



ARTICLE

Techno-Economic Analysis of a Power-to-Heat System with Waste Water Heat Recovery Powered Mainly by an Off-Grid Wind Turbine

Johannes D. Pelda*, Sebastian Aichele, Dmitry Romanov and Stefan Holler

HAWK University of Applied Sciences and Arts Hildesheim/Holzminden/Göttingen, Göttingen, Germany

*Corresponding Author: Johannes D. Pelda. Email: johannes.pelda@hawk.de

Received: 21 January 2026; Accepted: 28 April 2026; Published: 12 July 2026

ABSTRACT: The transformation of district heating systems in Germany is a central topic in energy and climate policy, given the 2045 climate neutrality targets. This study focuses on the main district heating system in the city of Göttingen in Germany, whose heat generation currently relies primarily on three Combined Heat and Power (CHP) plants subsidized under the German CHP Act, one wood chip boiler and two gas boilers. In 2025, the network's heating demand amounted to 89 GWh, which was mainly covered by wood chips or biogas (41%) and natural gas (21%). This paper examines an option for increasing the share of renewable energy in the main district heating system of Göttingen. Therefore, this work analyses the integration of a power-to-heat system from a technical and economic perspective. The power-to-heat system consists of a Heat Pump (HP) that uses waste heat from a sewage treatment plant and is primarily powered by an off-grid wind turbine. The scenarios simulated vary in the temperature difference at the waste heat source and the part-load range of the HP. The optimum rated output of the HP is then determined based on the Levelized Cost of Heat (LCoH). The results indicate that the economic optimum is achieved with a HP of 2 MW capacity reaching a LCoH of 38.85 EUR/MWh. The integration of an on-site wind power plant ensures a self-sufficiency ratio above 0.55 in all investigated scenarios. Furthermore, the partial load range of the HP has a very positive effect on the LCoH. Overall, this analysis demonstrates a significant and economically viable decarbonization of the district heating system using local resources. Based on these results, it is recommended to investigate the potential benefits of integrating additional thermal or electrical storage systems. This could increase the share of renewable energies in the district heating system as well as the degree of self-sufficiency, and enable the provision of system services for the electricity market. Such measures could also contribute to a further reduction in the LCoH.

KEYWORDS: Heat pump; district heating; simulation; levelized cost of heat; sewer; wind power plant; waste water treatment plant; self-sufficiency

1 Introduction

Greenhouse gas emissions caused by human activities are the primary cause of the observed warming of the climate system and one of the greatest threats of the 21st century [1]. Global greenhouse gas emissions have reached record levels in recent years, with energy-related CO_{2,eq} emissions continuing to rise and contributing significantly to the increasing carbon load in the atmosphere [2]. According to the latest estimates, meeting the temperature limits of the Paris Agreement requires a rapid and sustained reduction in all major greenhouse gas emissions [3].

Reducing CO_{2,eq} emissions is therefore both ecologically crucial and economically sensible, as climate protection measures that limit warming also reduce climate impacts and the associated socioeconomic

costs [4,5]. In particular, the deployment and expansion of renewable energy technologies, such as wind and solar power, can significantly reduce CO₂ emissions from the energy sector by displacing the use of fossil fuels [6] (p. 406).

In Germany, renewable energies account for around 55% of electricity generation, but only approximately 22% of heat supply. Overall, the heating sector is responsible for about 20% of total CO₂ emissions, which will reach 640 million tons of CO₂ in Germany in 2025 [7].

A significant reduction in annual greenhouse gas emissions is possible, particularly in District Heating (DH). In 2024, the share of renewable energy in this sector was only 19% [8]. Providing heat with large-scale heat pumps (HPs) is one option for decarbonizing DH. Industrial waste heat or waste heat from waste water can be efficiently tapped for this purpose [6] (p. 413).

As part of its ambitious climate protection goals, the city of Göttingen wants to make its DH supply more sustainable. Stadtwerke Göttingen, the operator of the analysed DH system, has contractually committed to a primary energy factor below 0.5 and a CO₂ factor below 120 g/kWh [9]. Therefore, the share of renewable energies in DH supply is to be expanded; by 2045, the aim is to achieve a feed-in of 100% renewable energies with a maximum share of 15% biomass, and, in the medium term, a reduction in the CO₂ factor to 0 g/kWh while taking economic conditions into account [9].

Currently, the district heating system in the city of Göttingen comprises two biomass boilers, several combined heat and power units fueled by biogas or natural gas, and direct utilization of industrial waste heat. In 2025, the DH system derived 41% of its energy from renewable sources and waste heat [10].

In addition to the existing renewable energy sources, one component in the transformation of DH supply in Göttingen could be the integration of waste heat from the treated waste water at the waste water treatment plant in Göttingen using a water-to-water HP. The electrical energy from an off-grid wind turbine promises low electricity procurement costs, since the economic viability of a HP depends mainly on electricity costs [11,12]. The system configuration is shown in Fig. 1.

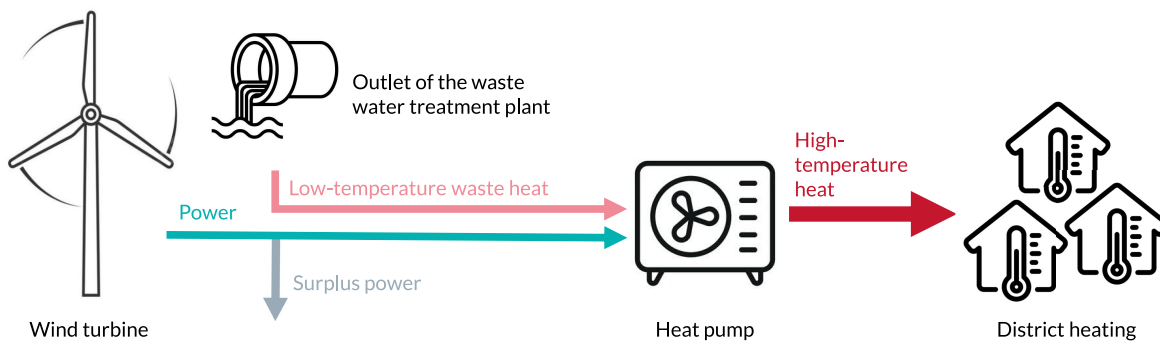


Figure 1: Schema of the analysed energy system (Icons used from istock, [pngtree.com](https://www.pngtree.com/), [freepik.com](https://www.freepik.com/), and [flaticon.com](https://www.flaticon.com/)).

There are several plants in Europe with HPs that utilize waste heat from waste water. Examples include [13] with a thermal capacity of 1.9 MW, [14] with 4.5 MW, and [15] with 40 MW, whereby the thermal energy of the waste water is increased from 8°C to 65°C. In addition, reference [16] provides a collection of projects on waste heat utilization in waste water treatment plants. However, no studies were found whose technical and economic results are directly transferable to this case study. This is because the HP are, without exception, powered by grid electricity and not supplied by a wind turbine via direct line. Furthermore, economic efficiency depends on hourly and site-specific data regarding weather, DH load profiles, and the

availability of waste heat. For these reasons, a site-specific analysis is necessary for a sound technical and economic evaluation.

This paper aims to address the techno-economic feasibility and optimal sizing of a HP and an off-grid wind turbine, as well as the associated energy flows when connected to the local DH network.

Using several scenarios, the energy and economic interactions of the most important system components—waste water flow, DH network, and wind turbines—are evaluated on the basis of hourly balances. The scenarios differ with respect to the temperature drop at the waste heat source, the nominal thermal output of the HP, and the Partial Load (PL) range. The PL range defines how a HP can reduce its power rating. 100% means a variation of 0 to maximum power rating is possible. Together with the investment and operating costs, economic parameters are calculated, including the LCoH. The LCoH is then used to determine the optimal system configuration.

The work begins with the fundamentals of the state of the art and current knowledge. The input data and methodology are then described. This includes data handling, energy balance calculations, formulation of adequate scenarios, and the basis for technical and economic analysis. The work concludes with the techno-economic results and further research questions.

