Monitoring an innovative cold district heating network with decentralized heat pumps and sewage water as heat source

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Abstract

The innovative heating network of a new development area in the city of Wiesbaden (**Germany**) is presented. The system uses waste heat from a sewer as the only source for heating via a cold heating network. Decentralized heat pumps in the buildings are used to raise the temperature level and electrical heating elements provide back-up. Possible advantages include high efficiency due to consistent wastewater temperatures and minimal noise and visual impact. The 2023 monitoring results are presented, showing that the heat pump systems provided 343 MWh to 5 multi-family buildings. Due to a leakage-related outage of the wastewater heat exchanger lasting several months and various problems in the operation of the heat pumps, the efficiency goals could not yet be fully achieved in operation. The total electricity consumption for heat supply in 2023 was 128 MWh. The average Seasonal Performance Factor (SPF) ranged from 2.7 (including network shutdown and use of electric heating elements) to 4.1 (fault-free operation).

Keywords: Renewable District Heating, Heat Pump, Sewage, Wastewater Heat, Ultra-low Temperature District Heating

1. Introduction

In the Germany city of Wiesbaden, a new development area is supplied with heat via a cold heating network and decentralized heat pumps. The development of the site is not yet completed. In 2023, five apartment buildings were built and have been supplied by the heating supply system in regular operation. When fully developed, the system is expected to provide up to 500 MWh/a of heat. A distinctive feature of this system is the utilization of high and relatively stable wastewater temperatures throughout the year as heat source, which is expected to significantly enhance the efficiency of the heat pump systems. Furthermore, the system presents several other advantages: it minimizes noise pollution compared to conventional air-to-water heat pumps, reduces fuel delivery traffic (e.g. wood pellets), and avoids adverse impacts on the densely developed urban landscape, such as visible plant technology installations. Cold district heating networks also offer potential advantages over conventional district heating systems. Operating at very low temperatures reduces or even eliminates heat losses which is especially significant while supplying high efficiency housing with low energy demand. Also, the decentralized nature over the systems offers flexibility and scalability in the development of the supply area. For this reasons, local cold district heating networks with decentralized heat pumps are an innovative heat supply system that has become increasingly popular in recent years.

Various publications deal with the operational evaluation of cold district heating networks. Ruesch et al. (2015) examine a low-temperature district heating network in Zurich, Switzerland, serving over 400 households and validating dynamic simulation models with operational data with a focus on pumping power prediction. The main heat source of the system is a datacenter. Four large decentralized heat pumps provide heat with an average COP of 3.7. Vetterli et al. (2017) presents the monitoring results of a one-year operational period of an ultra-low-temperature heating network in the district "Suurstoffi," located in central Switzerland. The study focuses on the first development phase of a new residential area with a design heat

10.18086/eurosun.2024.02.16 Available at http://proceedings.ises.org

demand of 1.2 GWh. The heat sources for the system include a geothermal borehole field and photovoltaic-thermal system. The heat pumps achieve a COP of 4.4, meeting the design expectations. However, the electricity consumption for auxiliary equipment, circulating pumps and electric heating, was higher than anticipated. Calixto et al. (2021) analyzed different modeling approaches for an existing cold temperature-temperature district heating network in Ospitaletto. Heat sources included industrial waste heat and aquifer wells. Year-round monitoring revealed efficient operation and alignment between different simulation model approaches. The decentralized heat pumps were maintaining stable performance and COPs between 4.2 and 4.5. Zeh and Stocking (2022) describe the long-term monitoring of a cold district heating network in Bad Nauheim, Germany with an 11.000 m²- geothermal ground collector system that supplies 400 residential units. The COP of the considered heat pumps is 3.9. It is pointed out that the 6 km long, uninsulated cold district heating network itself also acts as a form of geothermal collector and thus serving as an additional heat source.

Despite many publications and realized projects, there is still only limited information available on detailed real-life operating experience and the potential problems and challenges that can arise when operating a cold district heating network especially in the combination with a wastewater heat exchanger. This paper aims to provide a comprehensive overview of the system's structure and functionality, including the wastewater heat exchanger, the heating network, and the decentralized heat pump systems. Additionally, the monitoring concept and the results of the operational monitoring for the year 2023 are presented. The analysis covers the operating behavior of the wastewater heat exchanger and the performance of the decentralized heat pumps. Furthermore, the paper discusses the challenges malfunctions and outages observed during the operational monitoring, along with lessons learned and potential optimization approaches for the systems.

