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Spatiotemporal and economic analysis of industrial excess heat as a resource for district heating

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Abstract

Industrial excess heat may often be utilised for district heating and thus replace existing expensive or CO₂-emitting technologies. Previous works analysed the distribution of excess heat by temperature intervals and their geographical distribution relative to district heating areas. A more detailed analysis of the most suitable types of industries and the costs is required, allowing a targeted exploitation of this resource. This work extends the spatial and thermodynamic analysis, to account for the temporal match between industrial excess heat and district heating demands, as well as the costs for implementation and operation of the systems. This allows the determination of cost-effective district heating potentials, as well as the analysis of different industries and technological requirements. The results show that the temporal mismatch between excess heat and district heating demand and lack of demand, reduces the theoretical substitution potential by almost 30 %. If heat storages are introduced, the total potential is reduced by only 10 %. A majority of the excess heat can be utilised at socio-economic heating costs lower than the average Danish district heating price and the cost of solar district heating. Excess heat from oil refineries, building material and food production can be utilised at the lowest specific

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costs.

Keywords: excess heat, industry, district heating, temporal analysis, spatial analysis, economic analysis

Nomenclature

A	Area, m^2	DRY	Design Reference Year
C	Costs, €	EH	Excess heat
$\bar{c}$	Weighted mean specific costs, $€MWh^{-1}$	EPRTR	European Pollutant Release and Transfer Register
c	Specific costs, $€MWh^{-1}$	GIS	Geographic information system
I	Investment costs, €	HD	Heating Demand
i	Interest rate, %	HP	Heat pump
LMTD	Logarithmic Mean Temperature Difference, K	TES	Thermal Energy Storage
N	Lifetime, years	yr	Year
Q	Heat, MWh	<i>Subscripts</i>	
$\dot{Q}$	Heat flow, kW	Demand	Demand limitation
P	Demand and supply profile, -	DH	District heat
S	Share, %	EH	Excess heat
T	Temperature, °C	f	Fixed
U	Overall heat transfer coefficient, $W m^{-2}K^{-1}$	H	Heat delivered
V	Volume, m^3	HEX	Heat exchanger
ΔT	Temperature difference, K	HP	Heat pump
η	Efficiency, -	k	Storage unit
γ	Scaling exponent, -	m	Mean difference
<i>Abbreviations</i>		min	Minimum
BBR	Danish Register of Buildings and Dwellings	n	year
CHP	Combined heat and power	OM	Operation and Maintenance
COP	Coefficient of performance	p	Industrial site
CRF	Capital recovery factor	Pipe	Transmission pipelines
DH	District heat	q	District heating area
DHW	Domestic hot water	ref	Reference
		Storage	Heat through storage
		t	Time step
		TES	Thermal energy storage
		v	Variable

1. Introduction

District heating is an important way of delivering heat to consumers in Denmark, where 63 % of the citizens were connected to district heating networks in 2016 [1]. In order to reduce the environmental impact of district heating (DH) in Denmark, the share of renewable DH based on solar energy and biomass was increased steadily over the last two decades according to the national energy statistics [2]. The share of renewable energy was already approximately 50 % in 2015, with a high share originating from combined heat and power plants. Several studies agree that district heating is expected to be one of the main elements of the future Danish energy system. However, in order to reach the goal of a 100 % renewable energy system before 2050 [3, 4], stronger efforts have to be undertaken to replace fossil and environmentally harmful energy sources. The increased utilisation of excess heat for district heating purposes could be a part of the solution. However, many reports and energy scenarios do not analyse the role of industrial excess heat for district heating or do not emphasise it, but only agree that DH should be expanded in the future. In 2015, 2 % of district heat (DH) was from excess heat.

According to a study by Münster et al. [5], district heating should be expanded to cover between 55 % and 57 % of the heating demand in Denmark. An analysis of a future 100 % renewable Danish energy system by Lund et al. [6] showed that an optimal DH share is between 63 % and 70 % of the future heating demand. Both works did not consider excess heat in particular in their analysis, though Lund et al. [6] mentioned it as being probably important. Möller and Lund [7] investigated the expansion of DH into natural gas areas and recommended to expand district heating to cover between 50 % and 70 % of the future heating demand. They assumed that excess heat can cover between 83 GWh and 153 GWh of the net heating demand each year. However, this assumption was not elaborated further. Mathiesen et al. [8] proposed a vision of a 100 % renewable Danish energy system in 2050 including a description of intermediate scenarios for 2015 and 2030. The proposed solution included a drastic expansion

of district heating networks until 2030. As a result, heat supply from district heating remained constant until 2050 despite significant heat savings. Industrial excess heat was not considered as an alternative to current DH production. Limiting biomass use for heating in a 100 % renewable energy system was analysed by Mathiesen et al. [9]. Industrial surplus heat of 2.65 TWh per year was included in the study and the results showed that it is economically feasible. In the analysis of energy scenarios up to 2020, 2035 and 2050 published by the Danish Energy Agency [10] industrial excess heat contributed to the production of DH with 0.89 TWh and 0.42 TWh per year in central and decentral DH areas, respectively. None of the studies discussed the role of industrial excess heat in more details.

There are several studies which quantified industrial excess heat (EH), also referred to as waste heat, and its theoretical utilisation potential on a national sector-specific level [11, 12, 13, 14]. For Sweden, Broberg et al. [15] performed in addition an economic analysis for five cases and different scenarios with respect to the future value of the EH. A positive net present value was obtained in almost all cases and scenarios over a conservative 20 year lifetime. Brückner et al. [16] studied the potential for heating and cooling applications more specifically, as well as the feasible investment costs for different technologies and consumers. Electric heat pumps were found to be profitable for all consumers, when operating hours exceeded 4000 hours per year.

For the UK, Hammond and Norman [17] estimated the excess heat potential and Cooper et al. [18] investigated the potential of using industrial excess heat for district heating based on location and demand side seasonal variations. A spatial model of industrial heat loads and technical recovery potentials in the UK, was made by McKenna and Norman [19]. Aydemir et al. [20] considered heat integration between companies, for which a method and spatial model for determining heating demands at industry locations was developed. Weinberger et al. [21] analysed different configuration for cooperation between EH and DH in a Swedish DH network, from economic and environmental perspectives. Their study showed that it is a benefit for the DH system to integrate an extended EH

supply to the DH network. Karner et al. [22, 23] considered multiple case studies in Austria, where synergies between industries and urban areas were possible. The synergies included amongst others the utilisation of waste heat for heating, cooling or electricity generation. Persson et al. [24] assessed theoretical annual excess heat volumes from fuel combustion in energy conversion and industrial facilities based on CO₂ emission data from the European Pollutant Release and Transfer Register (E-PRTR). A study by Lund and Persson [25] mapped potential heat sources for district heating in Denmark, which could be exploited by using heat pumps. Even though they focused on low-temperature sources, the theoretical maximum industrial excess heat potential found by [24] was used, not performing an individual assessment. The sub-annual temporal distribution and temperature levels of industrial EH were not considered in these studies.

