International Journal of Sustainable Energy Planning and Management Vol. 41 2024 58–70

International Journal of
Sustainable Energy Planning and Management

Covering District Heating Demand with Waste Heat from Data Centres – A Feasibility Study in Frankfurt, Germany

Bjarne Jürgens[*], **Johannes Zipplies, Christian Sauer, Oleg Kusyy, Janybek Orozaliev, Ulrike Jordan, Klaus Vajen**

Institute of Thermal Engineering, University of Kassel, Kurt-Wolters-Straße 3, 34127 Kassel, Germany

ABSTRACT

Currently, the huge potential of data centre waste heat for the decarbonization of the heating sector is often ignored. Here, a feasibility study is presented for covering the heat demand of two districts of Frankfurt (Germany) mainly by data centre waste heat. Contrary to many other studies, the total heat demand (144 GWh/a) is to be covered almost exclusively with waste heat integration, the district heating network is not existing yet and the buildings to be connected are not particularly energy efficient. In this study, the potential and demand are estimated, a heating supply concept is presented and evaluated regarding costs, heat pump capacity, and storage size. As a result, the utilisation of data centre waste heat is not only possible, but it is the most promising way for decarbonizing heating in the area under consideration. With high-capacity heat pumps (37 MW_{th}), gas boilers (20 MW_{th}) and a thermal energy storage for daily peaks, 97.5% of the heat demand can be covered with waste heat usage. It is economically favourable compared to individual heat pumps for all types of buildings and with the proposed concept, CO_2 emissions in the district heating network area are reduced by 78% on average.

Keywords

Fourth-generation district heating;
Smart energy systems;
Waste heat;
Data centres;
Feasibility study

http://doi.org/10.54337/ijsepm.8149

1. Introduction

With the Paris Agreement in 2016, 195 nations agreed to limit global warming to 1.5 or 2 °C [1]. This indicates the urgency of taking measures against climate change in every sector and since then, more effort has been put into national laws for renewable energies and energy efficiency.

For instance, two novel laws were passed in Germany in 2023 tackling the heat sector: First, heat supply systems for buildings must successively become climate neutral [2]. This makes a district heating network (DHN) connection for house owners more attractive, given that the grid's heat supply becomes climate neutral. Second, data centres are required to reuse at least 10% of their waste heat if taken into operation in 2026 or later according to EnEfG [3]. This will push data centre owners to supply waste heat to a DHN. In synergy with the previous law, it sets a good starting point for data centre waste heat integration into DHN in Germany.

Several authors have shown that DHN play a crucial role for decarbonised smart energy systems due to the energy storage potential and the access to heat sources that would be locked otherwise [4–6]. One of those heat sources is waste heat. Many authors also refer to it as 'excess heat', which is seen as equivalent term here.

In [7], Lund and Østergaard estimate that half of the heating demand in Europe could be covered with waste heat when using district heating. Waste heat is provided at a wide range of temperatures depending on the specific process. Temperature levels of more than 95 °C are common for example in the iron and steel industry while other sectors, such as refineries, paper, or chemical industry, often provide waste heat at around 25 to 55 °C [8].

---

[*] Corresponding author – e-mail: solar@uni-kassel.de

Abbreviations

COP	coefficient of performance
sCOP	seasonal coefficient of performance
DHN	district heating network
LCoH	levelized cost of heat

The waste heat temperature level is crucial for the integration into DHN, because waste heat sources can only be used directly if the temperature level exceeds the DHN supply temperature [9]. Otherwise, the waste heat temperature level must be raised, most commonly by using heat pumps [10]. This can be referred to as 'indirect' integration. An exception is waste heat integration into the DHN return line, which is investigated but not common [11].

Data centre waste heat can usually only be integrated indirectly into DHN, since data centres normally use air-cooling which provides a waste heat temperature level of around 25 °C [12,13]. Currently, DHN are usually 2nd, 3rd, or 4th generation with supply temperatures of 70 °C and much more [14], so a heat pump is needed for waste heat integration, as it is also proposed in this study.

There has been a lot of research about heat pumps for district heating with the conclusion that centralised heat pumps can be a main part of future district heating, for example in [15,16]. David et al. demonstrated that large-scale heat pumps for DHN are reasonable at many locations in Europe [17]. Furthermore, in 2015 Lund and Persson mapped the potential heat sources for Denmark and compared it to the existing DHN [18]. They found that heat sources which could be used with a heat pump (not only waste heat) are available for 99% of the DHN.

Compared to other common heat sources that also need a heat pump for DHN integration like rivers, lakes, or ambient air, data centre waste heat provides higher temperatures, which results in low electricity costs for the heat pump [19]. Moreover, the temperature level and the waste heat potential are nearly constant throughout the day and year [20].

Moreno et al. stated in 2023 that in Denmark, data centre waste heat is mostly unused, but a potential baseload heat source, especially for 4th or 5th generation DHN [20]. Also in Germany, the potential is significant with approximately 16 TWh/a [21]. In 2023, Monsalves et al. examined the waste heat integration of three Danish data centres into district heating [22]. They concluded that the integration would be economically feasible for all three data centres, but only when the waste heat always can be integrated into the DHN. From the perspective of data centre owners, it is a convenient way to increase energy efficiency and reduce cooling costs [23]. To summarise, integrating data centre waste heat into DHN with heat pumps is not yet common, but its potential is increasingly being recognized.

Consequentially, there have been a lot of feasibility studies and planned or realised projects in recent years that utilise waste heat from data centres to supply district heating networks. Huang et al. in 2019 presented an overview on data centre waste heat reuse projects [24] and Wahlroos et al. have done the same for Northern Europe in 2017 [25].

In Odense, Denmark, a single data centre contributes more than 100 GWh/a to the city's district heating network by utilising waste heat with a heat pump capacity of 44 MW [26]. In 2020, it was the largest data centre waste heat usage in Denmark. Still, even in summer the total heat generation for the DHN in Odense exceeds 50 MW while in winter, it reaches more than 600 MW [27]. So, even though the amount of waste heat is massive, it covers only a minority of the total DHN demand.

Another example is found in Kirkkonummi, Finland, where 20% of the heat generation for the DHN is covered with a heat pump using data centre waste heat [28]. Further examples for the utilisation of data centre waste heat in DHN can be found in Stockholm, Sweden [29]; Mäntsäla, Finland [30]; and Val d'Europe, France [31].

In these examples, but also in all other projects mentioned in [25], the data centre waste heat only accounts for a minority of the heat demand and the network is already existing. No study was found where the DHN heat demand is almost only covered with heat pumps using data centre waste heat. Also, no project on a bigger scale was found where the network is newly built for an existing district to use data centre waste heat.

The present study focuses on this gap of knowledge with the following research question: How can large quantities of data centre waste heat be used to decarbonize the heating of existing buildings in the vicinity? This implies that the waste heat shall cover a vast majority of the demand (and not only base load) and that a DHN must be newly built, significantly raising the investment costs, so that it is challenging to develop a concept that is technically and economically feasible.

