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Design approach to extend and decarbonise existing district heating systems-case study for German cities

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ABSTRACT

This paper aims to present an approach for the planning of carbon low heat supply in a future district heating system based on open data for German cities with existing district heating networks. One focus is on the integration of industrial waste heat and the uncertainty of future waste heat sources as well as restrictions on the use of biomass. For that purpose, knowledge about the energy demand is necessary. In a first step it is shown how the demand around a heating network is estimated with spatial data and a load profile is generated. Local available heat sources are examined according to their suitability and their kind of integration in the heating network.

As heat production from different units are optimised, the development of a simulation model will be presented. The simulation is based on the optimisation of the operational costs of the used technologies for heating supply. Different scenarios covering various technologies and economic assumptions are applied. The results show the levelized costs of heating as well as the ecological performance. A sensitivity analysis shows the importance of uncertainties for the economic assumptions. The results showing levelized costs of heating as well as the ecological performance underlining the advantage of excess heat integration.

Keywords

District heating;
Spatial data;
Heat demand;
Excess heat;
Energy system model;
Public data

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Abbreviations

CHP	Combined heat and Power
COP	Coefficient of performance
DH	District heat
DoW	Day of Week
DoY	Day of Year
DWD	German weather service, from German: Deutscher Wetterdienst
EH	Excess Heat
GHG	Greenhouse gas emissions
HOP	Heat-only-Plant
KW	Customer Value, from German: Kundenwert
LCOHMILPNG	Levelized cost of heat Mixed Integer Linear Programming Natural gas

1. Introduction

Several countries signed the Paris Agreement from 2015 with the goal to reduce their greenhouse gas (GHG) emissions due to climate protection reasons [1]. In Germany the Climate Action Plan 2050 [2] was adopted to achieve the climate goals. The plan of the German government provides for a 55% reduction for GHG emissions by 2030 compared to the year 1990. Most potential is seen in the energy sector and in the building sector. Since the building sector is responsible for one fourth of Germanys end energy use (26.6% in 2021 [3])

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the government has set the goal to reduce GHG emissions for about 66% in this sector till 2030 compared to 1990. The increased use of district heating (DH) and the integration of excess heat for decarbonising the heat production are seen as key factors to the transition to a sustainable building and energy sector [2].

To transform the heat sector and include excess heat (EH) sources into DH systems, a deep knowledge about approaches, information and data is needed. Bühler et al. [4] concluded from several studies [5,6,7] a knowledge and information gap for those dealing with the topic. This is the challenge facing local energy providers and municipalities. To close the knowledge and information gap, research activities on the topic have increased in the past years.

For the estimation of the EH recent studies have been published. Miro et al. [8] investigated the industrial waste heat potential for 33 countries. They found out a correlation between the energy consumed by the country and the industrial waste heat as well as energy consumed by the industry and industrial waste heat. Persson et al. [9] identified annual EH potentials based on carbon dioxide emission data from the energy and industrial sector across EU-27 countries and elaborated heat synergy regions at NUTS3 level with a mapping of the emitting locations.

Furthermore, there are studies on national levels for different countries and industry sectors. Bühler et al. [10] studied and mapped the Danish industry sector for its EH and showed the potential for the supply of DH and mapped the results. Pieper et al. [11] showed a geospatial approach for identifying heat source potentials for the utilisation of heat pumps and chillers to district heating and cooling. They did a case study on the Baltic states, mapped and quantified the amount of excess heat from industrial processes. They pointed out, that sewage water treatment plants as a heat source are located in almost every city with existing DH supply.

A method developed by Brückner [12], based on the German industry sector, uses fuel consumption and EH ratios to estimate EH potentials of specific industrial sites. Sundell et al. [13] showed a systematic mapping method for industrial EH and other heat sources in urban areas. They found out that the mapping and identification of EH mainly depends on the available data and its quality.

Further investigations focus on municipal level and its potential of EH and meeting residential heating demand. Brückner et al. [14] have investigated a city quarter in Hamburg for a case study. They found out that the available EH potential is able to cover only 3.7% to 7.3% of the residential heat demand. They concluded that the residential heat demand from an average city quarter cannot be covered by small industries and commerce industries like bakeries or textile cleaners, but that these EH sources should be considered as an option when renovation and refurbishment is planned.

Tötzer et al. [15] investigated the role of manufacturers for a future energy system in an urban environment. They investigated eight Austrian cities for their waste heat potential in eight different manufacturing sectors, divided into three different temperature levels, and concluded that companies could feed small DH systems in the neighbourhood with heat. A case study about a DH system using industrial waste heat from a copper smelter in Chifeng, China is presented in Fang et al. [16]. They applied a developed method to integrate multiple EH sources with different temperature grades from one copper smelter to the DH system. As a result, 85 MW of EH was recovered and 35,000 t carbon dioxide emissions were saved.

In a case study for a city of northern Italy by Spirito et al. [17] a wastewater treatment plant and cooling water from a steel plant are utilised with heat pumps to the DH network. They show a supply of 59% heat to the DH network by using heat pumps to utilise the EH. In another case study, Pieper et al. [18] provided a modelling framework for the utilisation of low-temperature heat sources for large heat pumps. On the city of Tallinn in Estonia they showed that heat pumps, using low-temperature heat sources such as groundwater or seawater, are technically and economically able to cover 16% of the total heat demand.

With regard to the literature only a few studies focus on EH integration as a source in DH systems. There is still a gap of knowledge and approaches to evaluate and apply EH as low-carbon heat source to DH. With regard to that, the aim of this work is to show already existing and elaborated methodologies combined together and to deepen them on an advanced case study shown on a German city. The approach presented, allows a straight-forward assessment and planning of EH utilisation into already existing DH systems.

With regard to high turbulent energy markets the economic evaluation of possible solutions needs to be analysed continuously. In this study, a simulation model based on Mixed-Integer-Linear-Programming (MILP) is considered to optimise the heat supply under the consideration of EH sources to allow an economic assessment and an assessment on CO_2 emissions.

Sameti et al. [19] did a review on optimisation approaches for district energy systems and found out, that MILP is the most used method for solving optimisations on district level and Halmschlager et al. [20] used MILP to optimise the utilisation of EH for DH from a chipboard production plant and showed with the optimisation, that a higher amount of EH could be feed to the DH system than it is done at the actual state.

For that reason, first an estimation of the energy demand from residential sector and the commercial sector in the catchment area of the district heating system is made and a heat load profile is created. Then the available heat sources in this area are mapped and the potential of excess heat is calculated. A simulation model for the operation of heat generation aiming on minimising the operational costs is presented. Four different scenarios are created and simulated.

This work is structured as follows: In section 2, the used methods for the determination of the heat demand and the EH sources are explained. The simulation model is presented at the end of chapter 2. In chapter 3 scenarios are introduced and data collection on technical parameters is done. In section 4 the assumptions on investment costs and prices for fuel, electricity and carbon costs are explained. In section 5 results are presented, followed by discussion and conclusion in section 6.

2. Methods

The section is divided into four parts, the determining of heat demand, the determining of heat sources, the explanation of simulated scenarios and the description of the optimisation problem as MILP.