2. Design and function of the heat supply system

Structure and function of the heat supply system

At the periphery of a new real estate development area, heat is extracted from a passing sewer at a low temperature level (approx. 14°C) with an internal heat exchanger. The thermal energy is distributed via a cold local heating network and raised to a temperature level that can be used for domestic hot water and space heating purposes (30°-60°C) with decentralised heat pump system in the buildings. The cold heating network is designed without a central pump system. Circulation in the network is ensured entirely via pumps at the decentralized heat pump systems. Fig. 1 shows the structure schematically.

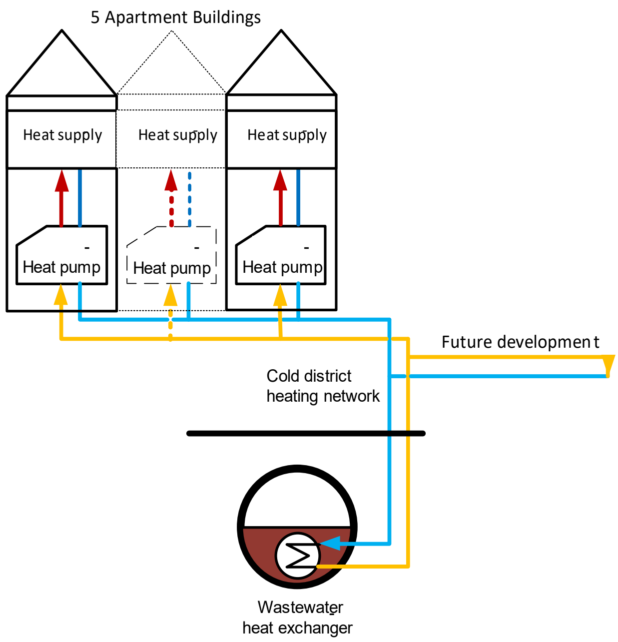

Fig. 1: Schematic representation of the heat supply system

District heating supply area

The cold local heating network supplies a new development area of around 2.5 hectares, which is divided into different construction phases. Only construction phase 1 is already fully completed. It comprises of five apartment buildings with a total of 67 residential units and a total living space of around 5000m². The buildings are constructed according to low energy standards with a specific design heat requirement < 30 kWh/(m²a) and low temperature underfloor heating systems. The total design heat demand for the buildings is 280 MWh/a with a peak load of 250 kW. Typically for high-efficiency multi-family houses, a high proportion of the heat requirement is needed for hot water preparation. A share of 42 % of the total heat requirement was projected here. As the project progresses, it is planned to connect a further 10 semi-detached houses (total design heat demand 220 MWh/a) and multiple single-family houses (maximum additional heat demand 80 MWh/a in total).

Waste water heat exchanger and cold district heating network

The wastewater heat is extracted from a larger channel (DN1500) that acts as a collector sewer for the adjacent urban area (not just the newly developed area) to the sewage treatment plant. For this purpose, a channel heat exchanger design was installed during ongoing sewer operation.

The heat exchanger is made from modular stainless-steel elements, which were installed as a retrofit solution via the existing shaft infrastructure. The heat exchanger has a length of 112 m, a transfer area of 151 m² and is designed for an extraction capacity of 340 kW. Fig. 3 shows a schematic representation of the heat exchanger including the measurement equipment (A), a 3D-illustration of the heat exchanger channel design (B), as well as a picture of the actual installation situation in the sewer (C).