In the following, the steps of the feasibility study are presented first. Afterwards the results for every step are shown and discussed in one chapter each. Finally, the findings are summarised and discussed.

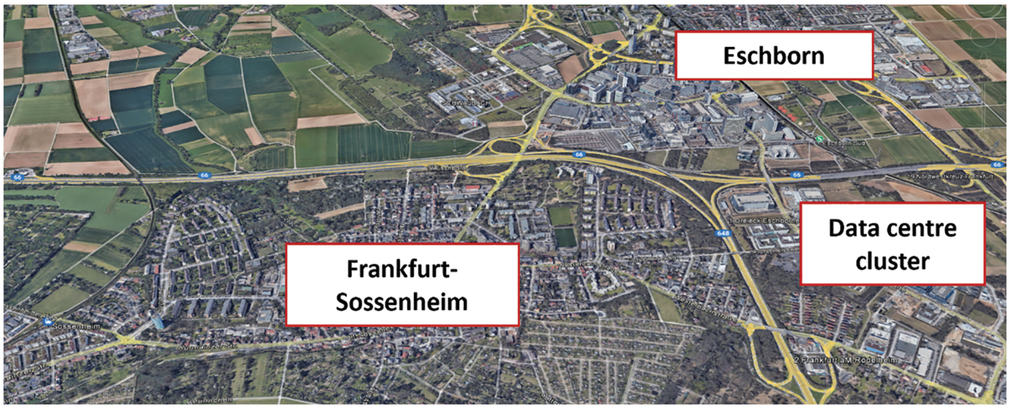

Figure 1: Examined area with data centre cluster and industrial/residential areas.

Source: Imagery © 2024 Google, Map data © 2024 GeoBasis-DE/BKG (© 2009), Google

2. Methodology

The area examined in the feasibility study is shown in Figure 1. It contains a cluster of data centres and two adjacent residential and industrial areas, Frankfurt-Sossenheim and Eschborn. Currently, the data centre waste heat is emitted unused into the environment and all buildings are heated with individual gas or oil boilers. The feasibility study shows how the waste heat could be used for district heating here, building a totally new DHN and replacing decentralized oil and gas boilers. The DHN is designed as part of the study, but not the focus of this paper. However, all costs for the network are included in the cost evaluation.

The study consists of four steps: Estimation of waste heat potential and heat demand, development of a heating supply concept and cost evaluation of the concept. The methodology of each step is described in the following, and applied in the subsequent sections.

2.1. Waste heat potential

To estimate the waste heat potential, the operators of all current and planned data centres in the cluster were contacted on major technical characteristics like nominal and real IT-load, floor space, temperature requirements and type of cooling system. For the most promising data centres, more information on technical properties, especially the detailed structure of the cooling system was collected. It was also investigated which development of IT-load can be expected from existing and newly established data centres in the area. Cumulated electricity consumption data from the grid operator was used for verification and to investigate daily or seasonal variability.

Combining all the information, the yearly waste heat potential, temperature level and effort of waste heat utilization is estimated for each existing and planned data centre. The waste heat potential is assumed to be 90% of the IT electricity demand according to [32]. Even 97% of the excess heat in server halls is transported via the cooling system, but the 90% also account for non-stationary operation and other technical constraints.

2.2. Heat demand estimation

The heat demand estimation is separated into two parts: First the annual heat demand must be estimated and second an hourly load profile is generated on that basis. The annual heat demand is mainly estimated based on gas consumption data, adjusted for weather, and aggregated on street level. Since gas boilers are used in nearly 90% of the buildings in the examined area, only a few buildings are missing. For those, the specific demand is estimated with building geometry and by interpolation of heat demands of neighbouring buildings.

Reductions of the future demand because of refurbishment and climate change are considered as well as a specific connection rate, both assumptions will be shown in the associated chapter.

To generate an hourly load profile, the “SigLinDe” standard load profile method is used, which has been developed and successfully applied in the German gas supply sector [33]. Here, the annual demand is divided over the hours of the year based on the daily mean outdoor temperature, day of the week and time of day. For this study, a synthetic, representative temperature time series for Frankfurt is used (base year 2030, realistic-optimistic climate scenario “IPCC AR4 A1B”), which is generated using the Meteonorm software [34]. To determine the peak load and investigate system operation at peak load, a day with a permanent outside temperature of –10 °C is artificially inserted.

2.3. Development of the heating supply concept

Based on potential and demand, the heating supply concept is developed, including the central heating system and the network. The network planning was conducted in collaboration with an engineering office, especially to yield a realisable network route and cost estimation that takes existing infrastructure into account and considers critical points such as the highway crossings.

The operation of the heating supply concept is simulated for one year in hourly resolution using the heat producer simulation gentool, a Python-based tool developed at the Department of Solar and Systems Engineering at the University of Kassel. The simulation results are used both for optimizing and verifying the supply concept and for the last step, its evaluation.

2.4. Cost evaluation

In the cost evaluation, the heat generation costs are calculated using the Levelized Cost of Heat (LCoH), as seen in Equation 1 [35]. Here, the LCoH are calculated for a period of T years using the investment costs I, the operating costs C_t on year t, the subsidies S_t on year t, the residual value RV, internal rate of return r, and the energy E_t generated on year t.

$$LCOH = \frac{I + \sum_{t=1}^{T} \frac{C_t - S_t - RV}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}$$

Equation 1: LCoH calculation

Then the LCoH for the centralised heat pump with DHN are compared to the costs for individual heat pumps calculated with the same method. This cost comparison was chosen instead of comparing with costs for gas or oil boilers because heat pumps, centralized or decentralized, will probably be the most common option for renewable heat supply in Germany [36], whereas existing oil or gas boilers are non-renewable heating systems. Furthermore, the effect of installed heat pump capacity and storage size on costs is examined by parameter variation.

3. Waste Heat Potential

The information about the data centre's waste heat potential is summarised in Table 1. There are ten data centres currently in operation in the study area which have a combined waste heat potential of 44 MW_{th} in January 2023. The electricity demand of the data centres and therefore the waste heat potential is only subject to minor seasonal and daily fluctuations, primarily due to the power requirements of the cooling systems depending on the outside temperature. The available waste heat output can therefore be regarded as continuous.

With the expected expansion of the existing data centres and considering the known information on three planned data centres, the total waste heat potential of the data centres will increase to approximately 112 MW_{th} by 2028, as seen in Figure 2. The data centre owners were also asked about waste heat temperature levels.