2.1. Determining the heat demand

The first step in this study is to estimate the heat demand that is needed for the simulation. For that reason, data from the individual buildings is needed. The investigated city Dortmund in this study is in the German federal state of North Rhine-Westphalia (NRW). Heat demand data were provided after a request to the federal state agency for nature, environment, and consumer protection (LANUV), as there is no public access to the dataset. A visualisation of the heat demand data can be found in [21] as a web map. The dataset contains the heat demand of a building and other useful data like the shape area, specific heat demand of a building and the type of usage. The calculation of the heat demand and the used data sources are described in [22].

For the investigated area in this study only buildings that are not more than 1000 m away from the DH network were considered, as this area is in first order of interest to expanse the DH network, increase DH sales and connect more customers. Fig. 1 (left) shows the 1000 m buffer around the DH network with subareas that are suitable for DH. The subareas were taken from the official land use plan of the investigated city [23]. For every subarea of the land use plan the heat demands of all buildings within this area were aggregated and then the heat demand density in kWh/m^2 was calculated. Only areas with a heat demand density over 70 kWh/m^2 [24] are considered as suitable to DH because of

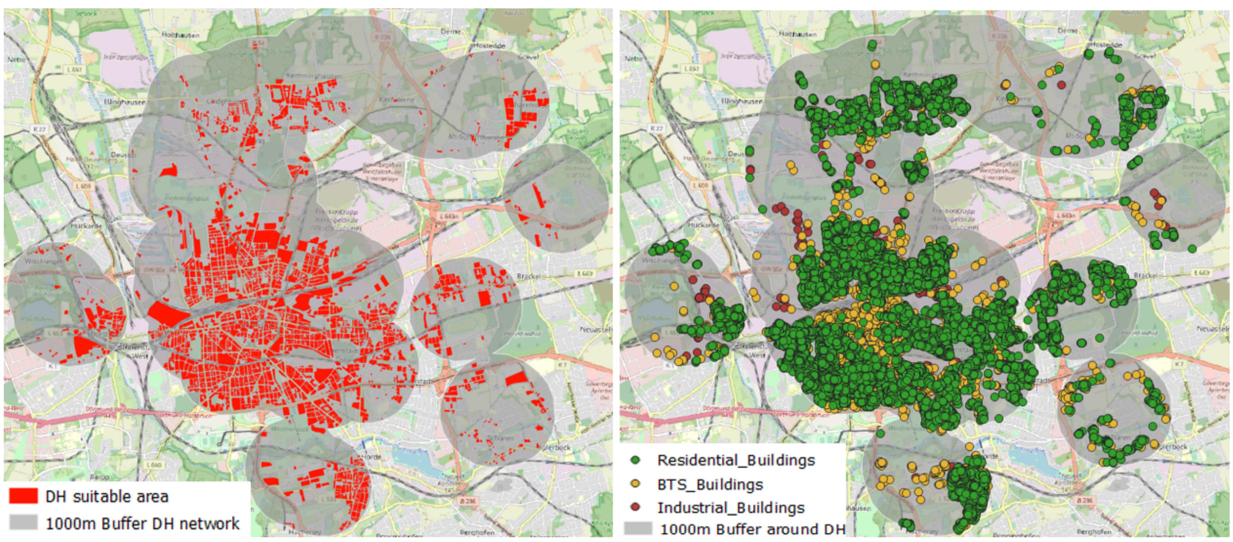

Figure 1: Left: Investigated area with subareas, Right: Investigated area with buildings as spatial points.

economic efficiency. Fig. 1 (right) shows the buildings within the determined land use areas.

The buildings within the area were divided by their type of usage in the categories residential sector, buildings from the commercial sector and buildings from the industrial sector.

Fig. 2 shows the total heat demand of the different sectors and the building counts. The residential sector's heat demand is about 892 GWh/a for 11,714 buildings, while the commercial sector needs 971 GWh/a for 4,309 buildings. The buildings of the industrial sector have the lowest heat demand with 49 GWh/a for 264 buildings. The industrial sector will be cut off completely in this study as its heat demand is only about 2.5% of the whole demand. Also, the construction of a load profile for the industry sector is difficult as there is no knowledge about shift operation and the method used for the load profiles later in this chapter does not include profiles for the industrial sector. Furthermore, temperature levels of various industrial process heat demands may exceed the temperature provided by the DH network.

After the yearly heat demand of each sector in the investigation area is determined, a level of development is necessary to define the number of connected buildings at a future state once the transformation of the local heat market is completed. Nussbaumer et al. [24] are assuming a level of development from 50% to 80% for an investigation area that is suitable to DH. In this study 65 % is choose. This means that it is assumed that 65% of the buildings will be supplied by DH in the future. It is assumed that the 65% level of development apply to both sectors in the same manner. Table 1 shows the application of the level of the development on this case study.

The lower heat demand is the demand of 65% of the buildings with lowest heat demand and the upper heat demand 65% of the buildings with the highest heat demand. It is assumed, that the DH provider will not only connect the buildings with the highest heat demand to DH, rather customers with interest close to the DH network will be connected first in future. For that reason, the mean heat demand of randomly chosen buildings within the investigated area are used. This was done thousand times and then the mean value of the random buildings is used. This is also the yearly heat demand used for simulations described further in

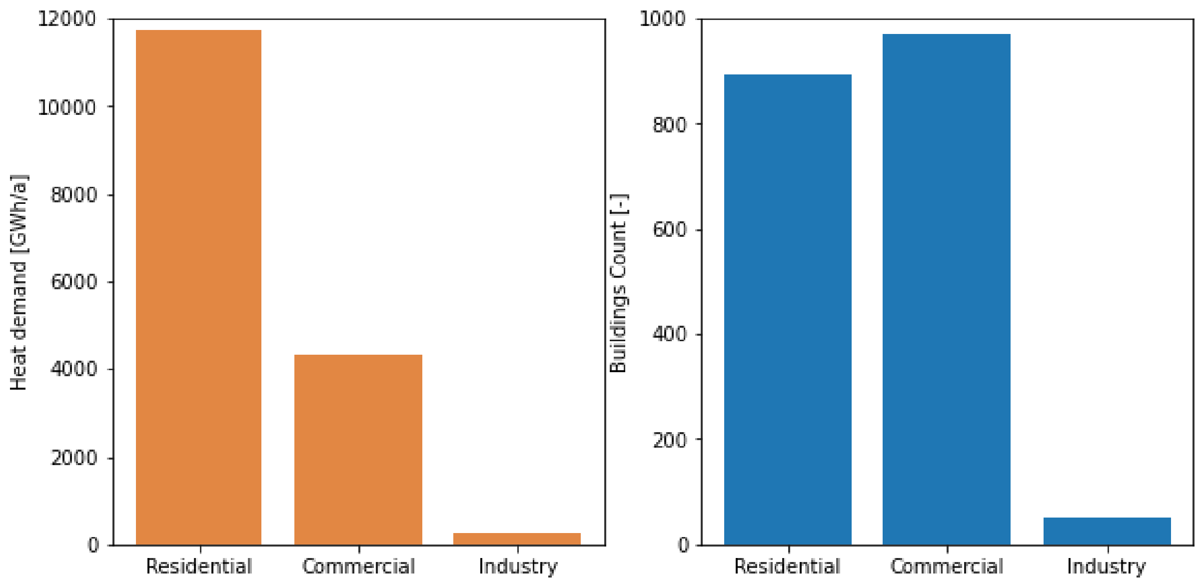

Figure 2: Left: Heat Demand, Right: Buildings count.