Even though several studies [18, 19, 24, 25] focused on industrial excess heat utilisation using spatial models, it is necessary to include temperature levels of EH and district heating networks as well as detailed geographical and temporal analyses of sources and sinks to bring the theoretical potentials closer to the realisable ones. Other studies [15, 16] considered the economical feasibility, but did not take overall and sectoral potentials into account. It is further necessary to assess the socio-economic costs of excess heat utilisation on a national level in order to determine not only the technical, but also the economic potential. Several barriers were identified with respect to the utilisation of EH for DH. The location of the sources and lack of infrastructure were identified as particularly important [26]. In addition, a lack of knowledge of possible EH consumers and about available EH were identified by [27]. The authors suggested that future work should analyse the potentials and tools, which promote heat collaborations on a regional level.

The current work is based on Bühler et al. [28], who presented a method for distributing EH to individual production units and a spatial analysis of EH sources and DH user in Denmark. Their work showed that out of the maximum excess heat potential of 3.43 TWh, up to 1.36 TWh could be supplied to consumers. These values were found considering temperatures and potentials of EH

originating from thermal processes in 22 industry sectors adopted from [29, 30].

In addition, temperatures of DH networks, a maximum distance for connecting
 95 sources to DH areas and the maximum demand of the DH areas were considered.
 However, the excess heat sources and district heating demands were matched
 on an annual level. The current work improves [28] by analysing industrial EH
 and DH demands with hourly discretisation.

The main aim of this work is to assess the suitability of EH from specific indus-
 100 tries for district heating. This is done by determining to which degree industrial
 EH can be cost effectively utilised for district heating. To do so the thermody-
 namic properties of the heat sources and DH areas as well as their geographic
 location have to be taken into account. The temporal patterns of heat demand
 and EH availability are further required, to allow the analysis of required heat
 105 storages and temporal mismatches. Lastly, an economic analysis has to be per-
 formed based on investment and O&M costs of the heat recovery equipment. By
 taking these parameters into account it is possible to conduct detailed analyses
 of heat synergies between industries and heating areas. Among others, these
 analyses include the need for thermal storages, obtainable district heating costs
 110 and preferable industries.

The overall approach can be summarised as:

- (i) Presentation of a methodology for the analysis of the utilisation of indus-
 trial EH for district heating, including thermodynamic, spatial, temporal
 and economic parameters
- 115 (ii) Creation of hourly profiles for EH availability and DH demand
- (iii) Assessment and comparison of industrial groups towards their suitability
 of being used for district heat.
- (iv) Analysis of socio-economic heating costs of the utilised industrial EH

The present paper is structured as follows. Section 2 consists of the method,
 120 describing the model elements and assumptions. Section 3 presents the results
 including a sensitivity analysis of relevant parameters. At the end, the validity
 of the methods and results are discussed and conclusions are drawn.

2. Methods

First, the spatial and thermodynamic analyses are summarised based on the previous works. This is followed by a detailed description of the methods developed for the temporal and economic analysis, as well as indicators used to describe the quality of the EH utilization.

Figure 1 shows the main system elements and pathways considered in this work. Each industrial site can have multiple EH sources at different temperatures, which are used directly or through a thermal energy storage (TES) depending on the temporal profiles. A heat pump or a heat exchanger are used if the temperatures of the source and sink require it. Based on the geographic location (within or outside of DH areas), transmission pipes for the delivery of DH could be required.

Figure 1: Principle conversion pathways of industrial excess heat to district heat with components and their placement considered in this work.

2.1. Industry and Heating Areas

2.1.1. Industrial excess heat

The excess heat amounts and thermodynamic profiles used in this study were based on [29, 30]. This work considered only thermal process energy, i.e. only fuels and electricity used for e.g. drying, heating and distillation processes. Excess heat from buildings and electric equipment, such as compressors was not considered. The EH amounts were included for 22 industrial sectors which

represented 80 % of energy use in the Danish manufacturing industry in 2012 [31]. A distribution of EH to individual production sites in Denmark was a part of previous work [28]. The thermal process-related CO₂ emissions and number
 145 of employees were, among others, used as keys for the distribution.

The main assumptions and limitations of the preceding works for determining amounts, temperatures and spatial distribution of EH are summarised:

- Only thermal processes were considered. Based on the process temperature a direct heating efficiency between 70 % and 100 % was chosen. The
 150 resulting losses were distributed to up to three EH temperature levels per process.
- For each industry sector the dominating processes were considered, which increased the uncertainty of diverse sectors, such as "other food industry" and "production of paint, soap and more".
- 155 • The production of combined heat and power at industrial sites was neglected impacting the accessibility of boiler losses.
- EH amounts were directly correlated to CO₂-emissions and number of employees at individual production sites.

2.1.2. Spatial Analysis

160 The present paper takes the spatial analysis from Bühler et al. [28] as the point of departure, which included two constrained factors for the utilisation of EH for DH - the cut-off distance and the lack of demand. The cut-off distance refers to the maximum allowed distance between EH source and DH network, while the lack of demand refers to the cases in which EH from an industrial
 165 facility minus the transmission and distribution losses is larger than the heating demand in a DH area. The lack of demand was analysed in the present paper, while the DH costs were calculated instead of limiting the potentials with the cut-off distance. Therefore, the procedure was further developed in the present paper. The main additions are briefly summarized in the following:

- 170 1. Excess heat sources and official DH areas [32] were projected on top of
a background map in ArcGIS 10.4 [33]. Average annual efficiencies and
seasonal supply and return temperatures to DH areas were assigned [34].
2. The BBR¹ database with all buildings presented as points were projected
on top of the previous layers [35]. This layer contained information about
175 the buildings' heated area, use, construction year, etc. The specific heat-
ing demand (per m² and year) was assigned to every building based on the
construction period and use [36]. The annual heating demands of build-
ings were calculated as a product of its heated area and specific heating
demand.
- 180 3. For each EH source, the nearest DH area was identified. It was assumed
that the EH is always delivered to the nearest DH area.
4. As in [28], the deliverable EH amount accounted for transmission and
distribution losses.
5. Analogue to [28], the heating demand of buildings supplied by DH was
185 summarized to get the heating demand which could be supplied from in-
dustrial EH (directly or through a heat pump). Unlike in [28], only build-
ings supplied by DH were considered as a perspective heating demand.
6. Analogue to [28], the priority for supplying DH demand was given to direct
use of industrial EH. If there was DH demand left, its remaining part was
190 supplied through a heat pump.