Table 1: Waste heat potential characteristics

Year	**2023**	**2028**
Number of data centres	10	13
IT-capacity in MW	49	124
Waste heat potential in MW_{th}	44	112
Waste heat temperature level in °C	25	25

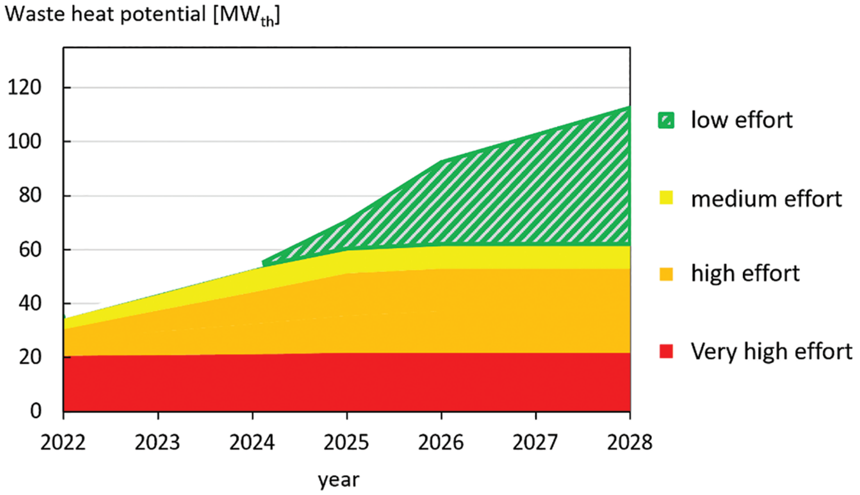

Figure 2: Data centre waste heat potential in the examined area between 2022 and 2028, classified by utilisation effort.

According to them, all data centres can provide waste heat at 25 °C. This is in good agreement with literature [12,13], so a waste heat temperature level of 25/15 °C was assumed.

The technical and therefore economical effort for waste heat extraction differs heavily for each data centre depending on the cooling system. To account for that, a classification for the heat extraction effort is introduced:

- **Low effort:** heat extraction was considered in planning and construction; waste heat can be extracted at a single point and either an adequately dimensioned heat exchanger is installed, or it can be easily integrated.
- **Medium effort:** moderate hydraulic changes in the cooling system are necessary; either one or only a few points for heat extraction; sufficient space.
- **High effort:** extensive hydraulic changes in the cooling system are necessary; decentralised cooling system so that many heat exchangers or collection pipes are needed.
- **Very high effort:** impossible: total replacement or severe changes of the cooling system are necessary; new operation mode for the cooling system is needed.

This classification is applied for each data centre in Figure 2. In 2028, approximately 50 MW_{th} of waste heat potential can be used with low effort. For all existing data centres in the examined cluster, the waste heat extraction effort is at least medium. More precisely, 20 MW_{th} of the current waste heat potential is almost impossible to use (very high effort), for example because the current cooling system is air cooling. However, new possibilities open up when the cooling system used reaches the end of its life cycle.

10 MW_{th} more can only be used with high effort, because the current cooling system is highly decentralised. Some of the data centres use more than a hundred individual cooling loops. Overall, none of the existing data centres is prepared for waste heat recovery, which locks a huge decarbonisation potential. Furthermore, the data centre owners are reluctant or even unwilling to make changes to the cooling system since it is a critical component and from their point of view, the rewards of waste heat extraction are small compared to the risks.

However, new data centres in Germany must reuse at least 10% of the waste heat if taken into operation in 2026 or later, according to a recent law [3]. This is why the waste heat extraction effort is rated low for all new data centres. So, a key finding of this study is that legal regulations are necessary for large-scale waste heat extraction from data centres.

4. Heat Demand

The total annual heat demand of both districts, Frankfurt-Sossenheim and Eschborn, is approximately 213 GWh/a in 2020. This is derived from data for gas consumption and building geometries, as described in section 2.2. A significant change in the heat demand of the connected buildings is expected over the service life of the heating network.

To estimate this development, the influence of refurbishments, the increase in outdoor temperatures due to global warming and the development of the heated area are considered. The influencing factors are very different for residential and commercial buildings, meaning that they are analysed separately.

For residential buildings, a constant demand reduction of 0.75%/a (related to the initial value) is assumed due to refurbishments and an additional reduction of 0.5%/a due to climate change [37–39]. Since the residential areas are already densely populated, the change of heated area is neglected.

For commercial buildings, the total demand reduction due to refurbishment and climate change is derived from [40,41]. The refurbishment rate is much higher, resulting in a mean reduction rate of 2.35%/a. On the other hand, the change of heated area in commercial buildings is supposed to increase by 1%/a.

Overall, there is a moderate reduction in heat demand of 24% for residential buildings over the period under consideration (2025 to 2045), while a very significant reduction of 43% is forecast for commercial buildings.

With that, the annual heat demand in 2025, which is used as start year for the heating supply concept evaluation, will be 192 GWh/a. A connection rate of 75% is assumed, resulting in 144 GWh/a of annual demand which must be covered by the DHN. The heat demand reduction is supposed to be compensated by connecting more buildings and, if a connection rate of 90% is reached, connecting new areas. This means that DHN pipes are designed for the final state in 2045, which is reasonable. Also, it is convenient for the calculations since the heat demand remains constant. All information about the planned DHN is summarized in Table 2.

The heat losses in the network were approximated based on route length (including house lead-in pipes), mean diameters, pipe properties (insulation series 3) and network temperatures and amount to 5.2% of the network's heat input, which is low but realistic due to a high linear heat density of 2.9 MWh/(m_{route}·a). Eventually, the annual heat supply for the DHN must be 152 GWh/a.

The corresponding hourly load profile is shown in Figure 3. The profile is obtained as described in section 2.1. It has a typical winter peak load of 55 MW and a summer heat load of 6 MW. The peak load for the design case at an outside temperature of –10 °C is 75 MW.

Table 2: Overview of the planned DHN characteristics for 2025

Route length in km	50
Connection rate in %	75
Annual heat demand in GWh/a	144
Annual heat input in GWh/a	152
Heat losses in % of input	5.2
Design peak load in MW_{th}	75
Typical winter load in MW_{th}	55
Typical summer load in MW_{th}	6
Linear heat density in MWh/(m_{route}·a)	2.9

5. Heat Supply Concept

The main characteristics of the heating supply concept are summarised in Table 3, as well as the main simulation results. Based on the previous sections, 50 MW_{th} of waste heat potential will be available in 2028, whereas the typical winter peak load is 55 MW_{th}. So, considering the electricity needed for the heat pumps and a storage for peak-shaving, the heat demand can be totally covered with data centre waste heat.

Table 3: Overview of the heating supply concept and simulation results for the operation

Heat pumps	
Thermal capacity in MW_{th}	37 (3 × 12,3)
Heat source temperatures in °C	25/15
Heat sink temperatures in °C	70/55 to 80/55
Heat output in GWh/a	148
Full utilisation hours per year	4,011
Fraction of heat generation in %	97.5
COP	3.76 to 3.9
Gas boilers	
Thermal capacity in MW_{th}	20 (2 × 10)
Heat output in GWh/a	4
Fraction of heat generation in %	2.5
Full utilisation hours per year	207
Heat storage	
Capacity in MWh	82
Volume in m^3	2,400