Table 1: Summary level of development.

Sector	Count Buildings	Lower heat demand [GWh/a]	Upper heat demand [GWh/a]	Mean heat demand [GWh/a]
Residential	7,614	383	740	580
Commercial	2,800	226	884	632
Total	10,414	609	1,624	1,212

this study. Heat losses from the network are neglected in this study.

2.2. Construction of a heat load profile

For the annual simulation, an hourly heat load profile for one year is required. For that purpose, the method presented in [25] is used. This method is mainly based on the ambient temperatures and is used for the construction of gas load profiles for residential sector and the commercial sector. As the gas is used for space heating and domestic hot water [25], the gas profiles are used for the construction for heat load profiles, as in this study the heat is used for the same purpose.

To develop the load profile, first the daily heat demand values are calculated (Eq. (1)).

$$Q_{Daily} = KW * h\left(\vartheta_{DoY}\right) * F\left(D_{DoW}\right) \tag{1}$$

KW is the customer value, which depends on the individual demand of each customer or in this case on the heat demand of each individual building. To calculate KW Eq. (2) is used, where Q_N is the heat demand for a time period, in this case it is the heat demand for one year. $h\left(\vartheta_{DoY}\right) * F\left(D_{DoW}\right)$ is calculated for every single day of the period. $h\left(\vartheta_{DoY}\right)$ is the load profile function and depends on the type of building and the mean daily temperature ϑ_{DoY}. The daily mean temperature is used from historical weather data provided by the German weather service (DWD) [24]. The calculation of $h\left(\vartheta_{DoY}\right)$ is done with Eq. (3). The factors A, B, C and D are used to calculate the profile. They differ for each type of building's usage, like single family housing, multi-family housing for the residential sector or the commercial sector. ϑ_0 is set to 40 °C and is the standard reference temperature in the used method. $F\left(D_{DoW}\right)$ are daily factors for each day of the week. The value of $F\left(D_{DoW}\right)$ for the residential sector is 1.0. For the commercial sector the factors are above 1.0 on weekdays and below 1.0 on weekend. The values are taken from [22].

$$KW = \frac{Q_N}{\sum_{i=i}^{N}(h\left(\vartheta_{DoY}\right) * F(D_{DoW})} \tag{2}$$

$$h\left(\vartheta_{DoY}\right) = \frac{A}{1+\left(\dfrac{B}{\vartheta_{DoY}-\vartheta_0}\right)^C} + D \tag{3}$$

With the described equations above, three different types of load profiles for SFH, MFH and the commercial are created with daily heat demand values for one year. For the SFH and MFH buildings, the dataset with the residential sector buildings is divided, as the input data allows a differentiation between the residential sector buildings. To calculate the hourly heat demand values, the practice information [27] is used to which reference is made in [25] and hourly temperatures for the historical weather data [26]. [27] contains tables with factors for each hour and temperature range, for every building type used in this study. The factors are multiplied with the daily value Q_{Daily}. This is done for all three heat load profiles. After that step, the three profiles were aggregated to one heat load profile.

As Meschede et al. [28] concluded, that one historical year as a reference for the investigation of an energy system is not suitable, three different years with different temperature profiles were investigated in this study. The historical temperature data from the years 2002, 2010 and 2020 were chosen. The average annual temperature from the historical weather data [26] from 2001 till 2021 was 10.56 °C. The coldest year during this period was 2010 with an average temperature of 8.86 °C. 2020 was the hottest year during the period with an average temperature of 11.52 °C. The average temperature of 2002 was 10.58 °C and was chosen because of its closest average temperature compared to the average temperature of the span from 2001 till 2021. The shape of the heat load profiles in this study were calculated with the described method above and the temperature from the chosen years and are visualised in Fig. 3.

2.3. Urban Heat Sources

To show up the possible heat sources, that can be included for DH, the sources have to be mapped and the potential needs to be estimated. The heat sources are provided by the federal state agency described above [29]. The dataset contains a list of industrial EH sources and natural heat sources. For the chosen case, the data shows 22 available industrial EH sources for the whole city. From these 22 sources, 13 sources are in the investigated area, that are seen in the first order of interest. The original dataset is fragmentary, and values based on assumptions have a wide range. Thus, additional information needs to be added from the federal register for carbon polluting assets of the production sector [30]. The additional data contains information about the fuel consumption of energy supply units, the operating time, and the economic sector. The data can be processed with the method developed by Brückner et al. [12].

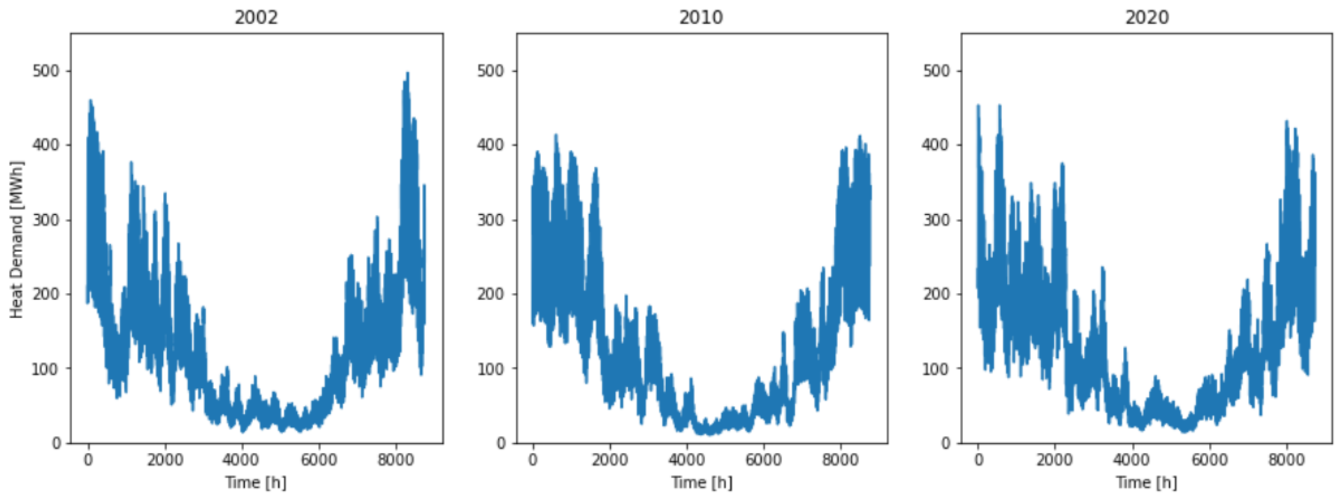

Figure 3: Possible Heat Load Profiles based on the mean heat demand.