2.1.3. Thermodynamic analysis

The utilisation of EH for district heating depends on the thermodynamic characteristics of the EH sources and heating demands. The temperatures of the heat source and sink, as well as the minimum temperature difference for the heat

¹BBR (in Danish "Bygnings- og Boligregistret") is an acronym for the Danish Register of Buildings and Dwellings

195 transfer, determine the thermodynamic utilisation potential and requirements for heat pumps. The temperature of the EH source was assumed to determine the carrier of excess heat (gas or water) and thus the minimum temperature difference, $\Delta T_{\min}$, obtainable in the heat exchanger. $\Delta T_{\min}$ was chosen to be 10 K for gases (EH above 60 °C) and 5 K for liquids (EH below 60 °C). It was
200 further assumed that gases may be cooled down to 40 °C and liquids may be cooled down to the average environmental condition which was set to be 15 °C.

It was further distinguished if the EH source could be utilised directly for district heating or if a heat pump was necessary. For the latter case, the Coefficient of performance (COP) of the heat pumps were based on the Carnot
205 COP, $\text{COP}_{\text{carnot}}$, and corrected by the heat pump efficiency, η_{HP} . A direct heat transfer is thermodynamically possible when the EH temperature, T_{EH} , is, $\Delta T_{\min}$ higher than T_{DH} . All other cases require a heat pump.

2.2. Temporal analysis

The temporal variations of heat demand and excess heat availability were
210 included in the present analysis to assess the temporal mismatches between supply and demand, the sizes of required thermal storages and the capacity of the components (heat pumps, heat exchangers and district heating pipes). The temporal variations of heat demands and EH have both an impact on the economic performance and the utilisation potential. As the district heating demands² and
215 industrial EH sources vary over a day, week and season, the temporal profiles used in this analysis had an hourly resolution over a year. The profiles with hourly resolution were created from hourly profiles for one representative week (Monday to Sunday) for each season (winter, spring, summer and autumn). A detailed description of the method and the profiles is given in the following.

²If not specified otherwise, heating demand is the sum of demand for space heating and domestic hot water.

220 2.2.1. Industry

This work considered 22 industries which can be divided into 43 sub-sectors. Based on similarities in the production processes of the sub-sectors, the industrial sectors were grouped into 11 categories (see Appendix A). The majority of the manufacturing industries can be described by production occurring in
 225 either one, two or three shifts. An additional load profile for one shift was used, when a base load exists. In addition, seasonal variations were included for industries, if applicable. Scheduled production stops, due to e.g. holidays or for maintenance, were not included.

To account for the relation between company size and production profile,
 230 the number of employees at each production site were used to determine the number of shifts for some industry categories. An overview of the categories and their profiles are given in Table 1. If more than one shift is given in the table, the company size was used to determine the number of shifts. The arrows further indicate if the production is higher or lower during certain seasons. The
 235 extent and quantification of seasonal distribution is presented in Appendix C. This quantification is specific to Denmark and the load profiles available for the reference year. The seasonal variation of the cement production could be greater, but was chosen constant due to a lack of data for the single site in Denmark.

240 The development of the profiles was based on industrial experience, available process information and data from the industry. Wiese and Baldini [37] created load profiles based on hourly natural gas consumption data over one year in Denmark, which were also available for a total of 17 subsectors used in this work. Each dataset was build of up to 6 production sites and was used to
 245 validate and refine the created profiles. The representative load profiles for 1, 2 and 3 shifts, as well as 1 shift with base load are shown in Figure 2. Each profile shown in the figure, distributes the weekly energy use on the hours of one week.

Table 1: Description of the temporal patterns for each industry category.

Industry Category	Week	Seasonal Variation
Gravel & Stone	1 Shift	Winter ↑↑
Oil Refineries	3 Shift	None
Food	1/2/3 Shifts	None
Sugar	2 Shifts	Autumn & Winter ↑↑
Wood, Pulp & paper	1/2/3 Shifts	None
Chemical & Pharmaceutical	1/2/3 Shifts	Winter ↑
Cement, Bricks & Rockwool	1/2/3 Shifts	None
Concrete products	1 Shift (base load)	Winter ↑
Asphalt	2 Shift	Winter ↓↓
Metal	3 Shift	None
Metalproducts	1/2/3 Shifts	None

2.2.2. Heating demand of district heating areas

250 For every district heating area, annual heating demands of buildings aggregated according to construction periods, use and whether they are supplied by district heating were calculated as described in Section 2.1.2. The distribution of the annual heating demand over one year followed two steps.

First, the buildings were aggregated into four groups according to common 255 use - residential, office & service, culture & public or leisure. The aggregation of 21 building uses into 4 was adopted from the BBR and presented in Appendix B.

Second, the heating demand was divided into demand for space heating and domestic hot water (DHW). The share of DHW demand on the annual level 260 was assumed to be 21 % for residential and leisure buildings and 10 % for office & service and culture & public [38]. Different hourly demand patterns were assumed for weekdays and weekend for each of the building groups. Around 80 % of the DHW demand was distributed to follow the daily living activities

Figure 2: Industrial load profiles for thermal processes based on the number of shifts at the industrial site.

and was independent of the outside air temperature. It was further assumed
 265 that the DHW demand was constant over the seasons. The remaining 20 %
 were uniformly distributed to the remaining hours. This was done to replicate
 the diversity within building groups. For example, even though most of the
 people sleep during night, some consumers require DHW in that period. The
 space heating demand constituted the remaining part of heating demand. Space
 270 heating demand depends on the heat loss through the elements of the buildings
 envelope, i.e. on the outside temperature. The outside temperatures were ob-
 tained from the Design Reference Year (DRY) dataset [39]. To illustrate how
 the aggregated heat demand profiles looked like, an example for the Ringkøbing
 DH network is shown in Figure 3. The heating demand in this network was
 275 constituted of 70 % residential, 20 % office & service, 8 % culture & public and
 2 % leisure users. The example presented in Figure 3 shows the distribution of
 annual heating demand over one week for each season. The artificially created
 heating demands were compared to samples from the actual heat load deliv-
 ered to the DH network. Examples are shown in Appendix D for a weekday
 280 and weekend in each season. All days were chosen as the third Monday of the

first month of each season. In addition, the data was compared on an annual level. The artificial profiles approximate the real ones and the seasons are in the same order of magnitude. The DH demand in the summer seems to be underestimated in the created profiles for the reference years and the specific case.

Figure 3: Annual distribution of DH demand in Ringkøbing, shown for one week in each season.