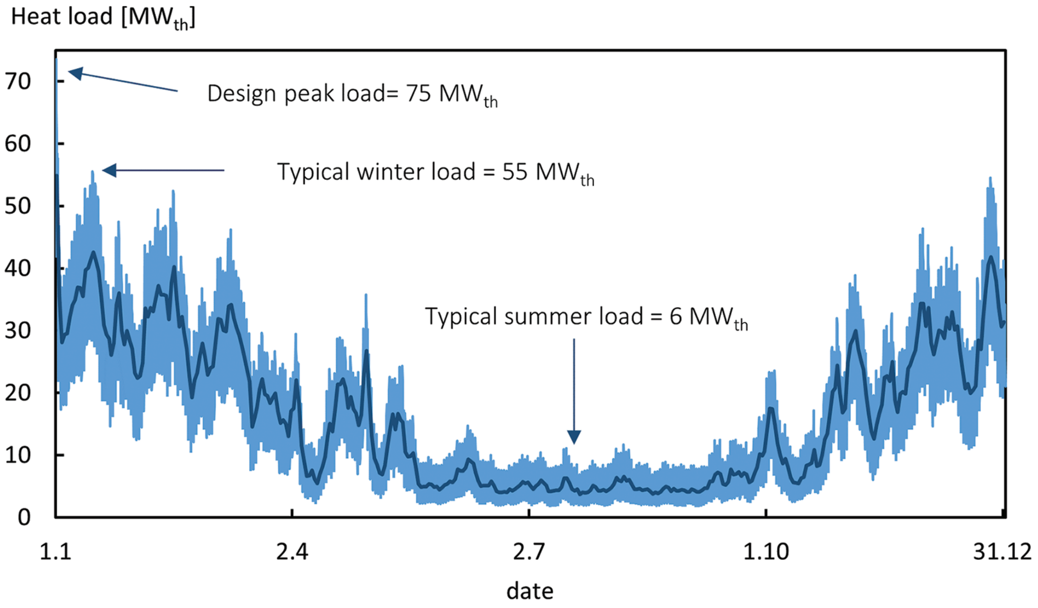

Figure 3: Load profile for the examined area including heat losses; light blue = hourly values, dark blue = daily mean.

However, since specific investment costs for gas boilers are much smaller than for heat pumps [42], it will be economically favourable to cover the peak loads with gas boilers. That is why gas boilers are also inserted in the heating supply concept. Additionally, they provide backup capacity. Now, the heating supply concept is proposed to find the optimum design parameters and evaluate it in the next section.

The heating supply concept consists of the central heating system, the collection network, and the distribution network, as seen in Figure 4. In the collection network with a length of less than 1 km, flow/return temperatures are 25/15 °C. For the 50 km distribution network, the supply/return temperatures are set to 70/50 °C to 80°C/50°C, with the supply temperature depending on the ambient temperature.

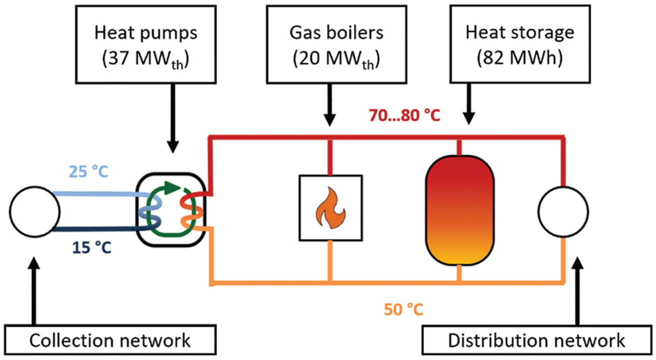

Figure 4: Scheme of the heating supply concept with design parameters and temperatures.

In the central heating system, three heat pumps with a total thermal capacity of 37 MW_{th} are installed, raising the waste heat temperature level, and covering base and medium load. The COP of the heat pumps is an extremely sensitive parameter because the electricity demand of the heat pumps is directly dependent on it, which in turn accounts for most of the total costs and CO_2 emissions.

Here, it was derived from a manufacturer's offer with COP_{max} = 3.9 at ΔT = 45 K and COP_{min} = 3.76 at ΔT = 55 K. As the temperature range is small, the COP characteristic curve is assumed to be linear for simplification purposes, so the COP varies linearly between 3.9 and 3.67, depending on the flow temperature.

Gas boilers with a total capacity of 20 MW_{th} are used for peak load and redundancy. Additionally, a heat storage is installed to compensate the daily load variations. It is designed for the maximum daily load variation, which is 82 MWh, transferring to a volume of 2,400 m^3 at the given temperatures. The maximum daily load variation is calculated with the deviation between load and rolling 24-hour-mean of the load. For each day, all positive and negative deviations are summed up, respectively. The design heat capacity of the storage is the maximum of all these sums. This ensures that the 24-hour-mean of the load can be achieved with peak shaving.

This concept is simulated as described in section 2.3. The annual generation profile resulting from the simulation is shown in Figure 5. It is evident that the heat pumps provide almost all the heat, and the gas boilers

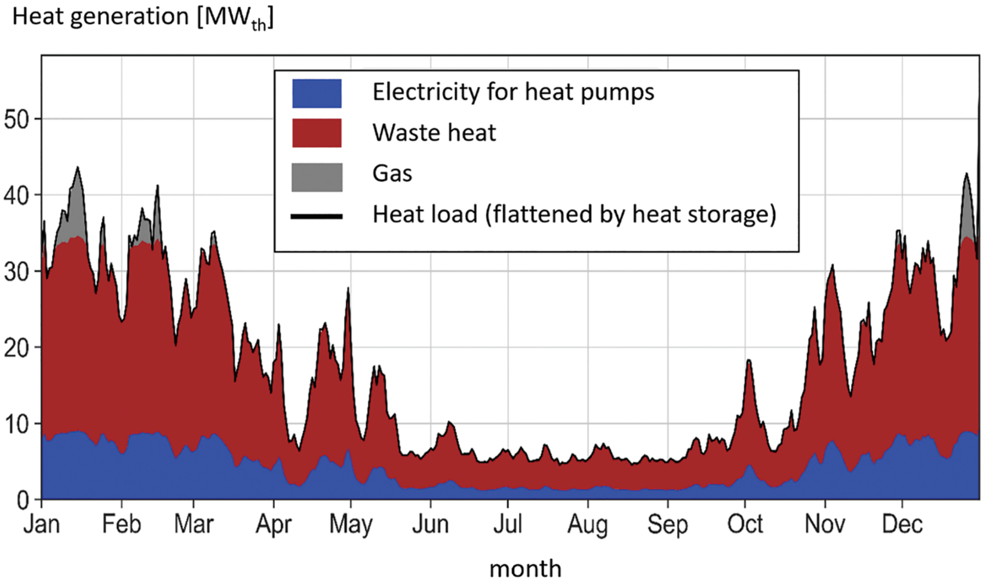

Figure 5: Simulated annual heat generation profile.

are only required on a few days in the winter months. In total, 76.5% of the heat generation is waste heat and 21% is electricity for the heat pumps. So, the heat pumps account for 97.5% of the heat generated, while the gas boilers only provide the remaining 2.5%.

The average heat output of the heat pumps is 16.9 MW_{th}, which means they achieve 4,011 full utilisation hours per year. Despite the high proportion of generation, the heat pumps are therefore not oversized. This is mainly due to the storage tank for peak load smoothing, which balances out the fluctuations in heat demand over the course of a day. The gas boilers, on the other hand, are utilised at 207 full load hours per year, which is not unusual for peak load generators.