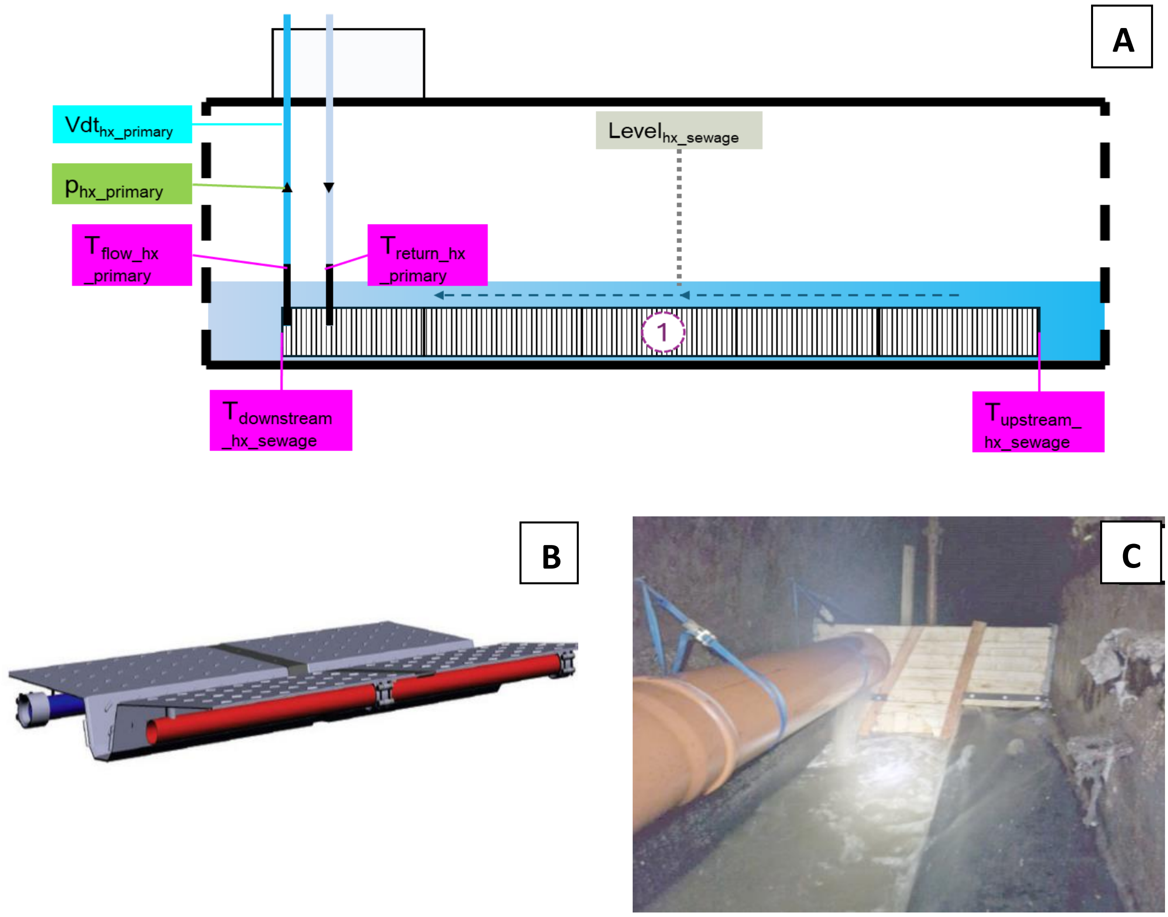

Fig. 2: A: Schematic illustration of waste water heat exchanger
B: 3D Illustration of the heat exchanger [UHRIG 2023]
C: On-site installation situation with wastewater bypass during a repair operation [UHRIG 2023]

The heat transfer fluid of the heating network flows directly through the primary side of the heat exchanger. A mixture of water and organic corrosion inhibitors is used. In terms of its thermal properties, it has no significant differences to pure water. It therefore also has no antifreeze protection. In the initial design phase of the system a heat transfer medium based on propylene glycol was planned. But because of local water protection regulations this had to be changed in the process.

The heating network is made of uninsulated PE pipes and is designed as a classic two-pipe system. The trench length in the current expansion status is only about 500 m. The different parts of the development area supplied by main lines that can be shut off individually. To minimize pressure losses, the main line in the multi-family house section is dimensioned in DN180 and the branches to the buildings in DN110.

The entire network and the heat exchanger are designed as completely passive elements. There are no pumps, actuators or an active control system in the heating network. There is also no permanent circulation in the network, the volume flow in the network is solely generated on demand by the decentralized source pumps at the heating systems of the individual buildings.

<u>Heat Pump Systems</u>

Each multi-family house has its own identically designed heating system. The centrepiece of each system is a water/water heat pump with a thermal output of 65 kW (B7/W50 according to EN14511). The heat pump is an on/off device with a fixed compressor speed without the ability to actively modulate the output power. Fig. 3 shows the layout of the system schematically

The source pump (1) feeds the heat transfer fluid from the network directly to the evaporator of the heat pump (2). For efficiency reasons and to avoid freezing, the heat transfer fluid is only allowed to cool down 5°K. Due to this low temperature difference, a high-volume flow is required to provide the required source energy for the heat pump. In order to match the resulting pressure losses in the network and heat exchanger, a sufficiently powerful source pump must be used (nominal flow rate: 18.7 m³/h, nominal head: 18.3 m). The pumps are designed without external speed control and deliver a constant flow rate during operation. The storage charging pump (3) transports the heating water through the condenser of the heat pump where it is heated by a small temperature range (approx. 5°K) each time it passes through. A 3-way motor valve (4) is used to control whether the storage charging pump loads the 1000 l domestic hot water buffer storage tank (5) or the 1500 l space heating buffer storage tank (6).

From the buffer storage tanks, heat is transferred to the building. With domestic hot water (DHW) preparation, this is done indirectly. For this purpose, cold tap water is heated from around 8°C to 60°C via a temperature-controlled heat exchanger installation, a freshwater station (7). Also, the thermal losses of the DHW-circulation are compensated. For hygiene reasons, the DHW-buffer itself does not contain any domestic hot water.