2.3. Economic Analysis

The economic analysis included the cost of equipment necessary to recover and transfer EH to DH areas. Investments in district heating pipelines were only needed if the EH source is located outside of existing DH areas. If the EH temperature was high enough to be used directly, heat pumps were not needed and only investments in heat exchanger installations should be made. Otherwise, investments in heat pumps were necessary. In the cases where there was a temporal mismatch between excess heat production and district heating demand, a thermal storage was needed additionally. This is also visualised in Figure 1. The investment costs of heat exchangers, heat pumps, pipes and thermal storages were assumed to depend on their required size to reflect the economy of scale, as described in more details in subsection 2.3.1.

For each match between EH source and DH area, an economic evaluation was performed. This evaluation was based on simplified socio economic principles, which exclude e.g. energy taxes and value added taxes. However, this analysis did not consider all externalities included in a socio-economic analysis, such as health and environmental effects. The aim was to determine the unit costs of the heat supplied and thus be able to benchmark EH to other heat sources, as well as to analyse the distribution of costs and compare between industrial sectors. The economic analysis was based on the investment costs, I , and the annual fixed and variable Operation & Maintenance (O&M) costs, $C_{f,OM}$ and $C_{v,OM}$. Investment costs were found for each match and included the DH pipes, heat exchangers, heat pumps and TES. For the operation of the system the electricity prices for heat pumps were used, together with maintenance costs for HP and heat exchangers as described in the following chapter. The simplified socio-economic unit costs of heat, c_H , were found with Eq. 1 as the sum of annuity of the investment costs and O&M costs over the lifetime divided by the annual DH production, Q_H . The capital recovery factor, CRF, used to annuitise the investment costs over the lifetime, n , was found using the interest rate, i as shown in Eq. 2.

$$c_H = \left(\text{CRF} \cdot I + \frac{\sum_{n=1}^N C_{f,OM,n} + C_{v,OM,n}}{N} \right) \frac{1}{Q_H} \quad (1)$$

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

A loan duration was chosen to be equal to the lifetime of the equipment (20 years), with a socio-economic interest rate i of 4 % [40]. All prices for equipment were adjusted to the reference year 2016 using the Chemical engineering plant cost index [41].

2.3.1. Cost estimation

DH pipes. The costs for DH pipes were taken from Nielsen and Müller [42], where the investment costs per meter of pipe were available for transmission capacities between 0.2 MW and 190 MW. Capacities in between the ones given

325 were found by linear interpolation and capacities outside were found by extrapolating using the Piecewise Cubic Hermite Interpolating Polynomial [43].

Heat exchanger. The investment costs for heat exchangers, used for the direct heat transfer from the EH source to the district heating network, $\dot{Q}_H$, were estimated based on the required heat transfer area A_{HEX} . Using Eq. 3, the
330 required area of the heat exchanger was found. The logarithmic mean of the temperature difference in counter-current heat exchanger, LMTD, was found for each match and EH temperature level. The DH supply and return temperature were known together with the ones of the EH source. It was assumed that the EH was rejected to the environment at a temperature of 10 K above the DH
335 return temperature. The overall heat transfer coefficient, U , was chosen for shell-and-tube heat exchanger, with gas at atmospheric pressure on the tube side and water on the shell side [44]. In this work it was set to $60 \text{ Wm}^{-2}\text{K}^{-1}$.

$$\dot{Q}_H = U A_{\text{HEX}} \text{LMTD} \quad (3)$$

For heat transfer areas below 80 m^2 the cost correlation established by Ommen et al. [45] and for areas above 80 m^2 the one presented in Andreasen et al. [46]
340 were used. Only fixed O&M costs were used for heat exchangers. These were set to $5000 \text{ € MW}^{-1} \text{ year}^{-1}$ [47].

Heat pump. The investment costs, economic and thermodynamic performance of the heat pump depend on many factors, such as the sink and source temperature, the temperature increase on the sink side, working fluid and compressor
345 type [48, 49]. To avoid the sizing of heat pump components for each match and temperature level, an approach relying on existing heat pump systems was chosen. The investment costs and operating conditions of 17 heat pumps utilizing EH between 25°C and 50°C , and delivering heat between 70°C and 85° were collected. This data was used to create a cost function for heat pumps. Because
350 the found heat pumps had relatively high heating capacities (above 420 kW), 12 additional ground water and air heat pumps with lower capacities were in-

cluded. The information about the heat pumps were available from previous projects and from the Danish Energy Agency [50, 51].

Figure 4: Analysis of the heat pump solutions.

From the fitted curves (Fig. 4), two cost functions were determined and used for the cost estimation. For heating capacities below 1.5 MW the fit function in Eq. 4 based on all heat pumps (Fit All) was used. For heat pumps with a higher capacity the fit function in Eq. 5 for was used based on the fit *EH HP*. These cost functions were also in accordance with the recommendation by the Danish Energy Agency [50], that for large heat deliveries, several heat pumps connected in series or parallel are used instead of increasing the size of the components. This typically leads to a cost increase between 70 % and 90 % for each doubling in capacity. Wolf et al. [52] analysed the costs for heat pumps from 8 manufacturers in the capacity range from 4.7 kW to 183 kW. For water-to-water heat pumps the cost curves show similar specific investment costs for very small sizes, however the decrease in costs is a lot stronger. Compared to Wolf et al. [52] the cost functions used in the present paper the investment costs are overestimated, however standard HP were used and units above 183 kW were said to be custom built.

$$c_{\text{HP}} = 1716 \cdot \dot{Q}_H^{-0.12} \quad (4)$$

$$c_{\text{HP}} = 8493 \cdot \dot{Q}_H^{-0.33} \quad (5)$$

370 The O&M costs for the heat pumps were estimated to be $2000 \text{ € MW}^{-1} \text{ year}^{-1}$ for fixed O&M and $2 \text{ € MWh}^{-1} \text{ year}^{-1}$ for variable O&M [51]. In addition, a net electricity price of 57 € MWh^{-1} and annual electricity price increases of 3.5% were used [53].

Thermal energy storage. The costs of the thermal energy storage were found 375 based on the volume of water which has to be stored. Three cost correlations were used to account for the different storage types. Vessels were used for volumes below 150 m^3 , tanks below 5000 m^3 and closed water pits for all other volumes. The required volume was based on the required energy to be saved and the temperature difference of the supply and return line of the given DH area. 380 The cost equation is shown in Eq. 6, where the total cost C_{TES} for the storage K depends on the reference storage size $V_{\text{TES,ref}}$, total reference costs $C_{\text{TES,ref}}$ and the scaling exponent γ . The reference values used are listed in Table 2. O&M costs were only included for storage tanks above 5000 m^3 and were 0.7% of the investment costs as recommended by the Danish Energy Agency [54].

$$C_{\text{TES},k} = C_{\text{TES,ref}} \left(\frac{V_{\text{TES},k}}{V_{\text{TES,ref}}} \right)^\gamma \quad (6)$$

Table 2: Data used for the investment cost estimation for TES.