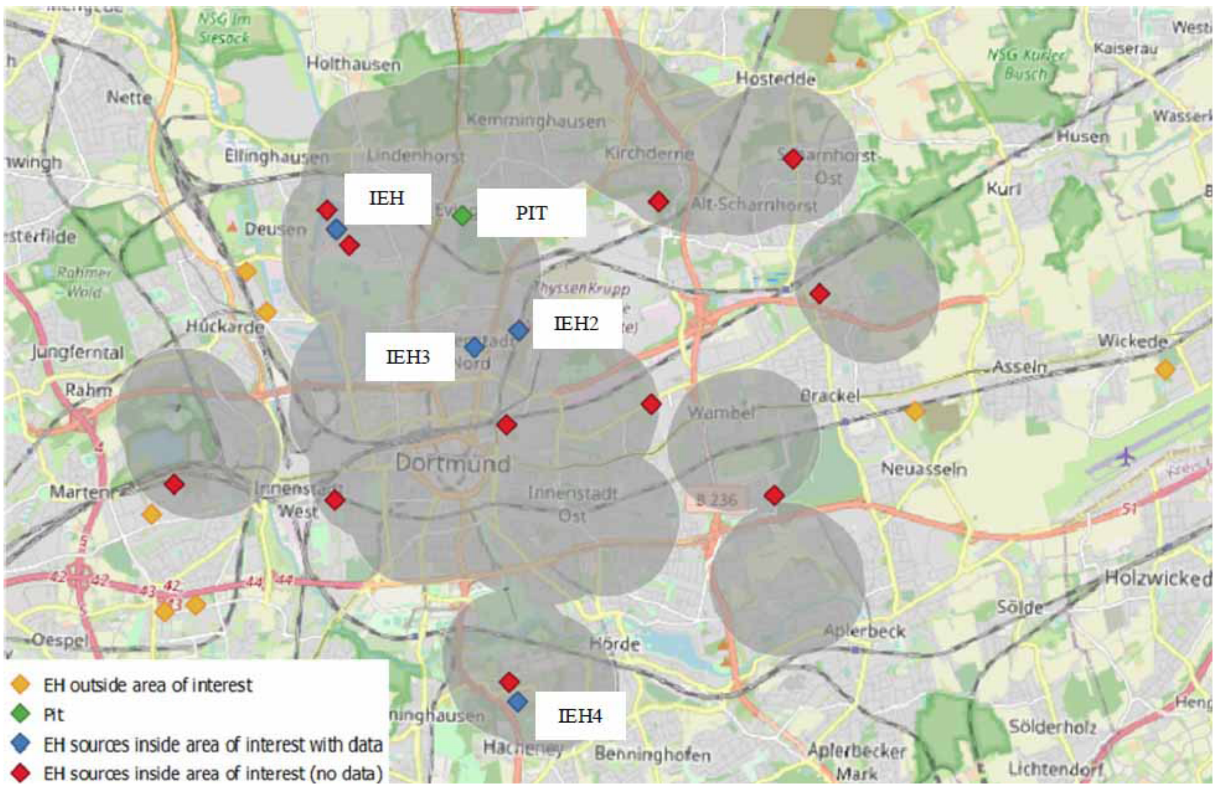

Figure 4: Overview of heat sources included in this study.

Furthermore, the data set is enriched by manual search for heat sources which lead to another heat source in [30] not included in [29]. After clearing and processing the data of possible heat sources, four industrial heat sources are left, as these are the only sources whose data are precise enough to calculate the waste heat potential. The EH sources outside the investigated area are not considered in the detailed determination of EH potential, as they also show incomplete data and low values for EH. These EH sources, the excluded in the investigated area and the EH sources outside the investigated area are considered in the theoretical scenario Industrial EH+ (see section 2.4). The locations of all EH sources are shown in Fig. 4. For IEH2, the information about the carbon dioxide emission is collected from the German EU-ETS report [31]. With the carbon dioxide emissions,

Table 2: Industrial heat sources calculated with waste heat ratios.

Source	Manufacturing Sector WZ2008	Fuel Input [MW]	EH ratio	Workload [%]	EH [MW]	Availability [h/a]
IEH3	Manufacturing of Beverages	25	0.14	40	1.4	>7000
IEH4	Manufacturing of machinery and equipment	2.4	0.16	50	0.2	>7000

it is possible to calculate the EH potential. The amount of EH for IEH1 is 35 MW at 130 °C [29].

Two sources of EH (i.e., IEH3 and IEH4) could be found that deliver heat at lower temperatures of approx. 35 °C. Here, an integration by heat pumps is necessary. According to [35] a COP of 2.3 is estimated to fulfil the needed temperature shift of 75 °C. IEH3 and IEH4 are calculated with the method described in [12] using the EH ratio. The EH ratio is described in Eq. (4) as the ratio between the fuel consumption and the EH. The results and the parameters are shown in Table 2. f_{EH} is used from [30]. The fuel input is used from [30].

$$f_{EH} = \frac{Q_{EH}}{Q_{FUEL}} \tag{4}$$

As for IEH2 only the carbon emissions are given, another way to calculate the EH is necessary. The carbon emission from IEH2 is 19,556 t/a from a hot dip galvanizing process of steel. Assuming 8760 operation hours this is equal to an average mass flow of 0.62 kg/s. Before the galvanizing, the steel is preheated in a glow oven. With regard to literature, an exhaust gas temperature of about 650 °C is assumed [33]. Furthermore, it is assumed that the exhaust gas from the glow oven is polluted with carbon emission at the temperature level of 650 °C. With a density of 0.57 kg/m^3 for the carbon dioxide at 650 °C, the volume flow is 1.08 m^3/s. The volume share of carbon in exhaust gas differs from 6.3% to 12.7% [32]. Here, 10% is assumed. This means a total volume flow $\dot{V}_{Gas,hot}$ of 10.8 m^3/s. For the utilisation of the heat, exhaust gas is cooled down to 110 °C. It is assumed that the exhaust gas mostly consists of nitrogen, so that the heat capacities and densities for nitrogen are used [32]. Thus, for the exhaust gas at 650 °C the density $\rho_{Gas,hot}$ is 0.37 kg/m^3 and $\rho_{Gas,cold}$ at 110 °C is 0.87 kg/m^3. This means a volume flow $\dot{V}_{Gas,cold}$ of 4.54 m^3/s. The heat capacity at 650 °C, $c_{p,hot}$ is 1.151 kJ/kgK and $c_{p,cold}$ is 1.044 kJ/kgK. With Eq. (5) the EH is calculated to 2.65 MW.

$$\dot{Q}_{EH} = \dot{V}_{Gas,hot} * \rho_{Gas,hot} * c_{p,hot} * T_{Gas,hot} - \dot{V}_{Gas,cold} * \rho_{Gas,cold} * c_{p,cold} * T_{Gas,cold} \tag{5}$$

Table 3: Summary of industrial EH sources

Source	EH [MW]	Temperature [°C]	Integration Technology
IEH1	35	130	Heat Exchanger
IEH2	2.65	650	Heat Exchanger
IEH3	1.4	35	Heat Pump
IEH4	0.2	35	Heat Pump

Pit gas from a pit is found as another heat source, used to produce 2.7 MW electricity [29]. It is assumed that the gas is fired in a small gas turbine with a simple cycle with an efficiency η_{GT} of 36% and thus, a fuel input of 7.5 MW pit gas. Instead using a gas turbine, generation for example in a gas engine, the total efficiency could be increased. With data collected from a manufacturer for gas engines, an electrical efficiency of 45% and a heat efficiency of 43% could be assumed. This would mean an additional heat source of 3.2 MW. The four possible sources of EH are summarized in Table 3.