2 Materials and Methods

The input data for the simulation include weather data, waste water volume flows and temperatures at the outlet of the waste water treatment plant, and the hourly DH demand in Göttingen. The energy system is influenced by local weather conditions. The German DWD Climate Data Center [17] provides weather data for the city of Göttingen including air temperature 2 m above ground level and wind speed 12 m above ground level. These data are available for all years in the study period; data from the year 2019 are used which match the year of measurement at the waste water treatment plan. In total, there are 122 h of missing outdoor temperature measurements, which are supplemented by the smoothed outdoor temperature of the measurements before and after. In the data set, there are 82 h of missing wind speed measurements, which are replaced by the monthly average wind speed.

2.1 Wind Power Plant

For the energy system model, a wind turbine of type Enercon E-160 EP3 E2 was selected which provides the electrical energy for operating the HP in addition to the grid connection. The electrical output is calculated hourly using the system-specific performance curve and the wind speeds from [17] extrapolated to 120 m hub height with Eq. (1), which specifies the electrical power as a function of wind speed at hub height.

$$v_{HH,i}(h_{HH}) = v_{MH,i} \cdot \frac{\ln\left(\frac{h_{HH}}{z_0}\right)}{\ln\left(\frac{h_{MH}}{z_0}\right)} \quad (1)$$

where $v_{HH}(h_{HH})$ is the wind speed at hub height, v_{MH} is the wind speed at measure height, h is the height, i indexes the time step, and z_0 takes the environmental conditions into account. Following [4], the surroundings around the city of Göttingen can be assumed to be $z_0 = 1$ m.

The wind turbine supplies the HP with electrical energy via a direct line, thereby avoiding grid fees. This results in electricity procurement costs from the wind turbine of 0.0735 EUR/kWh, which corresponds to the “[...] maximum value for tenders for onshore wind energy for the bidding dates in 2025 [...]” [18] set by

the Federal Network Agency. Although the wind turbine is grid-connected, only the direct electricity supply to the HP is considered within the system boundaries of this study. Electricity that is not consumed by the HP can be fed into the grid; however, the associated revenues are not included in the economic evaluation, as electricity market participation is outside the scope of this analysis. The grid electricity procurement costs, amounting to 0.166 EUR/kWh, are close to the industrial electricity price for 2024 according to BDEW [19].

2.2 Waste Water Heat at the Effluent Outlet of the Waste Water Treatment Plant

According to [20,21], the waste water at the outlet of a waste water treatment plant is on average 5 to 10 Kelvin warmer than the outside air over the course of a year. The difference is greatest during the winter months from October to April. This is also seen at the outlet of the waste water treatment plant in the city of Göttingen in Fig. 2. There, the waste water flow at the outlet of the treatment plant is given with daily temperature and daily volume flow for the year 2019.

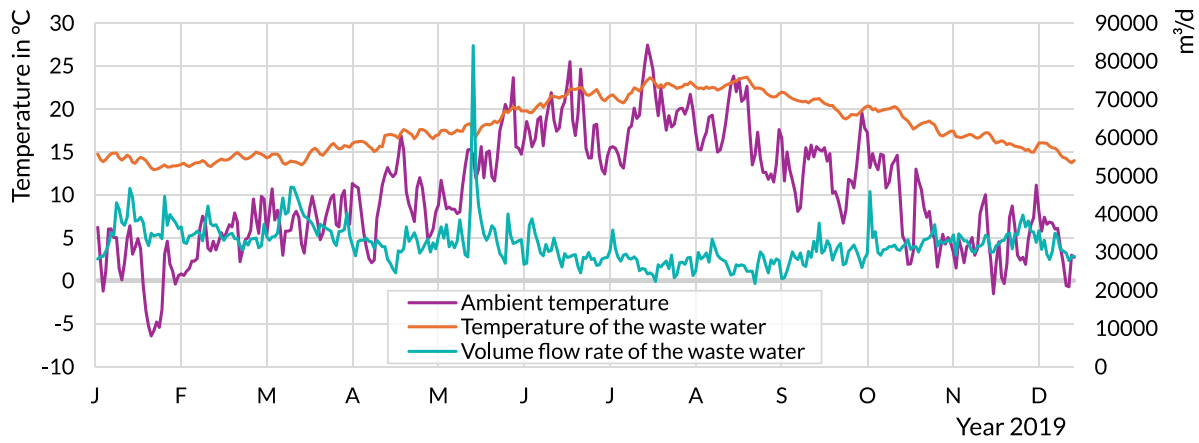


Figure 2: Temperature curve of the waste water stream at the waste water treatment plant. The difference in temperature between the waste water and the ambient temperature is greatest during winter months.

For the simulation, the daily values are distributed evenly across the hours of the day, with the heat extractable from the waste water being calculated using Eq. (2).

$$\dot{Q}_{WW,i} = \dot{m}_{WW,i} \cdot c_p \cdot \Delta T_{WW,i} \quad (2)$$

where $\dot{Q}_{WW,i}$ is the amount of waste heat, and $\dot{m}_{WW,i}$ is the mass flow rate of the waste water at time step i . c_p is the thermal heat capacity of water with 4.185 kJ/kgK, and ΔT is the temperature drop due to heat extraction.

It is assumed that the heat exchanger is capable of transferring the required heat load. The reduction in heat transfer performance due to biofilm formation is accounted for by appropriate over-sizing of the heat transfer area. This corresponds to common engineering practice, where fouling resistances are considered during the design stage using fouling factors or safety margins [22].

In practical operation, biofilm growth and removal processes (e.g., due to shear stress) typically reach a dynamic equilibrium, resulting in an asymptotic fouling resistance and a quasi-steady heat transfer performance [22] (p. 11–15). This approach is also consistent with industrial design practices as described in heat exchanger design guidelines [23].

2.3 Heat Pump

The HP is modelled on the basis of a standard thermodynamic cycle. The working medium evaporates in the heat exchanger on the heat source side, absorbing thermal energy in the process shown in Fig. 3 points ① to ②. A compressor in ② uses electrical energy to increase the temperature and pressure level of the working medium. Finally, the working medium releases its heat for heating purposes via a second heat exchanger, also referred to as the condenser on the heat sink side, between ② and ③. After passing through an expansion valve in ④, the temperature and pressure of the working medium drop back to their initial state. After condensation, the working medium begins the cycle anew. Overall, the HP raises the temperature of the treated waste water flow and feeds the thermal energy thus generated into the supply line of the district heating network. Ammonia (NH₃) is currently the most commonly used natural refrigerant for flow temperatures of around 90°C on the heat sink side [24].

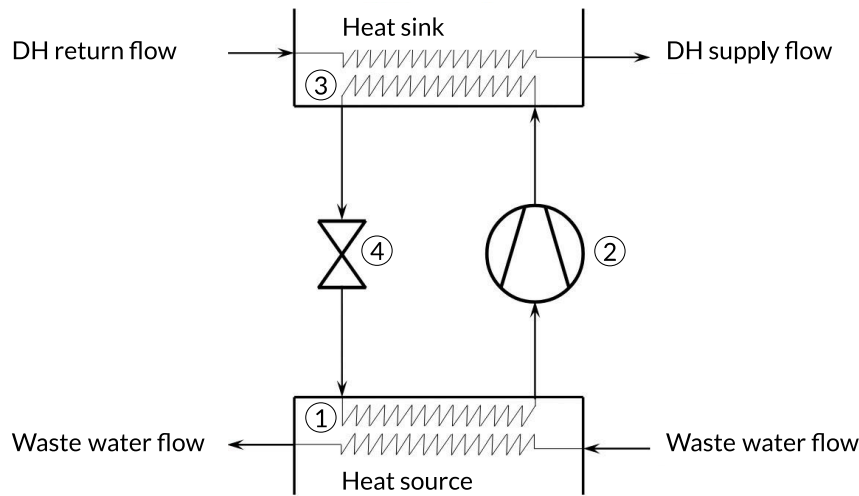


Figure 3: Schematic flow diagram of a waste water-based heat pump, showing the typical units and components. Adapted from [25].