The waste heat utilisation with this concept would reduce the CO_2-emissions of the connected buildings by 61% compared to the current situation in 2025. As the proportion of renewable energies in the electricity mix increases, emissions will continue to fall, meaning that the DHN will produce 78% less CO_2-emissions than the current situation over the 20-year period under consideration. The underlying CO_2-factors for this calculation are 201 kg/MWh for gas, 266 kg/MWh for oil, 293 kg/MWh for electricity in 2025, and 0 kg/MWh for electricity in 2045 [43].

6. Cost Evaluation

In addition to technical feasibility, the project must be economically viable for it to be realised. To calculate the LCoH as the main measure for economic feasibility, the following assumptions are made:

- Observation period 2025–2044
- Only the full expansion is considered, i.e., 75% connection rate in 2025
- Heat demand is the same in all years because the reduction in heat demand is compensated by densification and grid expansion
- Price change rate r = 3% p.a. for all costs
- Internal rate of return q = 3% p.a. without adjusting for inflation
- all costs in net terms, meaning that the German VAT of 19% is not included
- calculated with German subsidy, as described in the following two paragraphs
- Waste heat is provided free of charge, but the equipment and installation costs to integrate the waste heat are included in the investment

The capital costs are mainly given by recent manufacturers offers, whereas the lifetime and maintenance costs are taken from [42]. All capital costs except of the gas boilers and the house connection station are subsidised with 40% [44], and the subsidy for house connection stations is 30% [45]. In total, the capital costs are 87 M€, in which piping is the main part with 50 M€, followed by the central heating system including heat pumps and gas boilers with 28 M€. The capital costs for waste heat utilisation are approximately 2 M€, which is almost neglectable compared to the total investment.

Regarding energy costs, the prices for large consumers from 2022 in Germany are used [46]. For all subsequent years, a continuous price increase of 3% is assumed, as for all other costs. This leads to 199 €/MWh for electricity in 2025 and 80 €/MWh for gas. Regarding electricity, the German subsidy grants 145 €/MWh for the first ten years of operation, which makes up for approximately 55% of the electricity costs in this period [44].

For the gas price, the CO_2 price is also considered, as it is a significant part in later years. For the sake of simplicity, the CO_2 prices specified in German law are used until 2026 [47]. According to [48], an increase of 15 € per year is assumed until 2040, so that the CO_2 price in 2040 is 275 €/t and then, accounts for around a third of the gas price.

With these assumptions, the LCoH are 105 €/MWh with subsidies and 138 €/MWh without. The shares of LCoH are shown in Figure 6. A key finding is that, even with 55% of the electricity costs being subsidised for the first ten years, the electricity for the heat pump accounts for 55% of the total costs. This means that electricity costs and COP are the most sensitive parameters and when selecting the heat pump, a high COP should be chosen, even if the investment costs are significantly higher. The shares of capital costs mentioned previously can also be seen here.

To further derive transferable findings from this study, a parameter variation is done for the heat pump capacity and the heat storage volume. In the presented design (called ‘reference’ from now on), three heat pumps, each with a capacity of 12.3 MW, are used and they account for 97.5% of the heat generation. Since gas boilers are much cheaper than heat pumps regarding capital costs, an increase of the gas fraction might be economically favourable.

To examine this, the heating supply is simulated for five different heat pump capacities: 24.6 MW (called ‘2 HP’), 30.9 MW (called ‘2 ½ HP’), 37 MW (called ‘3

HP' or 'reference'), 49.2 MW (called '4 HP'), and 57 MW (called 'only HP'). In each case, the gas boiler capacity is varied so that the total thermal capacity of 57 MW remains constant. The resulting LCoH are presented in Figure 7.

For the case with the least heat pump capacity, the costs are much higher because the share of gas for the heat generation exceeds 10% and then the German subsidy is not granted. But for the case '2½ HP', where gas boilers account for 8.5% of the heat generation, the costs are increased by 5% compared to the reference case. For the variations with higher heat pump capacity, the costs almost remain the same.

Therefore, the economic optimum seems to be at a heat pump capacity between 65% and 100% of the total installed capacity and, in turn, at a gas share on the total generation between 2.5% and 0%. This is because energy costs and not capital costs are dominating the LCoH. The higher the internal rate of return, the more relevant are the capital costs. For 9% internal rate of return instead of 3%, the difference between LCoH is smaller, but the finding remains the same, as seen in Figure 7.

The heat storage capacity of 82 MWh is also varied to check the design. There are two variants with a smaller storage tank (0.5 or 0.75 × 82 MWh) and two

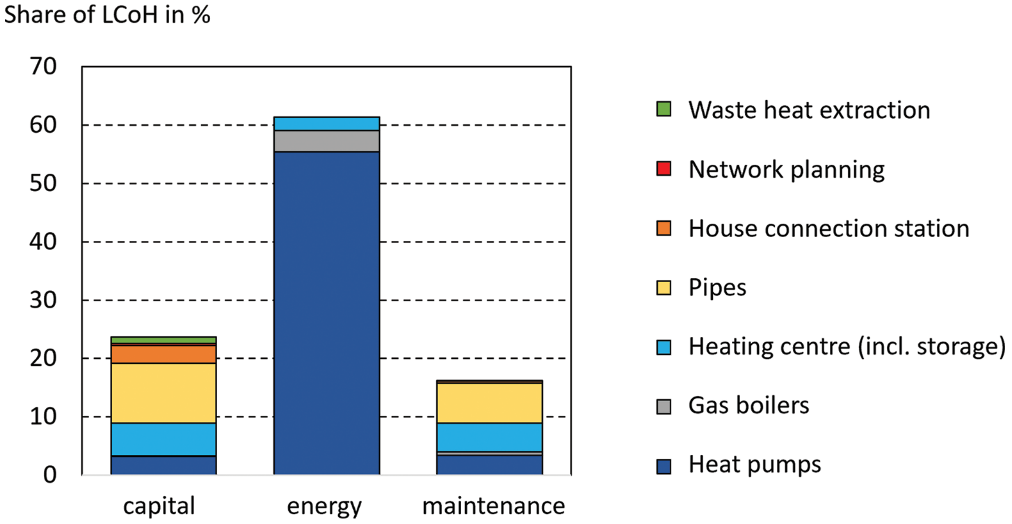

Figure 6: Distribution of the LCoH into capital, energy, and maintenance costs for each component.