V_{TES} [m ³]	$C_{\text{TES,ref}}$ [€]	γ [-]	$V_{\text{TES,ref}}$ [m ³]	Year	Source
< 150	10,000	0.65	10	2001	[55, 56]
< 5000	348,000	0.55	4000	2006	[57, 56]
> 5000	600,000	0.70	10000	2006	[57, 56]

385

2.4. Case evaluation

The spatial and thermodynamic operations described in Section 2.1 result in the maximum transferable amount of EH from each industrial site to the nearest DH area by direct heat transfer and through HPs. Using the temporal profiles established in Section 2.2 the total annual EH, Q_{EH} , for each industrial site p was distributed over the year as shown in Eq. 7. This was done by multiplying the hourly distribution, $P_{EH,t,p}$, with the annual EH amount. The total annual DH demand, Q_{DH} , was distributed over the hours of the year for each respective share of DH user, S_{DH} , using Eq. 8. This was done for each DH area q and type of DH use, r , as described in Section 2.2.2. The procedure was similar to the one for EH, using $P_{DH,t,r}$ of the HD distribution.

$$Q_{EH,t,p} = Q_{EH,p} \cdot P_{EH,t,p}, \text{ with } \sum_{t=1}^{8736} P_{EH,t,p} = 1 \quad (7)$$

$$Q_{DH,t,q} = \sum_{r=1}^4 S_{DH,r,q} \cdot Q_{DH,q} \cdot P_{DH,t,r}, \text{ with } \sum_{r=1}^4 \sum_{t=1}^{8736} P_{DH,t,r} = 1 \quad (8)$$

This distribution resulted in 2854 hourly time series for EH and 438 for the HD in each DH area. For each industrial site and its nearest DH area, a comparison of the hourly profiles was made, to find the direct EH utilisation and the requirement for TES. For each hour of the year, the share of DH coverable by (i) EH through direct heat exchange, (ii) EH through HP and (iii) EH from the TES was found. If the EH exceeded the HD during one hour t , the heat was added to the TES and was available for use from the next hour $t + 1$. EH from direct heat exchange was prioritised to the one from HP and TES. Furthermore, it was distinguished between storing EH requiring a HP and EH for direct heat transfer, as also shown in Fig. 1. If the TES had heat left at the end of the year ($t = 8736$), this heat was considered as unusable EH. Several iterations were required, setting the initial storage level in the new iteration to the last value of the preceding iteration.

The cost correlations in Section 2.3 used the capacity of the equipment. Transmission pipelines, heat exchanger and heat pumps were dimensioned based

on the maximum annual heat flows. The required TES size was found as the difference between the maximum storage level and the proceeding minimum.

415 2.5. Indicators

To compare the different industrial sectors according to their spatial, temporal, economic and thermodynamic suitability of delivering EH to DH areas, several indicators were introduced.

420 The indicator in Eq. 9 compares the maximum deliverable EH to DH after demand limitations in the DH areas were accounted for with the theoretical maximum EH potential.

$$S_{\text{demand}} = \frac{\text{EH to DH with demand constraints}}{\text{Theoretical maximum EH to DH}} 100\% \quad (9)$$

The second indicator in Eq. 10 describes the ratio of DH delivered through a thermal storage with the total DH delivered from an EH source. This indicator thus describes the temporal mismatch between heat sink and source.

$$S_{\text{storage}} = \frac{\text{EH to DH delivered through TES}}{\text{Total EH to DH}} 100\% \quad (10)$$

425 The third indicator (Eq. 11) describes analogue to second one, the share of DH delivered through a heat pump with the total DH delivered. As the amount of EH requiring a heat pump, depends on the relation between DH and EH temperature, this indicator compares the thermodynamic suitability.

$$S_{\text{HP}} = \frac{\text{EH to DH delivered through HP}}{\text{Total EH to DH}} 100\% \quad (11)$$

In Eq. 12 the COP of the heat delivered in each sector is shown.

$$\text{COP}_{\text{HP}} = \frac{\text{EH to DH delivered through HP}}{\text{Electricity needed for HP}} \quad (12)$$

430 In addition to these indicators, the weighted average mean specific heating cost, $\bar{c}_H$, was found for each industry category. Also the share of investment costs required for transmission pipelines, heat pump, heat exchanger and thermal storages was analysed.

3. Results

In the following, first an exemplary case for the spatio-temporal and economic analysis will be presented. This is followed by the aggregated results, indicators and economic analysis. Finally, the sensitivity analysis is presented.

3.1. Example case

To demonstrate the basis for the aggregated results, the evaluation of one industrial site is shown. This example case is a large meat processing plant located 3.2 km from the nearest DH area in Jutland, which had a supply and return temperature of 73 °C and 40 °C, respectively. In total 3300 MWh of EH were available each year of which 58 % were usable directly and the rest through a HP. In most cases the EH could not be used directly because the DH supply temperature (including the ΔT) was above the EH temperatures. The share of direct EH utilisation could be increased by combining direct heat transfer (e.g. preheating the DH water) and HP, however these configurations would require detail technical planning [58]. The HP would increase the EH temperatures of 50 °C with a COP of 5.8 and for EH at 60 °C with a COP of 6.3. This resulted in a total DH utilisation of 3500 MWh of which 2700 MWh were supplied to consumers after accounting for transmission and distribution losses. Around 14 % of the heat supplied to the DH users originated from the TES and 40 % from the HPs. An example of a daily heat balance for the case is shown in Fig. 5. During the presented hours, there was more EH than HD, which lead to EH being stored. When the EH amount reduced after 5 pm, some heat from the storage was used. It can be further seen that the HD was first covered by direct heat transfer, followed by DH through the HPs. The economic evaluation showed that a specific heating cost of 55 € per MWh would be achieved with investment costs of around 1.65 M€. The majority of the investment costs (49 %) were required for transmission pipes to the nearest DH area, followed by 41 % for the HPs, 7 % for heat exchangers and 3 % for the TES. The majority of the operation costs were for the HPs, which required more than 200 MWh of electricity per year. The heating price could be reduced to less than 31 € per MWh

if the investment only included EH sources which could be utilised without a
 465 heat pump.

Figure 5: Example of the heat flows and energy balances during one work day of the meat processing plant during summer.

3.2. Overall results

The results of the present study confirmed findings of [28] that a maximum of 1.88 TWh of DH (5.1 % of the DH demand in Denmark) could be supplied
 470 from EH without any demand or distance constraints. This total potential was reduced by 27 % (to 1.37 TWh) when the temporal mismatch between demand and supply was considered. However, if thermal storages with unlimited capacities were considered, the potential was only reduced by 10 % due to a lack of demand, i.e. due to instances in which there was more EH than there was a
 475 demand for DH.