Various key figures are used for technical and economic evaluation: the Coefficient of Performance (COP), the Annual Performance Factor (APF)¹, the Full Load Hour (FLH), the Levelized Cost of Heat (LCoH), and the Degree of Self-sufficiency (DSs).

Following [26], the operation of a HP can be described in a practical yet idealized manner by the Lorenz cycle. The corresponding $COP_{Lorenz,i}$ expresses the amount of heat (Q_i) that can be supplied per unit of work (W_i) at time step i and is defined by Eq. (3). Further discussions on the use of the Carnot or Lorenz cycle as a reference for HP performance can be found in [4,27].

$$COP_{Lorenz,i} = \frac{Q_i}{W_i} \quad (3)$$

According to [26], the COP_{Lorenz} can also be expressed by the average temperatures of the low-temperature heat source and the high-temperature heat sink. The average temperatures ($\bar{T}$) on the waste water side (WW) and the DH side are calculated for each time step i using Eqs. (4) and (5), respectively. Based on these average temperatures, the COP_{Lorenz} can be determined using Eq. (6) [28] (p. 349).

¹ Alternative terms used in the literature include Seasonal COP (SCOP) or Seasonal Performance Factor (SPF).

$$\bar{T}_{WW,i} = \frac{T_{WW,in,i} - T_{WW,out,i}}{\ln\left(\frac{T_{WW,in,i}}{T_{WW,out,i}}\right)} \quad (4)$$

$$\bar{T}_{DH,i} = \frac{T_{DH,in,i} - T_{DH,out,i}}{\ln\left(\frac{T_{DH,in,i}}{T_{DH,out,i}}\right)} \quad (5)$$

$$COP_{Lorenz,i} = \frac{\bar{T}_{DH,i}}{\bar{T}_{DH,i} - \bar{T}_{WW,i}} \quad (6)$$

Losses in the system components and peripherals are simplified and taken into account using the degree of quality (η) in order to indicate the actual efficiency (COP_i) of the overall system in accordance with Eq. (7). Based on the literature in Table 1, an average factor of 0.55 is reasonable.

$$COP_i = COP_{Lorenz,i} \cdot \eta \quad (7)$$

Table 1: Values for the degree of quality according to different literature.

Reference	Factor	Reference	Factor
[29] (p. 14)	0.5	[30] (p. 366)	0.5–0.6
[31] (p. 116)	≤ 0.5	[32] (p. 340)	0.45–0.55
[33] (p. 16)	0.6	[34] (p. 6)	0.55
[35] (p. 19, p. 21)	0.4–0.6		

With Eq. (8) the energy balance of the HP can be expressed. Depending on the consumed electric power (P_i) and the used waste heat ($\dot{Q}_{WW,i}$), the heat delivered by the HP ($\dot{Q}_{HP,i}$) can be calculated for time step i .

$$\dot{Q}_{HP,i} = P_i + \dot{Q}_{WW,i} \quad (8)$$

The APF shows the annual (a) efficiency of a HP and is the quotient of the annual thermal energy (Q^a) supplied divided by the sum of the annual electrical energy (P^a) consumed [32] (p. 338).

$$APF = \frac{Q_{HP}^a}{P^a} \quad (9)$$

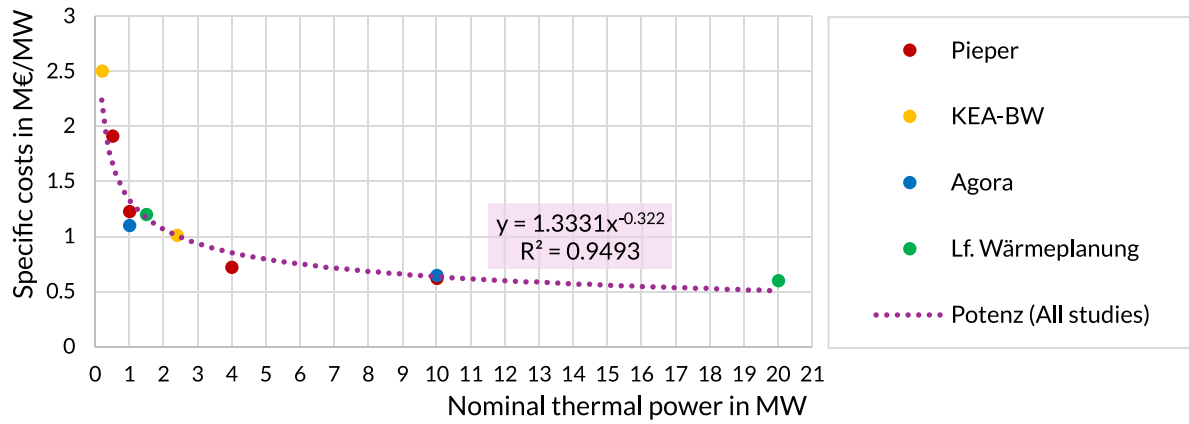
The FLH is calculated from the annual amount of thermal energy generated (Q_{HP}^a) divided by the nominal thermal output of the HP ($\dot{Q}_N$), as shown in Eq. (10).

$$FLH = \frac{Q_{HP}^a}{\dot{Q}_N} \quad (10)$$

The investment costs are derived from the costs of tapping the heat source, the HP itself, and other auxiliary equipment. The literature provides figures of different existing HP systems, given in Table 2. From these key metrics a regression function can be derived as shown in Fig. 4.

Table 2: Specific investment costs of several heat pump systems.

Reference	$\dot{Q}_N$	Specific Costs in M€/MW	Reference	$\dot{Q}_N$	Specific Costs in M€/MW
Pieper [36]	0.5	1.91	KEA-BW [37]	2.4	0.9
Pieper [36]	1	1.23	Agora [11]	1	1.1
Pieper [36]	4	0.72	Agora [11]	10	0.65
Pieper [36]	10	0.62	Lf. Wärmeplanung [38]	1.5	1.2
KEA-BW [37]	0.2	2.23	Lf. Wärmeplanung [38]	20	0.6

**Figure 4:** Specific investment costs of HPs and the regression function derived from them. The references can be found in Table 2.

Using the result from Fig. 4, the specific investment costs ($c_{I,HP}^*$) can be calculated as a function of the nominal heat capacity of the HP ($\dot{Q}_N$) given in Eq. (11). Thus, the investment costs ($C_{I,HP}^*$) are calculated by Eq. (12).

$$c_{I,HP}^*(\dot{Q}_N) = 1.3331 \cdot \dot{Q}_N^{-0.322} \quad (11)$$

$$C_{I,HP}^*(\dot{Q}_N) = c_{I,HP}^*(\dot{Q}_N) \cdot \dot{Q}_N \quad (12)$$

Additionally, the costs of Operation and Maintenance (O&M), excluding energy costs, must be determined. Literature assumes the O&M costs to be between 1.5% and 3% of the investment costs (see Table 3). In this paper, 3% is used.

Table 3: Operation and maintenance cost share of the investment costs.

Reference	Share of Investment Costs in %	Reference	Share of Investment Costs in %
[39]	1.5	[40]	2
[11]	3	[41]	1.5 to 2.5
[42]	1 Plus variable		

Given an expected lifetime (n) of 20 years and a discount rate (z) of 5%, the investment costs are increased by the annuity factor that is $\frac{z \cdot (1+z)^n}{(1+z)^n - 1}$. As the O&M are due yearly, they are assumed to be interest-free. Finally, the total annual costs of the system (C_I) can be determined by Eq. (13).

$$C_I = C_{I,HP}^*(\dot{Q}_N) \cdot \frac{z \cdot (1+z)^n}{(1+z)^n - 1} + C_{I,HP}^*(\dot{Q}_N) \cdot 0.03 \quad (13)$$

Following Eq. (14), the quotient of total costs ($\sum_i^n C_{I,i}$) divided by the amount of energy generated during lifetime ($\sum_i^n Q_{HP,i}$) is the LCoH. The LCoH is the most important key figure when dimensioning the system and should be as low as possible.

$$LCoH = \frac{\sum_i^n C_{I,i}}{\sum_i^n Q_{HP,i}} \quad (14)$$

The heat pump's DSs is defined as the ratio of the electricity supplied to the HP by the wind turbine to the total electrical energy used by the HP.

