Wynn, Henry (2019): Contracts, Business Models and Barriers to Investing in Low Temperature District Heating Projects. In *Applied Sciences* 9 (15), p. 3142. DOI: 10.3390/app9153142.

Ma, Q.; Luo, L.; Wang, R. Z.; Sauce, G. (2009a): A review on transportation of heat energy over long distance. Exploratory development. In *Renewable and Sustainable Energy Reviews* 13 (6-7), pp. 1532–1540. DOI: 10.1016/j.rser.2008.10.004.

Ma, Qiang; Luo, Lingai; Wang, R. Z.; Sauce, Gérard (2009b): A review on transportation of heat energy over long distance. Exploratory development. In *Renewable and Sustainable Energy Reviews* 13 (6-7), pp. 1532–1540.

Ma, Zhiwei; Bao, Huashan; Roskilly, Anthony Paul (2017): Study on solidification process of sodium acetate trihydrate for seasonal solar thermal energy storage. In *Solar Energy Materials and Solar Cells* 172, pp. 99–107. DOI: 10.1016/j.solmat.2017.07.024.

Manz, Pia; Fleiter, Tobias; Aydemir, Ali (2018): Developing a georeferenced database of energy-intensive industry plants for estimation of excess heat potentials: ECEEE Industrial Summer Study in Berlin (Proceedings 2018).

Manz, Pia; Kermeli, Katerina; Persson, Urban; Neuwirth, Marius; Fleiter, Tobias; Crijns-Graus, Wina (2021): Decarbonizing District Heating in EU-27+ UK: How Much Excess Heat is Available from Industrial Sites? In *Sustainability* 13 (3), p. 1439. Available online at https://www.mdpi.com/2071-1050/13/3/1439.

Masatin, Vladislav; Latõšev, Eduard; Volkova, Anna (2016): Evaluation factor for district heating network heat loss with respect to network geometry. In *Energy Procedia* 95, pp. 279–285.

Mathiesen, Brian Vad; Bertelsen, Nis; Schneider, Noémi Cécile Adèle; García, Luis Sánchez; Paardekooper, Susana; Thellufsen, Jakob Zinck; Djørup, Søren Roth (2019): Towards a decarbonised heating and cooling sector in Europe. Unlocking the potential of energy efficiency and district energy. Available online at https://vbn.aau.dk/ws/portalfiles/portal/316535596/Towards_a_decarbonised_H_C_sector_in_EU_Final_Report.pdf.

Mazet, Nathalie; Luo, Lingai; Stitou, Driss; Berthiaud, Julien (2009): Feasibility of long-distance transport of thermal energy using solid sorption processes. In *Int. J. Energy Res.* 32 (7), n/a-n/a. DOI: 10.1002/er.1578.

Mazzeo, Domenico; Matera, Nicoletta; Luca, Pierangelo de; Baglivo, Cristina; Congedo, Paolo Maria; Oliveti, Giuseppe (2021): A literature review and statistical analysis of photovoltaic-wind hybrid renewable system research by considering the most relevant 550 articles: An upgradable matrix literature database. In *Journal of cleaner production* 295, p. 126070. DOI: 10.1016/j.jclepro.2021.126070.

Meggers, Forrest; Leibundgut, Hansjurg (2011): The potential of wastewater heat and exergy: Decentralized high-temperature recovery with a heat pump. In *Energy and Buildings* 43 (4), pp. 879–886.

Ministère de la transition écologique (2021): Programmations pluriannuelles de l'énergie (PPE). Available online at https://www.ecologie.gouv.fr/programmations-pluriannuelles-lenergie-ppe.

Miró, Laia; Brückner, Sarah; Cabeza, Luisa F. (2015): Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries. In *Renewable and Sustainable Energy Reviews* 51, pp. 847–855.

Miró, Laia; Gasia, Jaume; Cabeza, Luisa F. (2016): Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review. In *Applied energy* 179, pp. 284–301.

Moser, Simon; Lassacher, Simon (2020a): External use of industrial waste heat - An analysis of existing implementations in Austria. In *Journal of cleaner production* 264, p. 121531. DOI: 10.1016/j.jclepro.2020.121531.

Moser, Simon; Lassacher, Simon (2020b): External use of industrial waste heat - An analysis of existing implementations in Austria. In *Journal of cleaner production* 264, p. 121531. DOI: 10.1016/j.jclepro.2020.121531.

Müller, Karsten; Fabisch, Florian; Arlt, Wolfgang (2014): Energy Transport and Storage using Methanol as a Carrier. In *Green* 4 (1-6), pp. 19–25. DOI: 10.1515/green-2013-0028.

Müller, Philipp (2019): Innovative Abwärmenutzung durch Wärmeverteilung über die Kanalisation „InnoA2". Teilvorhaben: TEK - Technik, Effizienz, Koordinierung.