3.3. Spatio-temporal analysis

In Table 3 the indicators defined in Section 2.5 are shown for all industry categories. Based on the value for S_{demand} it can be seen that the EH from the food and building material industries were subject to minor limitations

concerning the temporal patterns of EH and DH. This was in general due to constant production patterns of these industrial categories and the vicinity of DH areas with a high demand. The potential from oil refineries and metal production was, however, greatly reduced by the introduction of demand and temporal limitations. District heat supplied from EH from oil refineries and the cement production required large thermal storages, as more than 20 % of the DH was delivered indirectly. This was due to pronounced seasonality of these industries, as described in Table 1. The food, chemical and non-metal minerals supplied between 5 % and 10 % from thermal storages.

Table 3: Comparison of the utilisation potential of EH for DH by industry category based on the indicators defined in Section 2.5.

	S_{Demand} [%]	S_{Storage} [%]	S_{HP} [%]	COP_{HP} [-]
Gravel & Stone	93.4	12.9	60.2	4.8
Oil Refineries	75.4	19.3	82.3	5.6
Food	99.9	6.3	28.1	4.8
Sugar	100.0	0.9	29.9	2.6
Wood, Pulp & Paper	100.0	8.6	0.3	4.2
Chemical & Pharma	92.5	9.6	30.0	3.9
Cement, Bricks & Rockwool	94.8	31.1	13.3	4.3
Concrete products	100.0	1.6	18.5	6.3
Asphalt	100.0	7.2	33.9	7.5
Metal	75.0	6.4	6.4	4.6
Metal products	99.9	0.4	8.5	4.3

The share of heat supplied by a heat pump varied greatly, as presented in Figure 6. More than 50 % of DH in oil refineries and non-metal minerals was supplied by HPs. This share was below 10 % for wood, paper and metal production, which made them especially suitable for exploitation of EH for DH

since they did not require investments in heat pumps. The total COP for each category also shows that generally COPs above 4 can be expected, except for the chemical, pharma and sugar industry, where a larger share of low temperature EH was available.

Figure 6: Industrial load profiles for thermal processes based on the number of shifts at the industrial site.

3.4. Economic analysis

The heating costs were found for each match between EH source and nearest DH network according to the cost estimation in Section 2.3. Figure 7 shows the resulting cost curve for the heating prices below 150 € per MWh. For the values greater than 150 € per MWh the curve becomes nearly vertical. Figure 7a shows that approximately 1000 EH sources can deliver DH at a price below 53 € per MWh, which was the average DH price in Denmark in 2016 [59]. Figure 7b shows the heating prices for the cumulative DH generation from EH. Almost 1.5 TWh could be provided annually at a heating price below 53 € per MWh. This indicates that larger EH sources were more profitable to be exploited than the smaller ones and that the majority of the available EH can be used at DH

prices lower than the 2016 average in Denmark. In Figure 7b three flat parts of the curve can be identified, together representing around 0.75 TWh. These lines represent the three largest EH sources, namely cement production and oil refineries. All three sources can supply heat at comparably low heating prices. The weighted mean DH cost for all EH sources was found to be 35 € per MWh when including the cheapest 99 % of matches, which was cheaper than the average DH price in Denmark. The DH costs aggregated according to the industrial category can be found in Table 4.

Figure 7: Cost curve of the heating prices below 150 € per MWh.

The development of the Danish energy system towards renewable energy will lead to the change of DH prices. According to Ea Energianalyse [60] the future DH prices will be between 27.7 and 38.4 € per MWh in 2020 and will increase to between 32.6 and 45.7 € per MWh in 2035. It can be observed from Figure 7b, that these prices would result in a cost-effective potential of EH for DH between 1 and 1.5 TWh. Denmark experienced a strong growth of solar district heating installations in the last decade, increasing production by 16 times during the period [2]. The share of solar heating in district heating reached 2% in 2017. With 1.3 million m² of solar heating installations and

525 a population of 5.5 million, Denmark has the highest per capita area of solar heating collectors in the world. The favourable tax regime was one of the main reasons for its success. Therefore, the price of DH from EH was compared with solar DH. The cost for solar district heat, when considering a thermal storage covering 100 % of the demand, was 64.8 € per MWh only including the costs
 530 for the solar system and storage [54]. This lead to the assessment that the utilisation of industrial EH can probably be in several cases more favourable from a socio-economic perspective to the one of solar DH.

The distribution of the investment costs among the main system elements is shown in Table 4 and varied considerably among industry categories. Industries located far away from DH areas had a high share of investment costs in
 535 DH piping and tended to have a high cost for DH. The costs for thermal storages were only dominant for oil refineries and building materials, where large individual sources could be found which exceeded the demand during summer. The production of metal products required a large share of investment costs for
 540 piping. This was due to the relatively small size of thermal process related EH sources.

3.5. Sensitivity analysis

The performed analysis is subject to several degrees of uncertainty. Four major factors of uncertainty in the determination of the heating costs were
 545 investigated, namely the future development of electricity prices, the influence of the discount rate, the investment horizon and the assumption that the EH itself is available at no cost.

The future increase in electricity prices was estimated with 3.5 % per year until 2040 based on data from the Danish Energy Agency [53], which also recommended to perform a sensitivity analysis on this parameter as the develop-
 550 ment is very uncertain. The uncertainty in the future electricity price increase was included in the sensitivity analysis by varying it from 1 % to 5 % increase per year. As can be seen in Figure 8a, the future increase of electricity price has only a small impact on the EH potential for DH with heating costs below

Table 4: Summary of the weighted average heating price and the total share of components of the investment costs for each industry category.

	$\bar{c}_H$ [€ MWh ⁻¹]	S_{Pipe}^I [%]	S_{HP}^I [%]	S_{HEX}^I [%]	S_{Storage}^I [%]
Gravel & Stone	106	59.0	32.8	5.4	2.7
Oil Refineries	28	1.4	45.0	2.3	51.3
Food	81	80.1	10.6	6.2	3.0
Sugar	23	0.4	77.2	21.4	1.0
Wood, Pulp & Paper	134	92.6	0.1	3.7	3.7
Chemical & Pharma	118	84.9	9.4	4.3	1.3
Cement, Bricks & Rockwool	17	19.9	20.0	12.2	47.9
Concrete products	83	67.5	16.8	15.0	0.8
Asphalt	51	44.5	25.3	20.0	10.3
Metal	51	85.2	2.7	5.5	6.6
Metal products	348	96.2	1.0	2.8	0.1

555 50 € MWh⁻¹. Only for matches relying strongly on heat pumps (DH costs above 50 € MWh⁻¹), an impact can be observed, increasing the heating price by up to 5 € MWh⁻¹.