2.4. Simulation model

In this subsection the simulation model to minimise the operational costs under the constraint to provide the needed amount of heat at each time step is presented. First the general objective functions and constraints of the model will be introduced. Second, the application of the equations and inequations are shown on the individual plants.

Regarding to the main goal of minimised operation costs, the simulation is modelled as a MILP. The studied DH technologies are divided in Heat-Only-Plants (HOP) and CHP plants.

The general form of a MILP is shown in Eq. (6) as a vector. The target function is described with $c^\top x$, where c is the cost vector and x the variable vector. Furthermore, equations and inequations are used, which describe different characteristics of the optimisation problem as constraints.

$$\min\{c^\top x \,|\, Ax \le b, A_{eq}x = b_{eq}, x_j \in \mathbb{Z}\} \tag{6}$$

In this work, costs for the fuel consumption (c_{FUEL}) like NG or wood, (c_{ELEC}) for the heat pumps and (c_{EH})

for EH will be considered. $c_{REVENUE}$ is considered to include the earnings from the electricity generation. The polynomic of the target function then looks as follows:

$$c^{\top} x = c_{FUEL}^{\top} x + c_{ELEC}^{\top} x + c_{EH}^{\top} x - c_{REVENUE}^{\top} x \tag{7}$$

The main task of the DH system is to satisfy a certain heat demand. To fulfil the task, the constraint in Eq. (8) is used. $\dot{Q}_i^t$ is the variable for the produced heat for every plant i at each time t.

$$\dot{Q}_{demand}^t = \sum_i \dot{Q}_i^t \tag{8}$$

The investigated HOP in this study are gas boilers, the utilisation of EH with a heat exchanger and heat pumps with industrial EH as heat source. Furthermore, it is assumed that all technologies can work modulating except the heat pumps. Thus, the modulating heating technologies can provide heat in a range between a minimum and maximum load of the technology without a gradual regulation. Eq. (9) is the general equation for the energy costs of the investigated technology. The equation shows the relationship between the efficiency of the technology and the costs of the fuel consumption.

$$c_{FUEL,i}^t = C_{FUEL,i}^t \frac{1}{\eta_i} \tau \tag{9}$$

Eq. (9) is valid to represent the fuel costs of the gas boiler. As electricity for the heat pump and industrial EH are no fuels in a classical sense, Eq. (9) was adapted for the heat pump and industrial EH (Eq. (10) and (12)). In Eq. (10), ϵ_i is used for the COP of the heat pump i. The heat pump works in a staged operation to offer part load. j is used for the number of stages. For IEH3 and IEH5 four stages are used. IEH4 has two stages. It is assumed that the COP is constant in every stage. The binary variables $OP_{i,j}^t$ for each stage in constraint in Eq. (11) ensures that only one stage is used. τ is the time step used in the simulation and is set to one hour.

$$c_{ELEC,i}^t = C_{ELEC,i}^t \frac{1}{\epsilon_i} \dot{Q}_{N,i,j} \tau \tag{10}$$

$$\sum_1^j OP_{i,j}^t \leq 1 \tag{11}$$

$$c_{EH,i}^t = C_{EH,i}^t \frac{1}{\eta_i} \tau \tag{12}$$

The CHP plant used in this study is a biomass CHP, that is fueled with waste wood. CHP plants produce electricity and heat at the same time, so that its efficiency is in a thermal efficiency (η_{th}) and in an electrical efficiency. The correlation between the efficiencies is described with Eq. (13).

$$\eta_i = \eta_{th,i} + \eta_{el,i} \tag{13}$$

For the operation of the CHP under full load, $\eta_{th,CHP}$ is 75% and $\eta_{el,CHP}$ is 21% [34]. While working in part load the electrical efficiency is not constant. Given a constant total efficiency η_i, the heat output is at its maximum, when the electrical efficiency is at its minimum [35]. To consider that behaviour, a linearisation is made to the total efficiency and the factors $k_{var,i}$ (Eq. (14)) and $k_{base,i}$ (Eq. (15)) are introduced [36]. With this method, the fuel consumption $\dot{Q}_{FUEL}^t$ is divided in a load dependent part ($k_{var,i}$) and in a load independent part ($k_{base,i}$).

$$k_{var,i} = \eta_i \left(\frac{1}{\eta_{el,min,i}} - \frac{\frac{1}{\eta_{el,max,i}} - \frac{1}{\eta_{el,min,i}}}{\frac{P_{min,i}}{P_{max,i}} - 1} 1 \right) - 1 \tag{14}$$

$$k_{base,i} = \eta_i \left(\frac{\frac{1}{\eta_{el,max,i}} - \frac{1}{\eta_{el,min,i}}}{\frac{1}{P_{max,i}} - \frac{1}{P_{min,i}}} \right) \tag{15}$$

The load independent part depends on the operating status and is present when $OP_i^t = 1$. The load depending part is the factor for the heat production. On this way, the heat production is restricted in Eq. (16).

$$\dot{Q}_i^t - k_{var,i} * P_i^t - k_{base,i} * OP_i^t = 0 \tag{16}$$

With the dividing of the load also the fuel consumption and therefore the costs have to be divided. In Eq. (17) and (18), the specific fuel costs are multiplied with the factors from Eq. (14) and (15).

$$c_{FUEL,base,i}^t = C_{FUEL,i}^t * k_{base,i} \tag{17}$$

$$c_{FUEL,var,i}^t = C_{FUEL,i}^t * k_{var,i} \tag{18}$$

With a minimum load of 20% [34] of the nominal load, upper and lower bounds for the CHP have to be set:

$$P_{MIN,i} * OP_i^t \leq P_i^t \leq P_{MAX,i} * OP_i^t \tag{19}$$

3. Scenarios

The scenarios developed in this study are based on the findings in the previous chapter, information from the local DH system operator and own assumptions. The goal is, to develop scenarios that allow a realistic view on a future and feasible transformation of the DH supply.

The scenarios used are described as followed:

- *Reference Scenario*. The Reference Scenario is used to map the current situation of the supply. Within this scenario, it is assumed that currently DH demand is almost completely covered by natural gas (NG) boilers. In addition to the NG boilers a biomass combined heat and power plant (CHP) fed with reclaimed wood is used to cover the largest part of the base load.
- *Industrial EH*. In this scenario the gained findings from the EH mapping and estimation previously done are processed. This scenario involves the industrial EH sources summarised in Table 3.
- *Industrial EH and Pit*. The difference to *Industrial EH* is that the pit gas found as heat source is included. In contrast to the industrial EH sources, whose emissions are accounted to the industrial process resp. to the product produced by the industrial process, the emissions caused by the burning of the pit gas have to be considered, when ecological assessment is done.
- *Industrial EH+*. In this scenario an additional heat pump of 10 MW heat power (IEH5) for the utilisation of EH and an additional heat exchanger to utilise 10 MW of heat power (IEH6) is assumed. The mapping of the EH sources has shown that several IEH sources are not considered because of lack of information or are not detailed calculated as they were out of the investigation area. That is the reason for introducing this theoretical scenario. Also, it is known that source IEH2 is a big producer of galvanized steel. The EH calculated for IEH2 was derived from the carbon dioxide emissions. It can be assumed that there is a great need for cooling machine parts of the process plant by cooling water flows. The cooling water is assumed to a temperature of 35 °C when cooled down to utilise the heat pump.