Nasako, K.; Ito, Y.; Osumi, M. (1998): Intermittent heat transport using hydrogen absorbing alloys. In *International journal of hydrogen energy* 23 (9), pp. 815–824.

Neuwirth, Marius; Fleiter, Tobias; Manz, Pia; Hofmann, René (2022): The future potential hydrogen demand in energy-intensive industries-a site-specific approach applied to Germany. In *Energy Conversion and Management* 252, p. 115052.

Nussbaumer, Thomas; Thalmann, Stefan (2014): Sensitivity of system design on heat distribution cost in district heating. In *International Energy Agency IEA Bioenergy Task, Swiss Federal Office of Energy & Verenum, Zürich*.

Nussbaumer, Thomas; Thalmann, Stefan; Jenni, Andres; Ködel, Joachim (2017): Planungshandbuch Fernwärme. Edited by EnergieSchweiz, Bundesamt für Energie BFE. Available online at https://www.energie-zentralschweiz.ch/fileadmin/user_upload/Downloads/Planungshilfen/Planungshandbuch_Fernwarme_V1.0x.pdf.

OpenStreetMap contributors (2021): Planet dump [Data file from Nov. 11 2021]. Retrieved from https://planet.openstreetmap.org.

Ott, Alexander (2019): Lambda-Werte von Baustoffen. Available online at http://www.bau-igel.de/bautab_2.php3, checked on 1/11/2019.

Päivärinne, Sofia; Hjelm, Olof; Gustafsson, Sara (2015): Excess heat supply collaborations within the district heating sector: Drivers and barriers. In *Journal of renewable and sustainable energy* 7 (3), p. 33117.

Pehnt, Martin; Bödeker, Jan; Arens, Marlene; Jochem, Eberhard; Idrissova, Farikha (2010): Die Nutzung industrieller Abwärme–technisch-wirtschaftliche Potenziale und energiepolitische Umsetzung. Bericht im Rahmen des Vorhabens „Wissenschaftliche Begleitforschung zu übergreifenden technischen, ökologischen, ökonomischen und strategischen Aspekten des nationalen Teils der Klimaschutzinitiative". Edited by ifeu, Fraunhofer ISI, IREES GmbH. Available online at https://www.ifeu.de/fileadmin/uploads/Nutzung_industrieller_Abwaerme.pdf, checked on 5/17/2022.

Persson, Urban; Möller, Bernd; Werner, Sven (2014): Heat Roadmap Europe: Identifying strategic heat synergy regions. In *Energy policy* 74, pp. 663–681.

Petersen, B. A. (2017): Handbook: Experiences from other urban waste heat recovery investments: 25 cases of urban waste heat recovery. In *ReUseHeat Project (D6. 1), Denmark*.

Pezzutto, Simon; Zambotti, Stefano; Corce, Silvia; Zambelli, Pietro; Garegnani, Giulia; Scaramuzzino, Chiara et al. (2019): Hotmaps - Open Data Set for the EU28. Hotmaps - D2.3 WP2 Report. Available online at 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.

Pirouti, Marouf; Bagdanavicius, Audrius; Ekanayake, Janaka; Wu, Jianzhong; Jenkins, Nick (2013): Energy consumption and economic analyses of a district heating network. In *Energy* 57, pp. 149–159. DOI: 10.1016/j.energy.2013.01.065.

Potsdam-Institut für Klimafolgenforschung (2019): Bodentemperatur. PIK Potsdam. Available online at https://www.pik-potsdam.de/services/klima-wetter-potsdam/klimazeitreihen/bodentemperatur/index_html, checked on 1/7/2019.

Prognos; Öko-Institut; Wuppertal-Institut (2021): Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Langfassung im Auftrag von Stiftung Klimaneutralität, Agora Energiewende und Agora Verkehrswende. Available online at https://www.agora-verkehrswende.de/fileadmin/Projekte/2021/KNDE_2045_Langfassung/Klimaneutrales_Deutschland_2045_Langfassung.pdf.

Ranjekar, Apoorva M.; Yadav, Ganapati D. (2021): Steam reforming of methanol for hydrogen production: A critical analysis of catalysis, processes, and scope. In *Industrial & Engineering Chemistry Research* 60 (1), pp. 89–113.

Reddy, B. Sudhakara (2013): Barriers and drivers to energy efficiency–A new taxonomical approach. In *Energy Conversion and Management* 74, pp. 403–416.

Rezaie, Behnaz; Rosen, Marc A. (2012): District heating and cooling: Review of technology and potential enhancements. In *Applied energy* 93, pp. 2–10.

Schmidt, Ralf-Roman; Geyer, Roman; Lucas, Pauline (2020): The barriers to waste heat recovery and how to overcome them? AIT; Euroheat & Power. Available online at https://ec.europa.eu/futurium/en/system/files/ged/20200625_discussion_paper_v2_final.pdf, checked on 5/17/2022.