The assumption behind the results presented in Section 3 was that EH was available at no cost. This is not the case as it is for example for solar energy. 560 The emitter of EH has (i) costs for the utilisation of EH even if, in theory, no investments would have to be performed. It would require internal process adjustments and working hours to initiate the project, to oversee the delivery of EH and general administration. There are also (ii) risks involved, (iii) lack of knowledge and business models, need for use of non-standard equipment, and 565 (iv) ultimately the delivery of EH can decrease future options for fuel consumption reductions. This is in particular important as EH originates from e.g. the combustion of a fuel of which a part of the costs can be allocated to the EH. The industry has in theory thus a strong interest in reducing the EH amount

or profit from its utilisation. It is however difficult to determine a global price
 570 of EH as it will depend on many local factors, of which many can be hardly
 quantified (e.g. risks and technology lock-in). Other works have estimated the
 price of EH at 15 € MWh^{-1} [61]. A sensitivity analysis was performed with 5,
 10, 20 and 30 € MWh^{-1} , to see how such a cost would impact the potential. EH
 prices of up to 10 € MWh^{-1} would only marginally decrease the DH available
 575 at heating prices below 50 € MWh^{-1} . An EH price of 30 € MWh^{-1} reduced
 the potential by more than 50 %. However, a majority of the EH is still cheaper
 than solar district heating.

Figure 8: Sensitivity analysis of changes in the future electricity price increase and cost of excess heat.

Figure 9: Sensitivity analysis of changes in the discount rate and lifetime of the project. If two lifetimes are given, the second one refers to the DH pipelines.

In this work a uniform equipment and investment lifetime of 20 years was assumed. Some equipment, such as DH pipelines, have a considerably longer
 580 lifetime [42, 51]. On the other hand, industries would probably use shorter depreciation periods for the investments into the heat recovery equipment. This will thus require the investments in the whole project to pay-off earlier. After the initial utilisation phase of EH for DH, of e.g. 20 years, it is not guaranteed that the EH delivery will continue. In addition, it is seen as very likely that
 585 during a 20 year period, the manufacturing processes will change significantly at a production site, changing the availability of EH. In the worst case, the DH pipelines will no longer be used, as they were build for a single purpose. In the sensitivity analysis the lifetime of the investment was varied between 10 and 30 years. Furthermore, the technical lifetime of DH pipelines of 40
 590 years was coupled with the lifetimes of 10 years and 20 years for the remaining equipment as shown in Figure 9a. A decrease in lifetime of heat pumps and heat exchangers to 10 years would increase the costs only slightly and reduce the EH potential at a price below 50 € MWh⁻¹, by less than 250 GWh. On the other hand, expanding the lifetime to 30 years, has only a notable impact for a

few matches. By considering the technical lifetime of DH pipes, the potential can be slightly increased and unit costs for heat reduced. However, the lifetime of DH pipelines has generally a smaller impact on the cost-effective solutions, as they are characterised by low investment costs.

4. Discussion

The economic analysis performed in the present paper aimed at determining the socio-economic heating cost for using EH for DH. Several assumptions and simplifications were made, however it was possible to use this approach for all 2584 EH sources mapped in Denmark. When considering a private-economic heating price, several other parameters have an additional influence. There are currently subsidies available for systems comparable to the ones studied [62], however the delivered heat might also be subject to taxes [63]. In addition, the chosen ownership model, a high perceived risk of the investment and the cost of financing such a project, might increase the overall heating price. On the other side, additional cost savings might be possible as in some application the heat pump might supply a cooling need and thus reduce energy used for current refrigeration systems. Also, no economic optimization was performed leaving the opportunity to reduce storage tank and equipment sizes, which were dimensioned after the peak heating load. Finally, new business models are required to split the benefits between industries and utility companies. All together, each case has to be evaluated individually if a robust result is required.

Future electricity prices can affect the cost-effectiveness of EH which requires HP to become useable. If the electricity prices decrease, this EH would become cheaper. On the other hand, high electricity prices usually go hand in hand with high environmental targets. In the case of high renewable energy targets, EH becomes very important in the future energy system. It seems reasonable that EH should be used, from a socio-economic perspective, with both high and low electricity prices. However, this requires a full energy system analysis, which is part of future research using TIMES-DK [64, 65].

The results confirm a maximum potential of 1.88 TWh of DH from thermal
 625 process related EH in Denmark as found in [28] without demand limitations.
 If the temporal mismatch and demand limitations are included, together with
 seasonal thermal storages, the potential is reduced by 10 %. The results are not
 readily comparable to other works. For example, [9, 25] do not elaborate on
 the potentials, while [24] does not consider temperature levels. However, the
 630 potentials calculated in the present paper have the same order of magnitude as
 in [9, 24, 25].

The refineries and building material industries were identified as the most
 profitable ones, due to the large size of the individual EH sources. On the
 other hand, they require large seasonal storages. The installation of these stor-
 635 ages should be possible in most cases, as these industries are placed outside of
 densely built areas. The food, asphalt and basic metal industry had low heating
 prices and good thermodynamic properties. Even though piping accounts for
 a large share of the investment in these industries, a high share of direct heat
 transfer and high COPs can be obtained in combination with small storage
 640 sizes. Therefore, if a food, asphalt or basic metal industry would be located in
 a densely populated area, installation of a thermal storage should not represent
 a problem.

The results of this paper can be partly used for first assessments in other
 countries. The following needs to be considered for the results. Besides the
 645 industry characteristics, the COP depends on the local DH network supply
 and return temperatures. These DH temperatures can be generally higher or
 lower in different countries, affecting the obtainable COP and the share of EH
 requiring a HP. This has a direct influence on the heating price in each industry
 category. The industry categories, dominated by a few production units, such as
 650 oil refineries and cement production in Denmark make some results not directly
 applicable to other countries. If a majority of the EH originates from one source,
 its location will influence the whole category. This is in particular the case for
 the maximum deliverable EH to DH (S_{demand}), where the demand of a specific
 DH area can influence the overall results. In this study, specifically oil refineries

655 and cement plants have a great influence on the outcome of their respective categories. Both are very energy intensive and only a few factories exist. This can also be seen in the horizontal parts of the heating prices plotted against the cumulative DH demand covered by EH in Figure 7b.

The method described in this work is applicable to other countries. It relies
660 however on previous works, which use data specific to Denmark which might not be available for all countries. The required information on a national level for this analysis is the energy demand of industrial sectors and its distribution amongst thermal processes, as well as heating demands and temperature levels of the DH areas. This information can be used to create the spatial model and
665 determine heating prices of all matches.