The scenarios are summarised in Table 4. The efficiencies are taken from [34]. The COP for the heat pumps is taken from [37]. It is assumed to lift up the temperature from 35 °C (EH source) to 110 °C (DH feed

Table 4: Summary of the scenarios and efficiencies

Scenario	Heat Plant	Heat Power [MW]	Efficiency [%]	COP
Reference	NG boiler	500	95	
	CHP biomass	25	96	
Industrial EH	NG boiler	500	95	
	CHP biomass	25	96	
	IEH1 - HE	35	95	2.3
	IEH2 - HE	2.65	95	2.3
	IEH3 - HP	2.8		
	IEH4 - HP	0.4		
Industrial EH and Pit	NG boiler	500		
	CHP biomass	25	95	
	IEH1 - HE	35	96	2.3
	IEH2 - HE	2.5	95	2.3
	IEH3 - HP	2.8	95	
	IEH4 - HP	0.4	95	
	Pit Gas - HE	3.0		
Industrial EH+	NG boiler	500	95	
	CHP biomass	25	96	
	IEH1 -HE	35	95	
	IEH2 -HE	2.65	95	2.3
	IEH3 -HP	2.8	95	2.3
	IEH4 -HP	0.4	95	2.3
	Pit Gas - HE	3.0		
	IEH5 - HP	10		
	IEH6 - HE	10		

temperature), which means a temperature lift of 75 K. As trends for modern DH systems go to 4th and 5th generation DH, the forward temperature in that kind of DH systems are used be lower than 110°C e.g., 50°C – 60°C for 4th generation DH systems or less than 50°C in 5th generation DH systems. In this study, the system considered is an older DH system assumed poorly insulated pipes compared to modern DH networks and also an old building stock, that is supplied with DH.

4. Assumptions on costs and prices

The electricity price is used from a database for German electricity market data [38]. The prices are available as a time series in hourly resolution. The average price for electricity in 2021 was 96.85 €/MWh. The price is assumed for selling and using electricity. The average gas price for 2021 was 34.04 €/MWh for future contracts [39]. For the natural gas there have to be added a carbon dioxide price, that is paid for every ton of carbon dioxide polluted. The price was 25 €/t [40] in 2021 in the national emission pricing system for Germany. With a carbon dioxide emission factor for burning natural gas of 55.9 t/TJ [41] the price for carbon emissions is 5 €/MWh. For the pit gas it is assumed, that the operator of the pit sells the produced heat to the DH operator as EH. The same applies for the industrial EH. The price for EH in this study is assumed to 20 €/MWh. Recovery wood for the biomass CHP costs 10 €/MWh. In Table 5 all prices are summarised.

For the invest costs it is assumed, that there are no invest costs for the heat exchangers utilising IEH1, IEH2, IEH6 and for the pit gas. It is assumed that the invest costs are carried by the providers of EH, selling the EH to the DH operator, which justifies the EH price of 20 €/MWh. The annuity for the calculation of the capital costs is assumed with an interest rate of 5% and a repayment period of 25 years. The capital costs are increasing with the scenarios based on the investments that have to be made.

Table 5: Summary of prices

Price position	Price [€/MWh]	Reference
Electricity	96.85	[38]
Natural Gas	34.04	[39]
Excess Heat	20	Own assumption
Mature Wood	10	Own assumption
Carbon dioxide	5	[40]

The LCOH then is calculated from the operational costs and the capital costs and are decrasing in the scenarios mainly caused by the decreasing operational costs, as capital costs have no significant influence. Table 6 gives an overview on the assumptions made for the investment costs. The specific costs are taken from the technology data catalogue provided by the Danish Energy Agency [34].

5. Results

In Fig. 5 the simulation results are shown for the year 2002. In the Reference Scenario the heat is produced by the biomass CHP the whole year, which is the baseload technology caused by the lower price for fuel and the earnings from the electricity generation. The NG boiler provides heat, that cannot be covered by the CHP. In the Industrial EH Scenario the EH sources, determined in section 2, are included. It shows that the

Table 6: Assumptions on investment costs

Heat Plant	Reference in [34]	Specific Invest [M€/MW]	Total Invest [M€]
CHP	08 WtE CHP, Large, 50 degree	8.58	60
NG Boiler	44 Natural Gas DH Only	0.06	27
IEH3	40 Comp. HP, excess heat 3 MW	0.86	2.4
IEH4	40 Comp. HP, excess heat, 1 MW	1.24	0.496
IEH5	40 Comp. HP, excess heat, 10 MW	0.67	6.7

Table 7: Heat production of the Scenarios

	Reference Scenario [GWh]	IEH Scenario [GWh]	Pit Scenario [GWh]	IEH+ Scenario [GWh]
GB	981.6	698.8	680.8	616.0
CHP	217.8	217.7	217.7	217.7
IEH1		256.3	253.6	241.9
IEH2		16.9	17.7	15.3
IEH3		8.9	8.8	9.4
IEH4		1.3	1.2	1.3
Pit Gas			20.1	17.8
IEH5				0.1
IEH6				60.7