Scholten, Volker; Timm, Manfred (1978): Survey of existing district heating systems. In *Nuclear Technology* 38 (2), pp. 178–186.

Schorn, Felix; Breuer, Janos L.; Samsun, Remzi Can; Schnorbus, Thorsten; Heuser, Benedikt; Peters, Ralf; Stolten, Detlef (2021): Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations. In *Advances in Applied Energy* 3, p. 100050.

statista (2020): Anzahl der Gemeinden in Deutschland nach Gemeindegrößenklassen. Available online at 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., checked on 5/16/2022.

Statistische Ämter des Bundes und der Länder (2020): Ergebnisse des Zensus 2011 - Wohnungen und Gebäude je Hektar. Ergebnisse des Zensus am 9. Mai 2011 in Gitterzellen. Available online at https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html, checked on 8/16/2022.

Steinbach, Jan; Popovski, Eftim; Henrich, Jasmin; Christ, Catrice; Ortner, Sara; Pehnt, Martin et al. (2021): 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. Available online at https://irees.de/wp-content/uploads/2021/03/Comprehensive-Assessment-Heating-and-Cooling_Germany_2020.pdf.

Sun, Fangtian; Fu, Lin; Sun, Jian; Zhang, Shigang (2014): A new waste heat district heating system with combined heat and power (CHP) based on ejector heat exchangers and absorption heat pumps. In *Energy* 69, pp. 516–524.

Sun, Zhuang; Aziz, Muhammad (2021): Comparative thermodynamic and techno-economic assessment of green methanol production from biomass through direct chemical looping processes. In *Journal of cleaner production* 321, p. 129023.

Thollander, Patrik; Danestig, Maria; Rohdin, Patrik (2007): Energy policies for increased industrial energy efficiency: Evaluation of a local energy programme for manufacturing SMEs. In *Energy policy* 35 (11), pp. 5774–5783.

Thomson, A.; Claudio, G. (2019): The Technical and Economic Feasibility of Utilising Phase Change Materials for Thermal Storage in District Heating Networks. In *Energy Procedia* 159, pp. 442–447. DOI: 10.1016/j.egypro.2018.12.042.

Umweltbundesamt (2022): Energieverbrauch nach Energieträgern und Sektoren. Available online at https://www.umweltbundesamt.de/daten/energie/energieverbrauch-nach-energietraegern-sektoren#allgemeine-entwicklung-und-einflussfaktoren, checked on 7/12/2022.

Vallade, Julien; Mazet, Nathalie; Neveu, Pierre; Stitou, Driss (2012): Comparative assessment of processes for the transportation of thermal energy over long distances. In *Int. J. Thermo* 15 (3). DOI: 10.5541/ijot.352.

Viklund, Sarah Broberg (2015): Energy efficiency through industrial excess heat recovery—policy impacts. In *Energy Efficiency* 8 (1), pp. 19–35.

Viklund, Sarah Broberg; Johansson, Maria T. (2014): Technologies for utilization of industrial excess heat: Potentials for energy recovery and CO2 emission reduction. In *Energy Conversion and Management* 77, pp. 369–379.

Wanner, Oskar; Delavy, P.; Eugster, J.; Panagiotidis, V.; Siegrist, H. (2004): Wärmerückgewinnung aus Abwassersystemen. In *Schlussbericht (Heat Recovery from Wastewater Systems. Final Report)*.

Wärff, Christoffer; Arnell, Magnus; Sehlén, R.; Jeppsson, U. (2020): Modelling heat recovery potential from household wastewater. In *Water Science and Technology* 81 (8), pp. 1597–1605.

Werner, Sven (2017): International review of district heating and cooling. In *Energy* 137, pp. 617–631. DOI: 10.1016/j.energy.2017.04.045.

Wetter, Christof; Brügging, Elmar; Willenbrink, Hinnerk; Russel-Wells, Klaus (2017): Wärmenetzbenchmark. Qualitativer Vergleich bestehender Wärmenetze. Available online at http://www.wiefm.eu/wp-content/uploads/2017/11/2018-02-20-Bericht-W%C3%A4rmenetzbenchmark_web.pdf.

Xu, Z. Y.; Wang, R. Z.; Yang, Chun (2019): Perspectives for low-temperature waste heat recovery. In *Energy* 176, pp. 1037–1043. DOI: 10.1016/j.energy.2019.04.001.

Yu, Y. Q.; Zhang, P.; Wu, J. Y.; Wang, R. Z. (2008): Energy upgrading by solid–gas reaction heat transformer: A critical review. In *Renewable and Sustainable Energy Reviews* 12 (5), pp. 1302–1324.

Zalba, Belén; Marı n, José Ma; Cabeza, Luisa F.; Mehling, Harald (2003): Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. In *Applied Thermal Engineering* 23 (3), pp. 251–283. DOI: 10.1016/S1359-4311(02)00192-8.