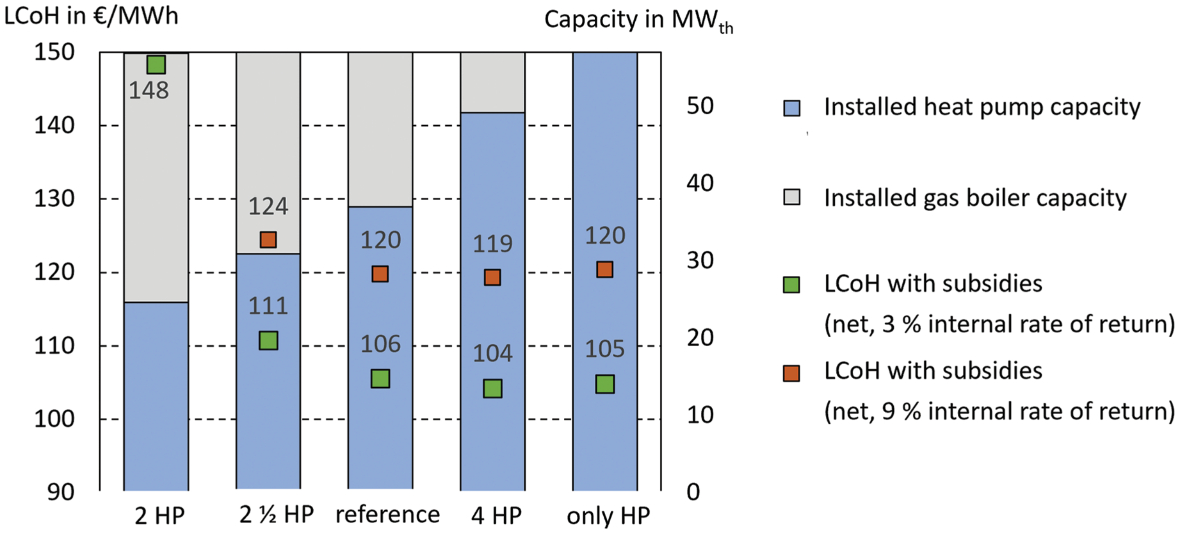

Figure 7: LCoH under variation of the installed heat pump capacity.

with a larger storage tank (2 or 4 × 82 MWh). The LCoH of all variants are shown in Figure 8. The cost optimum is still the main variant, even if the costs only differ by 0.5 €/MWh.

This is plausible if one considers the amount of heat stored in the variants: If the capacity is less than 82 MWh, not all daily peaks can be balanced anymore and accordingly the peak load gas boiler must be used more often, which causes higher running costs. If the capacity is greater than 82 MWh, then no more heat is stored, and only higher investment costs are required. A key finding is that the heat storage is always recommended, since it lowers the gas fraction and required total capacity at small investment costs of only 0.6 M€.

7. Comparison with Individual Heat Pumps

Comparative values must be used to interpret the heat generation costs of the heating network. For this purpose, the heat production costs of individual heat pumps for each building were calculated for 5 building types that are frequently found in Eschborn/Sossenheim. Individual heat pumps were chosen over other heating technologies like biomass, gas or oil boilers, because they fulfil the emission reduction goals unlike gas or oil boilers and there is no fuel shortage as it might be for biomass boilers when they are installed more frequently.

An air/water heat pump is assumed for the single-family house building type (SFH) and geothermal heat pumps for the multi-family (MFH) and commercial buildings due to the better seasonal performance factor. The seasonal COPs (sCOP) are taken from an evaluation of heat pump operation in existing buildings: For air/water heat pumps, it is sCOP = 3.1; for geothermal heat pumps, it is sCOP = 3.9 [49]. Any additional costs for necessary refurbishment measures are not considered.

For single and multi-family homes, the specific investment costs of 2018 from the evaluation of the German market incentive programme are used and extrapolated to the price level of 2025 using the construction price index [50]. Based on discussions with manufacturers, a surcharge of 10% is added to reflect the market situation for heat pumps in particular.

Heat pumps of a completely different order of magnitude are required for commercial buildings. The cost function from [42] is used here and extrapolated to the beginning of 2025 using the same method. The heat generation costs are calculated using the same economic efficiency parameters as for the heating network. All other economic assumptions are the same as for the DHN, and the German subsidy for the individual heat pumps is taken into account as well.

The results are shown in Figure 9. According to this, a connection to the heating network makes sense for all building types. For commercial buildings, it is even questionable whether individual heat pumps are even possible because the area is densely built-up, and it may be impossible to tap into a heat source.

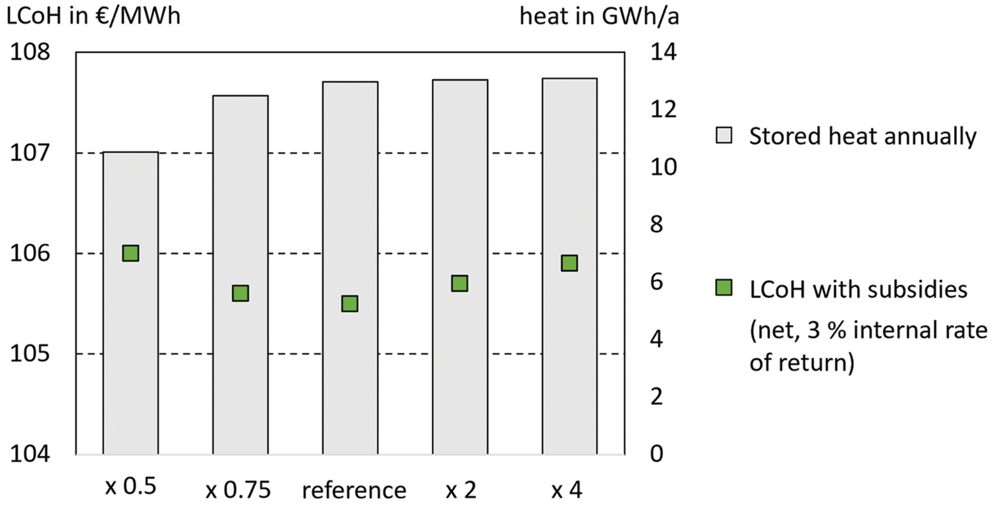

Figure 8: LCoH and annually stored heat under variation of the storage capacity.

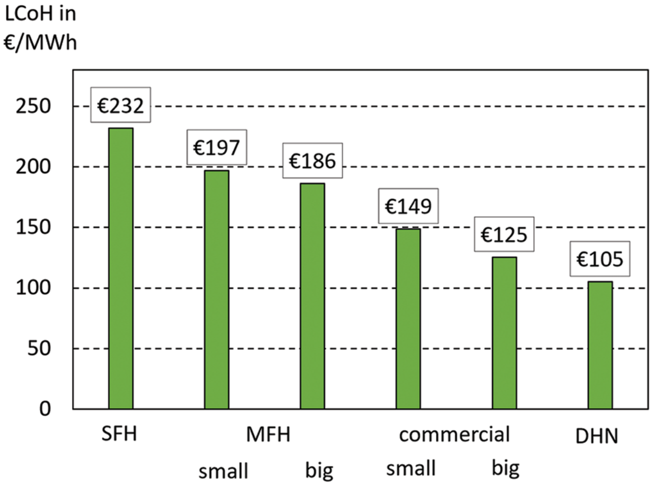

Figure 9: LCoH for individual heat pumps and different building types compared to the DHN.

A connection to the heating network is significantly cheaper because the electricity costs are much lower than for an individual heat pump. This is largely due to the operating cost subsidy in the first 10 years, which totals 55 M€. In addition, the sCOP of centralised heat pumps is significantly higher than that of individual air/water heat pumps.