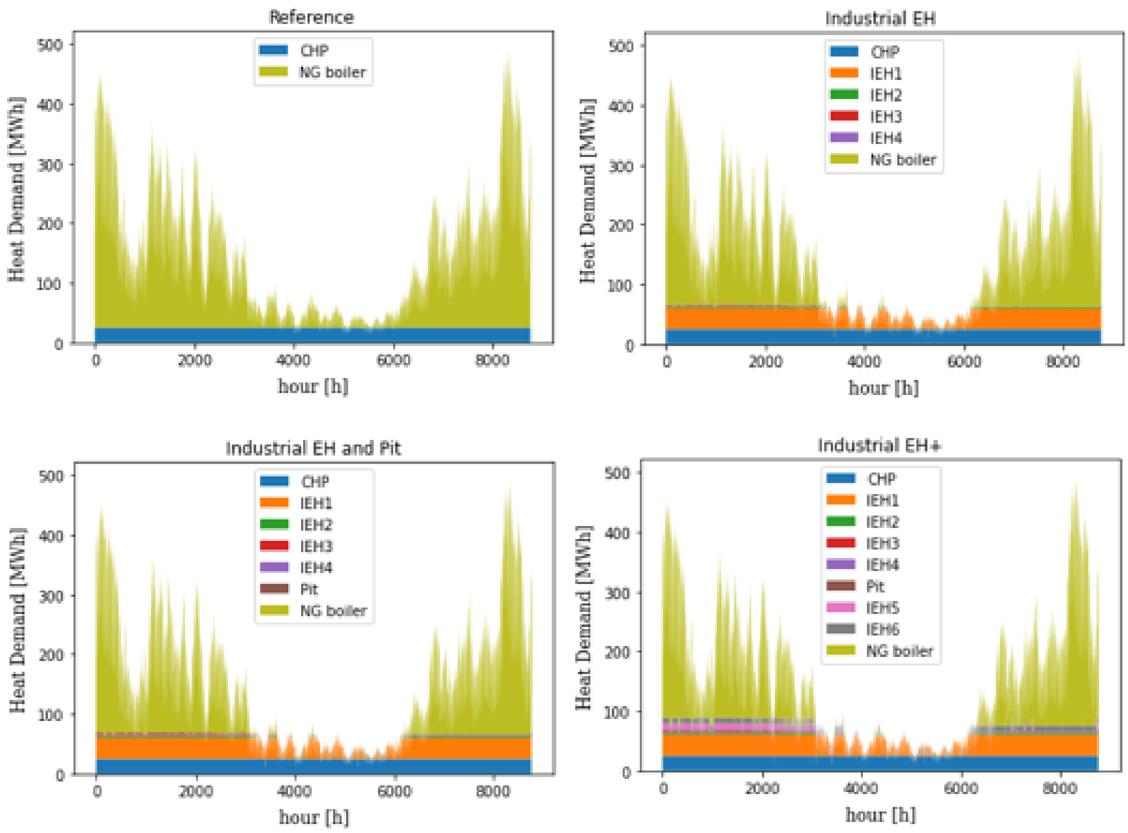

Figure 5: Simulation results of the 2002 heat load profile

CHP still provides the baseload followed by the integrated EH sources. The use of NG gets reduced by the integration of EH sources. This is caused by the general lower prices for the EH compared to NG use. In the summer months with lower heat demand, IEH1 replaces the NG boiler as peak load shifter. The same effect can be seen in the Industrial EH and Pit Scenario and the Industrial EH+ Scenario. With rising integration of EH, the heat provided by the NG boiler decreases.

In Table 8 the main findings are summarised. The main findings are the operational costs for the different scenarios and the total costs, including the investments. The operational costs contains only the costs for the fuel, the EH or electricity, needed to run the heat supplier. Operation and maintenance costs or electricity for the own consumption of the heat supply are not included, as in a previous investigation it was found that these costs only make up a fraction of the operating costs. The operational costs are decreasing with the integration of EH sources in every scenario. The simulation also shows, that the usage of different load profiles, represented by the different years, have only a minor influence on the operational costs and the emissions.

The emission factor for the DH from the reference scenario in 2002 is with 173 kg CO_2 eq./MWh_{th} at its highest. The integration of EH in the Industrial EH Scenario shows a significant decrease on the emission factor, as the NG boiler is displaced by EH. In the scenario Industrial Heat + Pit the emission factor is rising caused by the pit gas. The emission factor of pit gas is 68.1 t/TJ [41]. As there is no product produced in an industrial process, the emissions have to be allocated to the heat production. The heat generated in a CHP unit is allocated with the efficiency method, so that the emission factor of the pit gas is 220 kg/MWh. This fact causes the rise of the emission factor for DH compared to the Industrial EH Scenario. In the Industrial EH+ Scenario the emission factor for DH is at its lowest with a value from 118 kg/MWh_{th} in the 2002 profile.

A sensitivity analysis is done with the Industrial EH+ Scenario for the 2002 heat profile. This scenario has the lowest LCOH of 30.8 €/MWh_{th} and the lowest

Table 8: Summary of the main findings from the simulation

	Year	Operational Costs [€/MWh$_{th}$]	Capital Costs [€/MWh$_{th}$]	LCOH [€/MWh$_{th}$]	Emissions [kg/MWh$_{th}$]
Reference	2002	31.3	5.3	36.5	173
	2010	31.4	5.3	36.7	173
	2020	31.1	5.3	36.4	172
IEH	2002	26.7	5.4	32.1	127
	2010	27.1	5.4	32.5	130
	2020	26.4	5.4	31.8	124
IEH & PIT	2002	26.4	5.4	31.8	128
	2010	26.8	5.4	32.2	131
	2020	26.1	5.4	31.5	126
IEH+	2002	25.0	5.8	30.8	118
	2010	25.5	5.8	31.3	121
	2020	26.6	5.8	32.4	115

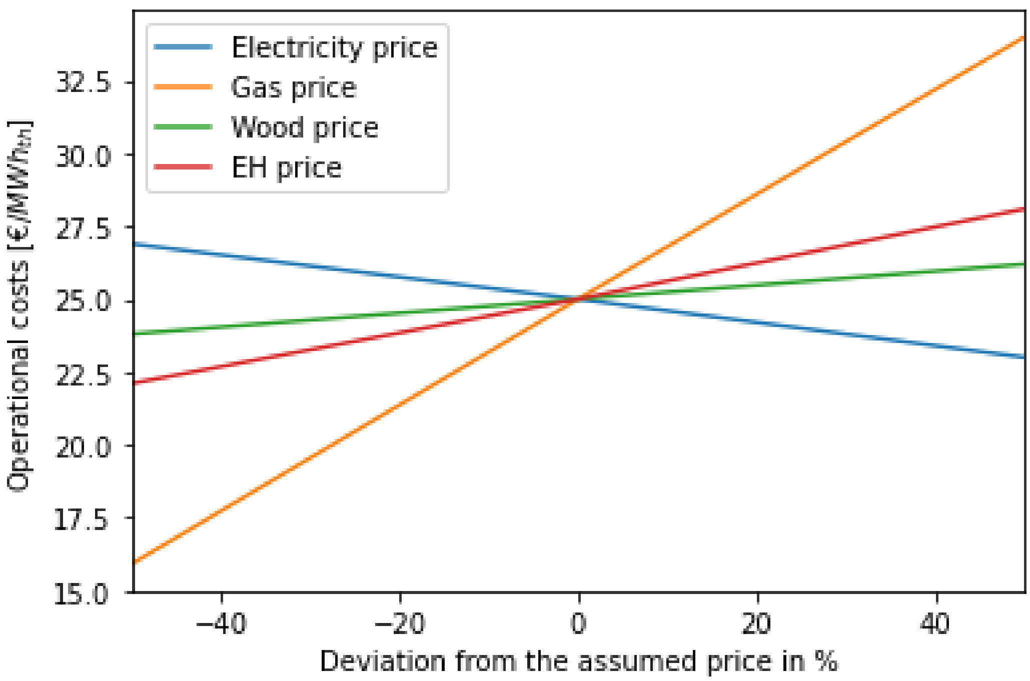

Figure 6: Sensitivity analysis of the Industrial EH+ Scenario with the 2002 heat load profile

operational costs of 25 €/MWh$_{th}$. Furthermore, this scenario has the best performance on CO_2 emissions. The majority of the LCOH is caused by the operational costs. In regard with turbulent energy markets, the prices for energy are very insecure and can show a wide range in a short period. As the operational costs depend on the energy costs, a sensitivity analysis is made on the energy costs to estimate the insecurities on the Industrial EH+ scenario.

For the sensitivity analysis every energy carrier is individually varied in a range from -50% to +50% around the assumed energy prices in Table 5. Figure 6 shows the results of the sensitivity analysis.