The Agora Energiewende study "The roll-out of large-scale heat pumps in Germany" [11] compares different heat sources for large HPs. They conclude that the investment costs for HPs that use the heat at the outlet of a waste water treatment plant are the lowest [11] (p. 75). Furthermore, plants are designed for a high annual operating time in order to achieve low heat production costs. Up to 7500 FLH are achieved, for instance in [43]. In 2023, HPs with a total rated thermal output of 60 MW were installed in Germany and 600 MW were in planning or under construction [34].

2.4 District Heating Load

The hourly heat load curve for the DH network from 2016 is adjusted to 2019 using the specific heating load curve. The geometric mean of the outside temperatures over the preceding four days, calculated in Eq. (15), is used to generate a smoothed outside temperature that takes into account the thermal inertia of buildings. Using the hourly DH demand and the smoothed hourly outside temperature, three specific heating load curves with the highest possible coefficient of determination are derived, see Eq. (16). With these three specific heating load curves, the DH demand is approximated for 2019 as a function of the outside temperature.

$$T_{g,i} = \frac{\frac{\sum_{i=0}^{i-23} T_i}{24} + \frac{\sum_{i=24}^{i-47} T_i}{24} \cdot 0.5 + \frac{\sum_{i=48}^{i-71} T_i}{24} \cdot 0.25 + \frac{\sum_{i=72}^{i-95} T_i}{24} \cdot 0.125}{1 + 0.5 + 0.25 + 0.125} \quad (15)$$

where $T_{g,i}$ is the outside temperature according to geometric mean and T_i is the measured temperature at time step i .

$$\dot{Q}_{DH,i} = \begin{cases} -155.89 \text{ kW/}^\circ\text{C} \cdot T_i + 5487.1 \text{ kW} & \text{for } T_i < 15.17^\circ\text{C} \\ -1070.7 \text{ kW/}^\circ\text{C} \cdot T_i + 19371 \text{ kW} & \text{for } 15.17^\circ\text{C} \leq T_i \leq 24.59^\circ\text{C} \\ 1700 \text{ kW} & \text{for } 24.59^\circ\text{C} < T_i \end{cases} \quad (16)$$

where $\dot{Q}_{DH,i}$ is the heat load of the DH system, and T_i is the outside temperature at time step i .

Data from the existing biomass plant of the Stadtwerke Göttingen show quarterly supply and return temperatures of approximately 90°C and 60°C, respectively, for 2019 and 2020. The emission factor for DH generation in 2025 is specified as 0.164 kg/kWh according AGFW FW 309-6 [44].

3 Results

The first result shows the potential of the heat source according to the scenarios in which heat consumption is guaranteed at all times. Next, the total heat that can be provided by the HP is only limited by the DH demand. Here, an inexhaustible heat source is considered. The combination of both results forms the basis for creating a time series over one year, calculating the electricity supply balance, and dimensioning the final HP.

3.1 Potential of the Heat Source

Fig. 5 shows that the amount of waste heat from the waste water increases linearly with the extraction capacity to just under 26 MW at a maximum temperature spread of ΔT 10 Kelvin. At a ΔT of 6 K, the annual heat quantity stagnates at an extraction capacity of 17 MW, at ΔT 5 K at 15 MW, and at ΔT 4 K at 11 MW.

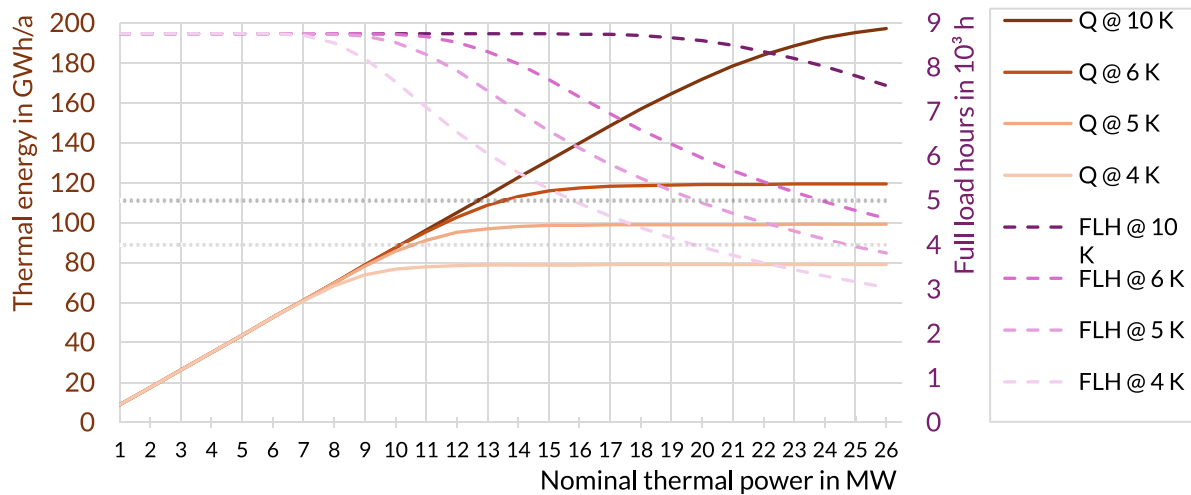


Figure 5: Influence of the temperature spread over the nominal thermal power of the heat pump. The available amount of waste heat from the waste water is not constrained by the district heating demand.

The temperature spread (ΔT) has a significant impact on the amount of recoverable waste heat. For a variable extraction capacity of up to 26 MW, the annual recovered energy is 200 GWh/a at $\Delta T = 10$ K, 120 GWh/a at 6 K, 100 GWh/a at 5 K, and 80 GWh/a at 4 K.

This indicates that, with few exceptions, the waste water temperature remains above 10°C throughout the year, since higher temperature spreads always allow more heat to be extracted at the maximum controllable capacity. Conversely, smaller temperature differences limit the total recoverable heat over the year.

The extraction capacity also influences the number of FLHs in an almost linear fashion. In the worst case, the FLHs begin to decrease from 8760 to 3000 h in the case of a ΔT 4 K and an extraction capacity of 7 to 26 MW. Furthermore, it can be observed that the temperature spread (ΔT) strongly affects the number of full-load hours (FLHs), shifting their decline toward lower extraction capacities. For example, with $\Delta T = 10$ K, FLHs of 8760 can be achieved up to an extraction capacity of 17 MW. For $\Delta T = 6$ K, this applies only up to 10 MW, for 5 K up to 8 MW, and for 4 K up to 7 MW. As a result, the limit of 5000 FLHs is first exceeded in scenario ΔT 4 K at a withdrawal capacity of 16 MW, followed by ΔT 5 K at 20 MW and ΔT 6 K at 24 MW. A ΔT of 10 K remains above 5000 FLH even at maximum withdrawal capacity.

3.2 Potential for Partial Load of the Heat Pump

The maximum heat quantity of 80 GWh/a is provided by a HP with a maximum PL range of 100% and a nominal thermal output between 21 and 26 MW (see Fig. 6). At a PL range of 75%, this is 70 GWh/a at a power rating of 17 MW, at 50% it is 62 GWh/a at 15 MW, and at 25% it is 52 GWh/a at 12 MW. In general, the lower the PL range, the greater the drop in heat output after the peak has been reached.