The disadvantage of the heating network compared to individual solutions is the investment costs for the DHN (especially pipes). However, due to the high heat density in the area under consideration, the grid investment costs account for less than 20% of the heat generation costs. And the specific investment for the heat pumps is significantly lower because the load peaks in the DHN are smoothened and there is a storage tank to level out daily load peaks. This means that the heat pump capacity for the DHN is smaller than the total capacity of individual heat pumps that would be necessary.

8. Conclusion & Discussion

In this case study, covering the heat demand of 144 GWh/a with data centre waste heat is possible and with LCoH of 105 €/MWh economically favourable compared to decentralised heat pumps. The heat pumps account for 97.5% of the total heat generation and the CO_2– emissions can be reduced by 78% or rather 25,000 t/a. The exact numbers are only valid for this case, however, the following general findings on data centre waste heat utilisation in DHN were found.

First, it can be difficult to utilise waste heat from existing data centres due to the decentralisation of the cooling system, a lack of space or a lack of incentives for the data centre owners. With legal regulations, it is much easier to plan those projects, therefore novel laws as the one in Germany obliging for at least 10% data centre energy reuse are highly recommended.

Second, data centre clusters provide a huge potential for decarbonisation of the heat supply for existing buildings in the adjacent districts and using this potential often is the economically favourable option for end customers. As seen for the examined cluster, the potential will strongly increase in the future.

Third, the costs for waste heat extraction are neglectable compared to the costs for the central heating system and the DHN.

And fourth, a very high share of heat pumps on the total generation must be considered, because in this project, a heat pump share of 97.5% or more is the most economical option.

A main weakness of the study is the dependency of the LCoH on electricity costs. As seen in Figure 6, electricity costs make up for around 50% of the LCoH, so for example a change of 10% in electricity costs will result in a 5% change of LCOH. Also, the internal rate of return was set to 3% p.a., resulting in no return when taking the inflation rate of 3% p.a. into account. This was discussed with the person responsible from the city of Frankfurt for this feasibility study, but most likely a company will implement such a project with a much higher internal rate of return. In this example, the LCoH rise by 13 to 15 €/MWh when the internal rate of return is set to 9% p.a., as seen in Figure 8.

Another simplification is the period in which the heating network is built. For the cost calculation, it is assumed that the complete network is built in one year. But really, it would be built in different steps, so the investment costs would be split up over a long period of time. Also, the amount of sold heat per year would slowly grow. It was too much effort to represent this in the cost calculation, but the LCoH would change because of this.

Eventually, this very area is particularly favourable for a DHN because of a very high linear heat density of 2.9 MWh/(m_{route}·a). This is due to large office buildings in one part of the area. So, the DHN share of LCOH is around 20% as seen in Figure 6. This is unusually small for such a project. In other areas, the costs for the DHN itself will probably be higher.

Acknowledgements

This paper is based on a conference paper first presented at the '9th International Conference on Smart Energy Systems' in Copenhagen from 12 to 13 September 2023. The work presented in this paper is supported by LEA LandesEnergieAgentur Hessen GmbH through the project 'Scientific support for projects in the context of the energy transition' under Grant No. 92020-V-011 Lot 2.

References

[1] United Nations Framework Convention on Climate Change. The Paris Agreement; 2016.

[2] Bundesrat. Entwurf eines Gesetzes zur Änderung des Gebäudeenergiegesetzes, zur Änderung der Heizkostenverordnung und zur Änderung der Kehr-und Überprüfungsordnung: GEG; 2023.

[3] Bundesrat. Entwurf eines Gesetzes zur Steigerung der Energieeffizienz und zur Änderung des Energiedienstleistungsgesetzes; 2023.

[4] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.

[5] Chittum A, Østergaard PA. How Danish communal heat planning empowers municipalities and benefits individual consumers. Energy Policy 2014;74:465–74. https://doi.org/10.1016/j.enpol.2014.08.001.

[6] Lund H, Mathiesen BV, Collony D, Østergaard PA. Renewable Energy Systems - A Smart Energy Systems Approach to the Choice and Modelling of 100% Renewable Solutions. Chemical Engineering Transactions 2014(39):1–6. https://doi.org/10.3303/CET1439001

[7] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F et al. Energy Storage and Smart Energy Systems. International Journal of Sustainable Energy Planning and Management 2016;11:3–14. https://doi.org/10.5278/IJSEPM.2016.11.2.

[8] Manz P, Kermeli K, Persson U, Neuwirth M, Fleiter T, Crijns-Graus W. Decarbonizing District Heating in EU-27 + UK: How Much Excess Heat Is Available from Industrial Sites? Sustainability 2021;13(3):1439. https://doi.org/10.3390/su13031439.

[9] Frederiksen S, Werner S. District Heating and Cooling. Lund: Studentlitteratur; 2013.

[10] Nielsen S, Hansen K, Lund R, Moreno D. Unconventional Excess Heat Sources for District Heating in a National Energy System Context. Energies 2020;13(19):5068. https://doi.org/10.3390/en13195068.

[11] Rohde D, Andresen T, Nord N. Interaction Between a Building Complex with an Integrated Thermal Energy System and a District Heating System. Aalborg University, Department of Civil Engineering; 2016.

[12] Sorknæs P, Nielsen S, Lund H, Mathiesen BV, Moreno D, Thellufsen JZ. The benefits of 4th generation district heating and energy efficient datacentres. Energy 2022;260:125215. https://doi.org/10.1016/j.energy.2022.125215.

[13] Oltmanns J, Sauerwein D, Dammel F, Stephan P, Kuhn C. Potential for waste heat utilization of hot-water-cooled data centers: A case study. Energy Science & Engineering 2020;8(5):1793–810. https://doi.org/10.1002/ese3.633.

[14] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P et al. The status of 4th generation district heating: Research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.

[15] Lund R, Østergaard DS, Yang X, Mathiesen BV. Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective. 5-18 Pages / International Journal of Sustainable Energy Planning and Management, Vol 12 (2017) 2017. https://doi.org/10.5278/IJSEPM.2017.12.2.

[16] Münster M, Morthorst PE, Larsen HV, Bregnbæk L, Werling J, Lindboe HH et al. The role of district heating in the future Danish energy system. Energy 2012;48(1):47–55. https://doi.org/10.1016/j.energy.2012.06.011.

[17] David A, Mathiesen BV, Averfalk H, Werner S, Lund H. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. Energies 2017;10(4):578. https://doi.org/10.3390/en10040578.

[18] Lund, Rasmus, Persson, Urban. Mapping of potential heat sources for heat pumps for district heating in Denmark. Energy 2016(110). https://doi.org/10.1016/j.energy.2015.12.127.

[19] Pieper H, Lepiksaar K, Volkova A. GIS-based approach to identifying potential heat sources for heat pumps and chillers providing district heating and cooling. IJSEPM 2022;34:29–44. https://doi.org/10.54337/ijsepm.7021.