In this work a sensitivity analysis, varying one factor a time, was conducted for four assumptions which were expected to have an impact on the results. From these, only the EH price and lifetime of the equipment were found to have a significant impact on the cost curves. There are several other parameters
670 which have a high uncertainty, such as excess heat temperatures, minimum temperature differences, investment costs, operating costs and real connection distances. Also the amount of EH which is based on disaggregated national energy use data is connected with a high uncertainty. On a case study basis, [66] determined the uncertainty of heating prices and determined the important
675 model parameters using advanced sensitivity analyses. It was shown that the EH temperature can contribute significantly to the uncertainty of the result. Especially in cases where the EH temperature is close to the DH temperature, a small change in the temperature can decide between the requirement of using or not using a heat pump. This has great impact on the investment but more
680 importantly on the operating costs.

Future research should focus on extending the scope of the EH mapping, including other EH sources such as data centres, supermarkets and other industrial sectors. It is further necessary to determine the degree of possible internal heat recovery at the site, which would require the analysis of the heating demands
685 and industry specific potentials for process integration. A tool for determining

cases for EH recovery based on the spatial model was developed [66], where also uncertainties have been assessed. An assessment of uncertainties of the overall potential and the mean heating price, would add further important information. Also the development of the industry in the future (e.g. electrification of processes), the costs of electricity and developments in DH systems (e.g. low temperature and ultra low temperature) has to be assessed on how they impact the role of industrial EH as a source for DH. The DH profiles could be further refined, e.g. changing the length of the different heating seasons, to better reflect the real consumption. It is however expected that this will only affect the results marginally.

5. Conclusion

This work determined the DH costs and potentials for using industrial EH from thermal processes for district heating, based on Denmark as a case. Both a method for the analysis and results of the case study have been presented. The evaluation included (i) the spatial distribution of EH sources and DH areas, (ii) the temporal patterns of DH demand from different user types (iii) the temporal availability of EH described in relation to the industry type and size, as well as (iv) the thermodynamic characteristics of the EH source and DH demand. For the economic analysis investment costs for heat pumps, heat exchangers, thermal storages and DH piping were included to find the simplified socio-economic costs of provided district heat.

The results showed that the technical and spatial EH potential was reduced by 27 % if the temporal mismatches of sinks and sources, as well as demand limitations, were included. When TES were introduced, the temporal mismatch was reduced, leading to the decrease in potential by only 10 % compared to the values without temporal mismatches and demand limitations.

The weighted mean DH cost was found at 35.6 € MWh^{-1} , however the distribution had a long tail spreading the possible costs. Almost 1.5 TWh of EH could be utilised at heating prices below the 2016 Danish average price of

715 53 € MWh⁻¹. Industries which had in general larger production sites, had low sectoral DH costs. This was partly due to the ratio of piping costs to EH size. Particularly low heating prices were found for oil refineries, food industries and the building material as well as basic metal production.

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950 **Appendix A. Industry Aggregation**

Table A.5: Industry categories and the associated industry sectors. The european classification NACE and the Danish DB07 are included [31, 67, 68].

Industry Category	Industry Sector	NACE	DB07
Gravel & Stone	Extraction of gravel and stones	08	080090
Oil Refineries	Oil Refineries	19.2	190000
Food	Slaughterhouse	10.1	100010
	Diary Processing	10.5	100030
	Production of compound feed	10.9	100050
	Other food industry	10.89	100050
Sugar	Production of Sugar	10.81	100050
Wood, Pulp & paper	Wood Industry	16.2	160000
	Paper Industry	17.1	170000
Chemical & Pharmaceutical	Production of Industrial Gasses	20.11	200010
	Production of Enzymes	20.14	200010
	Other chemicals	20.59	200010
	Pharmaceutical industry	21.00	210000
	Plastic and rubber	22.00	220000
	Production of paint, soap and more	20.59	200020
Cement, Bricks & Rockwool	Production of Cement	23.51	230020
	Production of Bricks	23.40	230020
	Production of Rockwool	23.99.90	230020
Concrete products	Other concrete and bricks	23.69	230020
Asphalt	Production of Asphalt	23.99.10	230020
Metal	Production of Metal	24	24000
Metalproducts	Metalproduct Industry	25	25000

Appendix B. BBR Aggregation

Table B.6: Aggregated groups of heat users and the associated use types [35].

Aggregated group	Use code	Use
Residential	110	Farmhouse
	120	Detached house
	130	Terrace house
	140	Block of flats
	150	Student residence
	160	Residential institution
	190	Other dwelling
Office/ service	310	Transport
	320	Trade and commerce
	330	Hotel and service
	390	Other trade
Culture/ public	410	Cultural building
	420	School
	430	Hospital
	440	Kindergarten
	490	Other public institution
Leisure	510	Summer house
	520	Tourism
	530	Sports
	540	Allotment house
	590	Other leisure building

Appendix C. Seasonal Distribution of Excess Heat

Table C.7: Generalised seasonal distribution of the EH.

Industry Category	Seasonal Excess Heat Distribution			
	Winter	Spring	Summer	Autumn
Gravel & Stone	0.33	0.25	0.17	0.25
Oil Refineries	0.25	0.25	0.25	0.25
Food	0.25	0.25	0.25	0.25
Sugar	0.36	0.18	0.09	0.36
Wood, Pulp & paper	0.25	0.25	0.25	0.25
Chemical & Pharmaceutical	0.33	0.22	0.22	0.22
Cement, Bricks & Rockwool	0.25	0.25	0.25	0.25
Concrete products	0.38	0.25	0.13	0.25
Asphalt	0.00	0.25	0.50	0.25
Metal	0.25	0.25	0.25	0.25
Metalproducts	0.25	0.25	0.25	0.25

Appendix D. Profile Comparison for District Heating

Figure D.10: Comparison of the artificially created hourly district heating profile to the one of Ringkøbing for weekdays in 2017.

Figure D.11: Comparison of the artificially created hourly district heating profile to the one of Ringkøbing for weekends in 2017.

Figure D.12: Comparison of the artificially created hourly district heating profile to the one of Ringkøbing for weekdays in 2016.

Figure D.13: Comparison of the artificially created hourly district heating profile to the one of Ringkøbing for weekends in 2016.

Figure D.14: Comparison of the artificially created hourly district heating profile to the hourly heat load Ringkøbing DH for 2016.

Figure D.15: Comparison of the artificially created hourly district heating profile to the hourly heat load Ringkøbing DH for 2017.

Highlights: Spatiotemporal and economic analysis of industrial excess heat for district heating

- Method for assignment of temporal profiles to industries and heating areas
- Excess heat utilisation with thermal energy storage, heat pump and direct heat transfer
- Economic analysis of industrial excess heat utilisation for district heating
- 80 % of excess heat potential is recoverable cost-effectively in Denmark