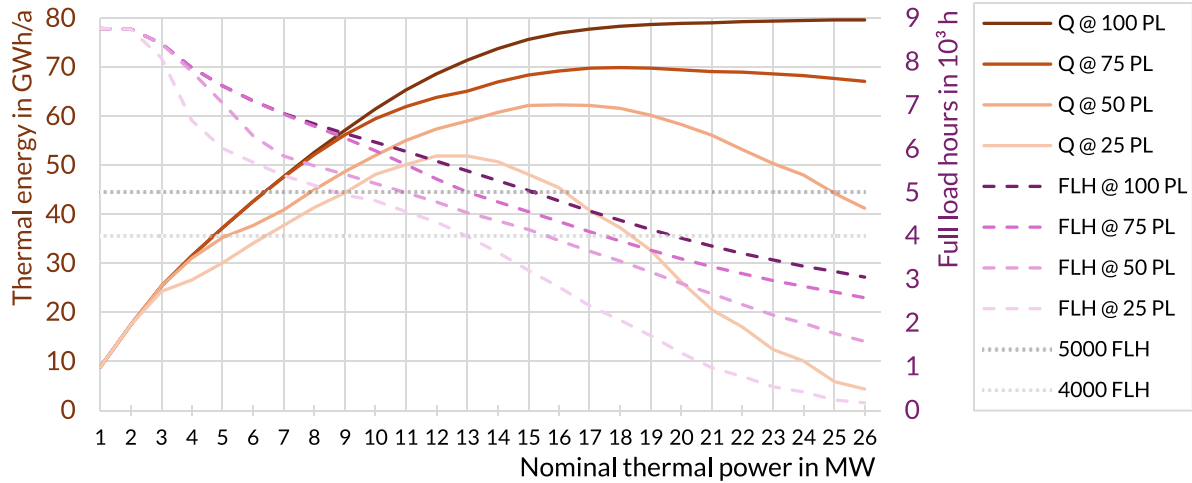


Figure 6: Influence of the partial load (PL) range over the nominal thermal power of the heat pump. The available amount of waste heat from the waste water is constrained by the district heating demand.

Up to a power rating of 2 MW, 8760 full utilization hours can be achieved. At maximum power rating, these are reduced to around 3000 h at 100% PL range and to just over 100 h at 25% PL range. FLHs decrease more significantly with increasing power rating and lower PL ranges.

3.3 Potential of the Overall System and System Design

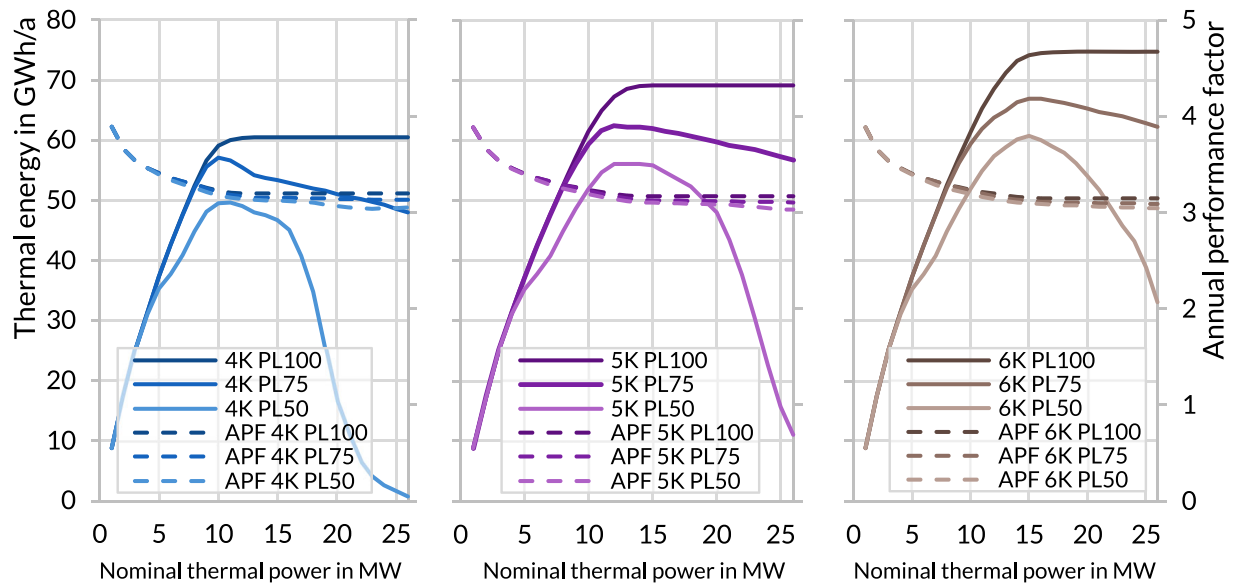
According to Fig. 5, up to 7 MW of heat output can theoretically be extracted from the waste water stream, with the heat quantity and FLHs remaining the same across all scenarios. According to Fig. 6, however, the annual heat quantity increases sharply up to a nominal output of 3 MW. The increase slows down above 3 MW. At 3 MW, the ratio of heat quantity to nominal output is optimal with maximum annual heat quantity. Looking at Fig. 6, the FLHs are greatest up to a nominal thermal power of 2 MW. Therefore, an optimal LCoH can be assumed for a nominal output of up to 2 MW.

This is confirmed by the overview of the LCoH in Table 4. In accordance with the maximum achievable FLH in Fig. 6, all scenarios up to a nominal output of 2 MW have a favorable LCoH. These remain constant for increasing temperature spreads or PL ranges. The greater the nominal output, the greater the influence of the PL range on the LCoH. In general, the greater the PL range, the greater the nominal output of the HP can be. The temperature spread has a negligible influence on the LCoH. In summary, it should be noted that the HP is designed for the most advantageous LCoH at 2 MW.

The sensible choice of a rated power of 2 MW is also confirmed by the course of the APF. Fig. 7 shows the thermal energy and the APF over the nominal thermal power of the HP. The APF drops down strongly from nearly 4 to approximately 3.5 until a rated power of around 2 MW is reached for every scenario. For higher nominal thermal power, it levels out at around 3.

Table 4: Levelized costs of heat of different scenarios.

Partial Load in %		25				50				75				100			
ΔT in K		4	5	6	10	4	5	6	10	4	5	6	10	4	5	6	
Q_N in MW																	
EUR/MWh	1	39.12	39.12	39.12	39.12	39.12	39.12	39.12	39.12	39.12	39.12	39.12	39.12	39.12	39.12	39.12	
38.85	2	38.85	38.85	38.85	38.85	38.85	38.85	38.85	38.85	38.85	38.85	38.85	38.85	38.85	38.85	38.85	
39.72	3	40.12	40.12	40.12	40.12	39.56	39.56	39.56	39.56	39.56	39.56	39.56	39.56	39.56	39.56	39.56	
40.58	4																
41.44	5																
42.31	6																
43.17	7																
44.03	8																
44.90	9																
45.76	10																
46.62	11																
-	12																

**Figure 7:** Thermal energy and annual performance factor of the scenarios.

As the temperature spread has no impact on the LCoH, Fig. 8 is important to determine ΔT as it gives the degree of self-sufficiency. Fig. 8 plots the electrical energy generated by the wind turbine against the temperature reduction of the waste water. Analysis of the overlap between the maximum hourly waste heat available and the hourly wind energy shows that the electrical energy from wind power that can be used by a HP increases from 12 to 13.2 GWh/a at a temperature spread of ΔT 5 K. This corresponds to an increase of 1.2 GWh. From the ΔT 5 K scenario to the ΔT 6 K scenario, the increase is reduced to 0.6 GWh and falls to 0.1 GWh from the ΔT 6 K to the ΔT 10 K scenario. The degree of self-sufficiency is greater than or equal to 0.6 for the $\Delta T = 4$ or 5 Kelvin scenarios.

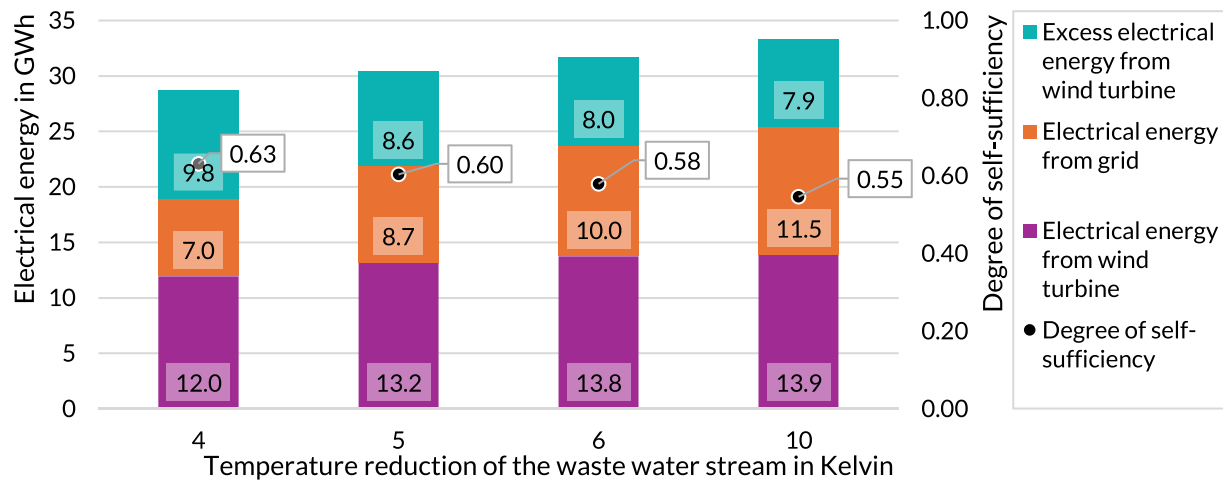


Figure 8: Energy balances and degree of self-sufficiency over different temperature spreads at waste heat source.