Electricity prices, gas prices and EH prices are causing the most insecurities on the scenario. The varying of the gas price shows a wide spread from 15.9 €/MWh$_{th}$ to 34.0 €/MWh$_{th}$ for the operational costs and is the most insecure parameter in the scenario. The EH price is a very significant parameter to the economic performance of this scenario. A price range from 22.1 €/MWh_{th} to 28.1 €/MWh_{th} is caused from EH prices to the operational costs. Electricity prices are also an important sensitive parameter. Conspicuous are the rising costs when electricity prices are decreasing and vice versa. This is caused by the lower revenues for the generated electricity by the CHP biomass plant. With increasing electricity prices, the CHP biomass plant gets more profitable. The operational costs vary from 26.9 €/MWh_{th} when electricity prices are low and 23.0 €/MWh_{th} when electricity prices are high. The wood price has less influence on operational costs. The spread is from 23.8 €/MWh_{th} to 26.2 €/MWh_{th}.

The CO_2 pricing is an insecure value. As mentioned in section 2.4, the price is used from the national emission pricing system for Germany. These prices will grow in future up to 65 €/t in 2026. Also, politics can change, and the price can reach a higher level like the price for CO_2 emissions in the European Union Emissions Trading system or above, like in other countries. To show the effects on higher CO_2 pricing, a sensitivity analysis is made to emission pricing with heat demand profile for 2002 and operational costs for the Industrial EH+ scenario. The prices assumed are in the range from 25€/t to 150 €/t CO_2 emissions in 25 € steps. The results are summarised in Table 9. With the highest assumed price of 150 €/t the operational costs rise up to 38.1 €/MWh_{th}.

Table 9: Sensitivity of CO_2 emission prices for Industrial EH+ scenario

CO_2 emission price [€/t CO_2]	Operational costs [€/MWh_{th}]
25	25.0
50	27.5
65	29.1
75	30.2
100	32.8
125	35.5
150	38.1

A price of 100 €/t leads to 32.8 €/MWh_{th}. The price targeted by the German government for 2026 leads to 29.1 €/MWh_{th} operational costs.

An important fact is that the heat demand used to calculate the three different heat load profiles is a fixed value, so that rising heat demand in a cold year and a decreasing heat demand in warm year is not taken into consideration. To pay attention to that fact, a sensitivity analysis is made to the heat demand in the industrial EH+ scenario. With 2010 as a cold year, each heat demand value of its heat demand profile is increased up to 5% and 10% for the sensitivity analysis. For 2020 as a hot year, the heat demand is decreased in the same way down to -5% and -10%. The calculation is summarised in Table 10. With a lower heat demand for the hot year operational costs are decreasing, and capital costs are increasing. The difference to the average year 2002 and to the initial results in Table 8 are minimal. The same applies to the cold year, except that here the operational costs are increasing, and capital costs are decreasing. The LCOH in sum stays in an almost equal state.

6. Discussion and conclusion

The results have shown how the presented approach enables extending and decarbonising existing district heating systems. The focus is on assuming the future DH demand and the determination and integration of EH sources. With a simulation model, the operation costs, the total costs and the emission factors of the DH system are determined, showing that EH is able to improve the economical and ecological performance of the DH system.

The EH sources were mapped with publicly available data. This data is fragmentary, thus, the potential of EH is calculated from the fuel input data combined with EH ratios and carbon dioxide emission data. The EH ratios are representing a whole manufacturing sector. It is not possible to consider the specific characteristics of a single manufacturing plant, thus, an inaccuracy should

Table 10: Sensitivity analysis for the heat demand in Industrial EH+ Scenario

	2020		2010	
Deviation from Heat Demand [%]	–10	–5.0	5	10
Heat Demand [MWh/a]	1,090,800	1,151,400	1,272,600	1,333,200
Operational Costs [€/MWh_{th}]	23.2	23.9	26.1	26.6
Capital Costs [€/MWh_{th}]	6.4	6.1	5.5	5.3
LCOH [€/MWh_{th}]	29.6	30.0	31.6	31.9

be taken into account. Furthermore, not all EH sources of the city could be mapped and determined because of the data quality, so that promising EH sources may not be considered. In all of these fragmentary data, the mass flow of CO_2 emissions or information about the fuel input is necessary to generate values for EH.

Another point that makes it hard to process the data from reference [29] is the wide range of values for EH provided in this reference. Comparing the calculated value for IEH2, which is calculated to 2.65 MW, the value in reference for IEH2 is in the range from 10 kW to 1000 kW. IEH3 and IEH4 are not considered in reference [29], so that the approach of EH ratios is used for determination and no comparison is possible. At, this point, a unified recording system for EH with real values, not only assumed values, is necessary.

The results in the considered case depend on the assumptions made in this study. The heat demands of the buildings considered are taken from an official federal agency to calculate the heat demand for the investigation area of the DH system. At this point an accurate data quality is needed. As the data is calculated on the base of geometry and the decade the building was built, refurbishment is not considered, leading to a higher demand for DH. As it is known from the local DH operator, there are also buildings supplied with DH that are not in a suitable area for DH, so that possible demands from future DH customers nearby the DH network are not considered in the heat demand.

The simulation model allows a first statement about the integration of the EH sources and its impact to the DH system. As some technical and economic constraints are not considered in the simulation model e.g., start-up times, start-up costs or ramp-up, it should be assumed that the results from the simulation have uncertainties. Depending on the assumptions for the technical and economic constraints, other results can be expected. With regard to the chosen assumptions, it can be seen that the use of biomass in CHP is advantage due to the low cost for fuel as well as the high revenue by selling electricity. However, the sensitivity analysis shows how changing cost assumptions will affect the LCOH, especially the gas and electricity price. Sensitivity analysis of CO_2 pricing showed an effect on the operational costs

A major point on the costs is the price for carbon dioxide emissions. As it is known that national carbon pricing will rise in future to 65 €/t, the rising costs for operation have to be considered when planning the DH system for the future. Also politics can change and prices above that level are possible. Varying heat load profiles and heat demands have only a minor effect on the performance of the investigated district heating system.

Furthermore, the results underline that integration of EH is beneficial in terms of CO_2 reduction. Although biomass utilisation has lower CO_2 emissions than the use of natural gas, it cannot be considered as carbon neutral. Here, the integration of EH has further ecological potential. Thus, future work will analyse the break-even and changing points at which EH can replace biomass use in CHPs. In addition, the use of CHP units should increasingly be considered against the background of fluctuating feed-in from RES, so that a more flexible operation of the plants can be advantageous from an overall system perspective. Considering this aspects as well as the use of biomass with regard to its sustainability in ongoing deeper analyses may change the previous outcome of biomass use as a base load.

The temperature of 110°C is a very high temperature for DH systems and is not comparable to modern 4th and 5th generation DH systems, which have lower forward temperatures. To lower the temperatures of the considered system in this study, investments in building refurbishment and pipes with better insulations is needed. This will lead to two advantages. The demand for DH will decrease, what automatically leads to lower production and to lower emissions caused by the production. The second point is, that the efficiencies of the heat pumps will rise. This means a higher COP and more heat production by a heat pump, which strengthens the aspect of integrating EH.

From the knowledge extracted from this study, future work of fields can lead to field work investigating the cities EH potential in field work by measurement and quantifying the amount of available EH. Another future work could lead to the determination of EH potential for the federal state of Northrhine-Westfalia with the sources presented in this study, to get a first order understanding of the states EH potential.

Author Contributions

Denis Divkovic: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing.

Lukas Knorr: Methodology; formal analysis; writing – review and editing.

Henning Meschede: Conceptualization; investigation; methodology; writing – review and editing

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