[20] Moreno D, Nielsen S, Sorknæs P, Lund H, Thellufsen JZ, Mathiesen BV. Exploring the location and use of baseload district heating supply. What can current heat sources tell us about future opportunities? Energy 2024;288:129642. https://doi.org/10.1016/j.energy.2023.129642.

[21] Ahrendts F, Drechsler B, Hendricks J, Küpper J, Lang S, Peil T et al. Roll-out von Großwärmepumpen in Deutschland. Fraunhofer-Gesellschaft; 2023.

[22] Monsalves JJ, Bergaenztlé C, Keles D. Economic feasibility of data center waste-heat integration into district heating: what does it require? Proceeedings of the 2023 19th International Conference on the European Energy Market (EEM) 2023:1–6. https://doi.org/10.1109/EEM58374.2023.10161985.

[23] Ülkü U, Karadeniz ZH, Akkurt GG. Waste Heat Recovery from Cooling Systems of Data Centers. In: Sogut MZ, Karakoc TH,

Secgin O, Dalkiran A, editors. Proceedings of the 2022 International Symposium on Energy Management and Sustainability: ISEMAS 2022, 1st ed. Cham: Springer International Publishing; Springer; 2023, p. 381–390.

[24] Huang P, Copertaro B, Zhang X, Shen J, Löfgren I, Rönnelid M et al. A review of data centers as prosumers in district energy systems: Renewable energy integration and waste heat reuse for district heating. Applied Energy 2020;258:114109. https://doi.org/10.1016/j.apenergy.2019.114109.

[25] Wahlroos M, Pärssinen M, Rinne S, Syri S, Manner J. Future views on waste heat utilization – Case of data centers in Northern Europe. Renewable and Sustainable Energy Reviews 2018;82:1749–64. https://doi.org/10.1016/j.rser.2017.10.058.

[26] Nguyen C. Utilizing Facebook Data Center Surplus heat for District heating in Odense – Denmark; Available from: https://www.ca-eed.eu/wp-content/uploads/2021/10/2_IS6.6_Facebook_DK_Chan-Nguyen.pdf.

[27] Copenhagen Centre on Energy Efficiency. District Heating in Denmark, the case of Fjernvarme Fyn. [February 21, 2024]; Available from: https://c2e2.unepccc.org/kms_object/district-heating-in-denmark-the-case-of-fjernvarme-fyn/.

[28] Fortum Corporation. Fortum and Ericsson sign collaboration agreement on utilising data centre's waste heat for district heating: Press release. [February 21, 2024]; Available from: https://www.fortum.com/media/2016/11/fortum-and-ericsson-sign-collaboration-agreement-utilising-data-centres-waste-heat-district-heating.

[29] Stockholm Exergi. Heat recovery with Open District Heating; Available from: https://www.stockholmexergi.se/varmeatervinning/.

[30] Sitra. District heating from data centre waste heat - Mäntsälä; Available from: https://www.sitra.fi/en/cases/district-heating-from-data-centre-waste-heat-mantsala/.

[31] Boye Petersen A. ReUseHeat Experiences from other urban waste heat recovery investments: Handbook. 25 cases of urban waste heat recovery. Kolding, Denmark; 2018.

[32] Huang F, Lu J, Zheng J, Baleynaud JM. Feasibility of heat recovery for district heating based on Cloud Computing Industrial Park 2015(International Conference on Renewable Energy Research and Applications (ICRERA)):287–91. https://doi.org/10.1109/ICRERA.2015.7418711.

[33] BDEW/VKU/GEODE. Leitfaden Abwicklung von Standardlastprofilen Gas. Berlin; 2020.

[34] Meteonorm. Bern: Meteotest AG; 2018.

[35] Baez MJ, Larriba Martinez T. Technical Report on the Elaboration of a Cost Estimation Methodology: Work Package 3 - Estimating RHC energy costs. Madrid, Spain; 2015.

[36] Deutsche Energie-Agentur GmbH. dena-Leitstudie Aufbruch Klimaneutralität: Eine gesamtgesellschaftliche Aufgabe 2021.

[37] Bürger V, Hesse T, Palzer A, Köhler B, Herkel S, Engelmann P et al. Klimaneutraler Gebäudebestand 2050 - Energieeffizienzpotenziale und die Auswirkungen des Klimawandels auf den Gebäudebestand. Dessau-Roßlau; 2017.

[38] Matzarakis A, Thomsen F, Mayer H. Klimawandel und Heizgradtage in Freiburg im Breisgau, Südwestdeutschland. Gefahrstoffe- Reinhaltung der Luft 2009(7/8):319–24.

[39] Cischinsky H, Diefenbach N. Datenerhebung Wohngebäudebestand 2016: Datenerhebung zu den energetischen Merkmalen und Modernisierungsraten im deutschen und hessischen Wohngebäudebestand. Darmstadt; 2018.

[40] Herrmann A, Mädlow A, Gross U, Krause H. Auswirkungen des Klimawandels auf den Energiebedarf von Gebäuden und den Ertrag erneuerbarer Energien. In: 14. Symposium Energieinnovation; 2016.

[41] Schlesinger M, Hofer P, Kemmler A, Kirchner A, Strassburg S, Lindenberger D et al. Energieszenarien für ein Energiekonzept der Bundesregierung. Basel, Köln, Osnabrück; 2010.

[42] Große R, Christopher B, Stefan W, Geyer R, Robbi S. Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU: External study performed by ILF Consulting Engineers Austria GmbH, and AIT Austrian Institute of Technology GmbH for the Joint Research Centre; 2017.

[43] BAFA. Informationsblatt CO2-Faktoren: Bundesförderung für Energie- und Ressourceneffizienz in der Wirtschaft - Zuschuss.

[44] BMWK. Richtlinie für die Bundesförderung für effiziente Wärmenetze "BEW"; 2022.

[45] BMWi. Richtlinie für die Bundesförderung für effiziente Gebäude – Einzelmaßnahmen (BEG EM); 2021.

[46] Destatis. Erdgas- und Stromdurchschnittspreise. [March 22, 2023]; Available from: https://www.destatis.de/DE/Themen/Wirtschaft/Preise/Erdgas-Strom-DurchschnittsPreise/_inhalt.html#421260.

[47] Bundesministerium der Justiz. Gesetz über einen nationalen Zertifikatehandel für Brennstoffemissionen (Brennstoffemissionshandelsgesetz - BEHG): BEHG; 2022.

[48] Öko-Institut, Berlin, Fraunhofer ISI, IREES, Thünen-Institut, Braunschweig. Projektionsbericht 2021 für Deutschland; 2022.

[49] Günther et al. Wärmepumpen in Bestandsgebäuden: Ergebnisse aus dem Forschungsprojekt "WPsmart im Bestand" (Abschlussbericht) 2020.

[50] Destatis. Baupreisindizes: Deutschland, Jahre, Messzahlen mit/ohne Umsatzsteuer, Gebäudearten, Bauarbeiten (Hochbau). [March 22, 2023]; Available from: https://www-genesis.destatis.de/genesis//online?operation=table&code=61261-0001&bypass=true&levelindex=0&levelid=1679478704219#abreadcrumb.