Fig. 9 shows DH generation in 2019, totaling 80 GWh, broken down by the types of heat generators used and the scenarios analysed in this study. In addition, the amount of heat generated by the HP is shown, which cannot be fed into the district heating network due to a lack of simultaneity between generation and demand.

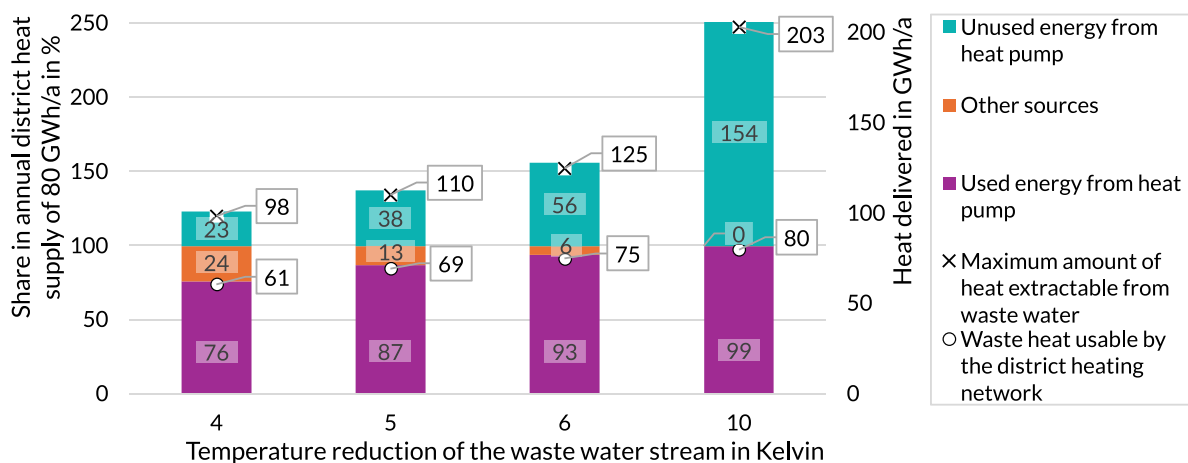


Figure 9: Share of heat generation in the district heat demand and unused heat pump heat due to lack of simultaneity.

As an example, the scenario with a temperature spread of 4 Kelvin shows that 76% of the potential HP energy could be used, while 24% of the DH was provided by other heat generators. A further 23% of the total amount of district heat demand could also have been covered by the HP if demand and generation had been simultaneous.

It also shows that with a temperature spread of 5 Kelvin, the ratio of usable HP heat to total HP heat generated is highest at 1.59.

Taking everything into account, the system would be optimally designed according to the operating parameters in Table 5. This results in the costs and emission reductions shown in Table 6.

The HP has a power rating of 2 MW, and a PL capacity of 90% ensures a high degree of flexibility. The amount of heat provided over the course of the year 2019 is 17.5 GWh/a. The electrical energy required to operate the system comes from two sources: On the one hand, around 1.18 GWh/a is provided by the power

grid, and on the other hand, 3.60 GWh/a is sourced directly from the connected wind turbine. This results in a total electricity consumption of 4.78 GWh/a. With a total of 8741 FLH, the HP is used intensively. The degree of electricity self-sufficiency is particularly noteworthy: with a self-sufficiency rate of around 75%, the majority of the electricity demand can be covered by renewable, locally generated wind energy. This results in low electricity costs and low CO₂ emissions.

Table 5: Technical parameters of an economic optimal dimension of the heat pump.

Parameter	Value	Unit
Nominal thermal power	2	MW
Partial load capacity	90	%
Delivered heat	17.482	GWh/a
Electrical energy from grid	1.180	GWh/a
Electrical energy from wind turbine	3.602	GWh/a
Sum of electrical energy	4.782	GWh/a
Full load hours	8,741	h
Annual performance factor	3.66	–
Degree of self-sufficiency	0.753	–

Table 6: Overview of the costs of the heat pump and its potential to reduce CO₂ emissions.

Parameter	Value	Unit
Investment costs	171,000	EUR/a
O&M costs	43,000	EUR/a
Electricity costs from grid	200,589	EUR/a
Electricity costs from wind turbine	264,721	EUR/a
Sum of electricity costs	465,311	EUR/a
Sum of the costs of the heat pump	679,200	EUR/a
LCoH	38.85	EUR/MWh
Specific costs of CO ₂ emission reduction	0.237	EUR/kgCO ₂
Reduction of emissions	2867	CO ₂ t/a

The economic parameters in [Table 6](#) show that the annual investment costs for the HP amount to 171,000 EUR/a, plus 43,000 EUR/a for O&M. The electricity costs are divided proportionally between grid electricity, at approximately 200,707 EUR/a, and electricity from the wind turbine, at around 264,721 EUR/a. The total annual electricity costs therefore amount to approximately 465,311 EUR/a. The total annual system costs for the HP are therefore around 679,200 EUR/a. These total costs result in a LCoH of 38.85 EUR/MWh. The system achieves annual CO₂ savings of around 2867 t. The specific costs of the avoided emissions are 0.237 EUR/kgCO₂.

4 Discussion

The DH demand of 2016 has been transferred to 2019 using a smoothed outdoor temperature. This approach minimizes the influence of short-term weather fluctuations and allows the typical DH load curve to be represented more accurately. The data set has only minor data gaps in September. While the deviation

between the generated load data and the climate-adjusted heat demand in 2016 is negligible in terms of annual balance, the accuracy of hourly values cannot be verified. As a result, peak loads and short-term variations in the simulated DH demand may differ from actual operation, which could lead to slight over- or underestimation of the HP performance and the corresponding LCoH and CO₂ reduction. In addition, the greater the proportion of climate-independent industrial heat demand, the greater the deviations in the determined heating load curves. Here, real load profiles can improve the reliability of the results.

Similarly, the waste water flow data are only available on a daily basis, which introduces additional uncertainties. Due to the hourly resolution of the simulation, short-term fluctuations in waste water availability might not be captured, potentially affecting the hourly heat supply from the HP. Access to higher-resolution data (e.g., 15-min intervals) would improve the reliability of the results and allow a more precise assessment of the economic and environmental impacts, such as sector coupling, wind power trading, and electricity demand of the HP.

The investment costs correspond to those in [45]. Since electricity prices in particular influence the economic efficiency of a HP, a sensitivity analysis should be carried out here. Nevertheless, assuming a trend toward lower electricity prices with increasing shares of renewable energy, the LCoH could be expected to decrease. If additional flexibility of large HPs to support the electrical grid is considered, further economic benefits may result. Moreover, the costs of connecting the HP to a wind turbine via a private line are currently uncertain, as the exact turbine location and applicable legal requirements are not yet determined. These factors could influence the overall economic assessment.

Furthermore, only a small portion of the waste heat potential of the waste water is utilized with a 2 MW HP. Given the relatively low LCoH compared to other renewable thermal sources such as geothermal, deploying a larger nominal capacity may be justified if it leads to greater CO₂ reductions. The extent to which thermal or electrical storage systems can economically increase the proportion of waste heat used should be investigated in a future work. As shown in Fig. 10, there is a clear mismatch between waste water heat availability and DH demand, particularly during summer when significant potential remains unused. Incorporating thermal storage would enable the use of larger HPs more effectively and increase seasonal waste heat recovery, thus enhancing both economic and environmental outcomes.

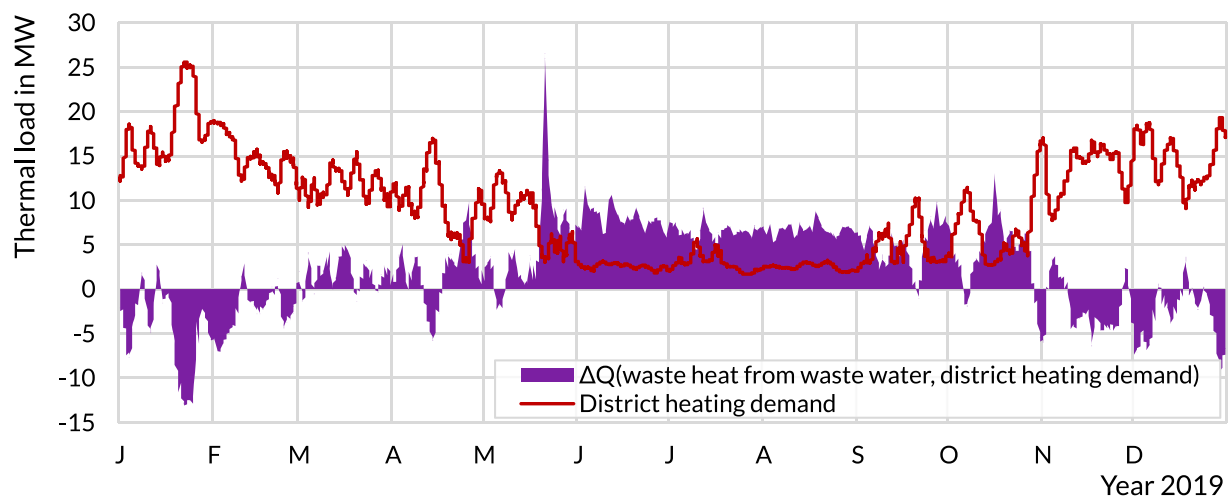


Figure 10: Hourly heat demand and difference between heat demand and thermal output of the heat pump.

5 Summary and Outlook

The study shows that the use of waste water heat via HPs can be an attractive concept for decarbonizing municipal DH. The concept can be implemented economically, particularly with the wind turbine, which operates the HP via its own power grid. For the site in Göttingen, the best LCoH is achieved by installing a 2 MW HP covering up to 75% of its electricity requirements from wind power. The heat generated is cost-effective with a LCoH of 38.85 EUR/MWh, and the system enables 2867 t of CO₂ savings annually. The limiting factors for even greater waste heat usage are, on the one hand, the mismatch between waste heat supply and heat demand and, on the other hand, a lack of storage options.

The combination of wind power and large-scale HPs using waste heat from waste water is an effective tool for the climate-friendly transformation of DH supply. From an economic and ecological perspective, it is important in Germany to supply the HP with local, off-grid, renewable, and cost-effective electricity as this is exempt from taxes and levies. The methodological assessment underscores the fundamental feasibility, but also identifies limitations in terms of data quality and influences that have not been taken into account: e.g., industrial base load, flexibly controllable loads.

Further analyses should use input data with higher temporal resolution. This applies in particular to load and source profiles. Heat and, where applicable, electricity storage should also be integrated in order to reduce the mismatch between heat source and sink. The resulting added value of balancing out possible fluctuations as a system service on the energy market could have a positive impact on the LCoH.

Acknowledgement: We would like to thank Stadtwerke Göttingen for providing data on district heating demand and GEB Göttinger Entsorgungsbetriebe for providing measurements of the waste water flows.

Funding Statement: The work described in this publication has received funding from the EU-Life-Program under grant agreement No. 101120948, <https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE22-CET-HeatMineDH-101120948/low-grade-renewable-and-waste-heat-mapping-and-investment-planning-for-efficient-district-heating> and is part of the HeatMineDH research project. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.



Co-funded by
the European Union



HeatMineDH

Author Contributions: Conceptualization, Johannes D. Pelda, Sebastian Aichele; funding acquisition, Dmitry Romanov, Stefan Holler; methodology, Sebastian Aichele, Johannes D. Pelda; data curation, Sebastian Aichele; writing—original draft preparation, Johannes D. Pelda, Sebastian Aichele; validation, Johannes D. Pelda, Stefan Holler; writing—review and editing, Johannes D. Pelda, Sebastian Aichele, Dmitry Romanov, Stefan Holler; supervision, Johannes D. Pelda, Stefan Holler. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Data not available due to legal/commercial restrictions. Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data are not available.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. IPCC. Climate change 2023: synthesis report. In: Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC; [cited 2026 Apr 7]. Available from: <https://www.ipcc.ch/report/ar6/syr/>.
2. International Energy Agency. International Energy Agency, editor. Global energy review 2025: CO₂ emissions. [cited 2026 Apr 7]. Available from: <https://www.iea.org/reports/global-energy-review-2025/co2-emissions>.
3. United Nations Environment Programme. Emissions gap report 2025 [cited 2026 Apr 7]. Available from: <https://www.unep.org/resources/emissions-gap-report-2025>.
4. Quaschnig V. Regenerative Energiesysteme: Technologie, Berechnung, Klimaschutz. 12th ed. München, Germany: Hanser; 2024. (In German). doi:10.3139/9783446478398?locatt=mode:legacy.
5. Brown PT, Saunders H. Approximate calculations of the net economic impact of global warming mitigation targets under heightened damage estimates. PLoS One. 2020;15(10):e0239520. doi:10.1371/journal.pone.0239520.
6. Sahling U, editor. Klimaschutz und Energiewende in Deutschland: Herausforderungen—Lösungsbeiträge—Zukunftsperspektiven. Berlin/Heidelberg, Germany: Springer; 2022. (In German).
7. Bundesverband der Energie- und Wasserwirtschaft e V, editor. Wärmewende: um die Klimaziele zu erreichen, braucht es eine Wärmewende. In: Wie kann diese umgesetzt werden und welche Rolle spielt dabei die Energiewirtschaft? 2025 [cited 2026 Apr 7]. Available from: www.bdew.de. (In German).
8. BDEW. Die Energieversorgung 2024 [cited 2026 Apr 7]. Available from: https://www.bdew.de/media/documents/2024_12_18_Die_Energieversorgung_2024_Final.pdf.
9. Rappenecker G. Wirtschaftliche Fernwärme [German]. Göttingen; 2024.
10. AGFW. waermepreise.info. 2026 [cited 2026 Apr 8]. Available from: waermepreise.info.
11. Agora Energiewende, Fraunhofer IEG. The roll-out of large-scale heat pumps in Germany: studie. 2023 [cited 2026 Apr 8]. Available from: https://www.agora-energiewende.org/fileadmin/Projekte/2022/2022-11_DE_Large_Scale_Heatpumps/A-EW_316_Large_Scale_Heatpumps_EN_WEB.pdf.
12. Pelda J, Salaymeh A, Holler S, Reuter S, Gebetsroither-Geringer E, Paradiso R, et al. MEMPHIS 2.0—advanced algorithm for spatial identification, evaluation of temporal availability and economic assessment of waste heat sources and their local representation. Frankfurt, Germany: IEA DHC; 2023.
13. Stadtwerke Duisburg. Stadtwerke Duisburg nehmen erste Großwärmepumpe in Betrieb. 2023 [cited 2026 Apr 8]. Available from: <https://www.stadtwerkeduisburg.de/presse/medieninformationen/newsdetail/stadtwerke-duisburg-nehmenerste->.
14. Güntert T. Die Schweizer machen's vor: So wird aus Abwasser quasi Gold. 2024 [cited 2026 Mar 15]. Available from: <https://www.suedkurier.de/region/kreis-konstanz/singen/die-schweizer-machens-vor-so-wird-aus-abwasser-quasi-gold;art372458,11978680>. (In German).
15. GEA. How GEA heat pumps are decarbonizing district heating in Sweden: EON turns sewage into a valuable resource with GEA heat pump technology. [cited 2026 Apr 8]. Available from: <https://www.gea.com/en/customer-cases/heat-pump-technology-eon-malmo/>.
16. NIRAS. Economic benefits of energy efficiency in danish wastewater treatment. Allerød, Denmark: NIRAS; 2021.
17. DWD Climate Data Center. Open source database. 2025 [cited 2026 Apr 8]. Available from: <https://opendata.dwd.de/>.
18. Bundesnetzagentur. Windenergieanlagen an land. 2024 [cited 2026 Apr 8]. Available from: https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Ausschreibungen/Wind_Onshore/start.html. (In German).
19. BDEW. Strompreisanalyse Dezember. 2024 [cited 2026 Apr 8]. Available from: <https://www.bdew.de/service/daten-und-grafiken/bdew-strompreisanalyse/>. (In German).
20. Ostlender S, Kannengießer R, Kröning P, Vering C, Müller D. The agony of the choice in district heating: the impact of heat source for heat pumps. HPT Magaz. 2023;41(3):14–17.
21. Pieper H, Ommen T, Kjær Jensen J, Elmegaard B, Brix Markussen W. Comparison of COP estimation methods for large-scale heat pumps used in energy planning. Energy. 2020;205:117994. doi:10.1016/j.energy.2020.117994.

22. Bott TR. Fouling of heat exchangers. Amsterdam, The Netherlands: Elsevier; 1995. doi:10.1016/B978-0-444-82186-7.X5000-3.
23. Heat Transfer Research, Inc. HTRI heat exchanger design guidelines. 2015. Available from: <https://www.htri.net/design-manual>.
24. Vannoni A, Sorce A, Traverso A, Fausto Massardo A. Large size heat pumps advanced cost functions introducing the impact of design COP on capital costs. *Energy*. 2023;284:129204. doi:10.1016/j.energy.2023.129204.
25. Frederiksen S. District heating and cooling. 1st ed. Lund, Sweden: Studentlitteratur; 2013 [cited 2026 Apr 7]. Available from: <https://www.lesestoff.ch/de/detail/ISBN-9789144085302/Frederiksen-Svend/District-Heating--Cooling>.
26. Sofrata H. Carnot and Lorenz cycles for dual absorption system. *Wärme-und Stoffübertragung*. 1993;28(3):107–16. doi:10.1007/BF01541106.
27. Tipler PA, Mosca G, Kersten P. Tipler Physik. Berlin/Heidelberg, Germany: Springer; 2024. doi:10.1007/978-3-662-67936-4.
28. Dehli M, Doering E, Schedwill H. Grundlagen der Technischen Thermodynamik: Für eine praxisorientierte Lehre. 11th ed. Wiesbaden, Germany: Springer Vieweg; 2025. [cited 2026 Apr 7]. Available from: <https://link.springer.com/book/10.1007/978-3-8348-8615-6>. (In German).
29. Köfinger M, Geyer R, Basciotti D. Task 5.2 Methoden zur Auswahl, Auslegung und Integration von Wärmepumpen. Wien, Austria: AIT Austrian Institute of Technology GmbH; 2017. [cited 2026 Apr 7]. Available from: https://www.ait.ac.at/fileadmin/mc/energy/downloads/News_and_Events/2016-2017/2016_11_15_2.Praxis_und_Wissensforum_FWK/BI_Koefinger_20161115_AIT-Forum_nachhaltige_Waermenetze_MKoefinger.pdf. (In German).
30. Zahoransky R. Energietechnik. Wiesbaden, Germany: Springer Fachmedien Wiesbaden; 2022. (In German). doi:10.1007/978-3-658-34831-1.
31. Roth S, Stahl A. Wärmelehre. Berlin/Heidelberg, Germany: Springer; 2023. (In German). doi:10.1007/978-3-662-67213-6.
32. Frey H. Energieautarke Gebäude. Berlin, Heidelberg, Germany: Springer; 2019. (In German) doi:10.1007/978-3-662-57874-2.
33. Huhtinen M, González RM, Pöntynen L. Large heat pumps in district heating systems. Kuopio, Finland: Savonia University of Applied Sciences; 2023 [cited 2026 Apr 7]. Available from: <https://urn.fi/URN:NBN:fi-fe2024061955510>.
34. Gruber-Glatzl W, Brunner C, Meitz S, Schnitzer H. From the wastewater treatment plant to the turnstiles of urban water and district heating networks. *Front Sustain Cities*. 2020;2:523698. doi:10.3389/frsc.2020.523698.
35. Fraunhofer ISE. Verbundvorhaben: FernWP. 2025 [cited 2026 Apr 7]. Available from: <https://www.ise.fraunhofer.de/de/forschungsprojekte/fernwp.html>. (In German).
36. Pieper H, Ommen T, Buhler F, Paaske BL, Elmegaard B, Markussen WB. Allocation of investment costs for large-scale heat pumps supplying district heating. *Energy Procedia*. 2018;147:358–67. doi:10.1016/j.egypro.2018.07.104.
37. Peters M, Bartenstein B, Hebisch H, Kaiser C, Anders F. Kommunale Wärmeplanung: einföhrung in den Technikkatalog. KEA Klimaschutz- und Energieagentur Baden-Württemberg GmbH. 2024 [cited 2026 Apr 7]. Available from: https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/2_Presse_und_Service/Publikationen/Energie/Kommunale-Waermeplanung-Einfuehrung-in-den-Technikkatalog.pdf. (In German).
38. Ortner S, Köhler B, Ott B, Kluge C, Bartsch A, Langreder N, et al. Leitfaden Wärmeplanung. 2024 [cited 2026 Apr 7]. Available from: https://www.bmwsb.bund.de/SharedDocs/downloads/DE/veroeffentlichungen/wohnen/leitfaden-waermeplanung-lang.pdf?__blob=publicationFile&v=2.
39. Metz J. Entwicklung und experimentelle Analyse eines Mehrquellen-Wärmepumpensystems aus Erdröich und Außenluft. 2023 [cited 2026 Apr 7]. Available from: <https://publica.fraunhofer.de/entities/publication/ef8af94a-3cd4-478a-8881-a01656365515>. (In German).

40. Mathiesen BV, Blarke MB, Hansen K, Connolly D. The role of large-scale heat pumps for short term integration of renewable energy. Aalborg, Denmark: Aalborg University; 2011 [cited 2026 Apr 7]. Available from: <https://vbn.aau.dk/ws/files/58142269/>.
41. AGFW. Praxisleitfaden Großwärmepumpen. Frankfurt am Main. 2024 [cited 2026 Apr 7]. Available from: <https://www.agfw-shop.de/leitfaeden-umsetzungshilfen/agfw-praxisleitfaden-grosswaermepumpen.html>. (In German).
42. Popovski E, Aydemir A, Fleiter T, Bellstädt D, Büchele R, Steinbach J. The role and costs of large-scale heat pumps in decarbonising existing district heating networks—a case study for the city of Herten in Germany. *Energy*. 2019;180:918–33. doi:10.1016/j.energy.2019.05.122.
43. GEA. Mit GEA-Technologie Wärme aus Abwasser gewinnen und Wärmewende der Stadt Lemgo gestalten. 2024 [cited 2026 Apr 7]. Available from: <https://www.gea.com/de/news/trade-press/2024/heatfrom->. (In German).
44. AGFW. AGFW-Regelwerk: FW 309 Teil 6—Energetische Bewertung von Fernwärme und Fernkälte—Emissionsfaktoren nach Arbeitswert—und Carnotmethode. 2024 [cited 2026 Apr 7]. Available from: <https://www.agfw-shop.de/regelwerk/fw-309-teil-6-emissionsfaktoren-nach-arbeitswert-und-carnotmethode.html>. (In German).
45. Generation of electricity and district heating: technology data. Copenhagen, Denmark: Energy Agency; 2025 [cited 2026 Apr 7]. Available from: <https://ens.dk/en/analyses-and-statistics/technology-data-generation-electricity-and-district-heating>.