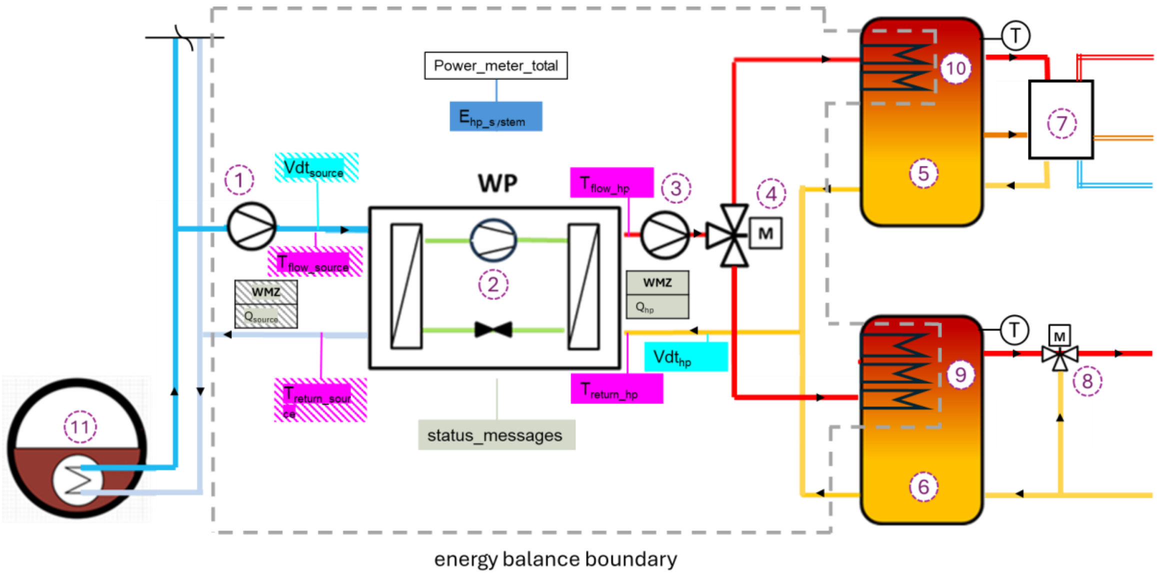

Fig. 2 Schematic diagram of heat pump system with measurement locations and energy balance boundary.

The heating buffer storage tank is hydraulically connected directly to the underfloor heating circuit of the building. The temperature is regulated to the required heating temperature via a circuit mixer (8).

The heat pump is controlled by a hysteresis-based control scheme with a temperature sensor in each of the buffer tanks and a temperature sensor in the return flow of the heat pump. As the temperature of the heating water is only increased by a few kelvins with each "pass-through" the storage volume may has to be circulated several times for complete charging. DHW-preparation has a higher priority than heating operation, i.e. loading of the heating buffer storage tank is interrupted when DHW is required and resumed when the required DHW temperature is reached.

The heat pump systems and the heating network are sufficiently dimensioned to ensure that the building's heating requirements can be supplied by the heat pump alone at the design temperatures (-15°C). As backup in the event of an outages, electric heating elements (HE) are installed in both buffer storage tanks as alternative heat generators. The DHW-HE (9) has an output of 12 kW (2x6 kW) and the heating-HE (10) has an output of 27 kW (3x9 kW).

3. Data acquisition and monitoring

The focus of this study is on the wastewater heat exchanger, the section of the heating network that supplies the completed construction area and the decentralized heat pump systems in the five multi-family houses. principle of monitoring the innovative heat supply system is to view it as a whole and from a system perspective. The internal processes of the individual components, e.g. the cooling circuit functionality of the heat pumps, are not examined.

Fig. 2 A shows the various sensos in the heat exchanger. The temperatures in the heat exchanger flow and return on the network side (primary) as well as the flowrate in the network, the absolute pressure in the network, and the pressure drop across the heat exchanger are measured. In the wastewater flow, the wastewater temperatures upstream and downstream of the heat exchanger are measured. For cost considerations, the flowrate of the wastewater is not measured directly. Instead, the water level of the wastewater channel is measured using an ultrasonic level measurement, from which qualitative conclusions about the wastewater volume flow can be derived.

All temperatures are measured with PT100 class A sensors. A robust thermal flow-velocity sensor is used to measure the flowrate in the network. However, the sensor has a high measurement uncertainty of +-17% in the occurring measurement range due to very low flow velocities. This high measurement uncertainty is propagated in the measurement chain for thermal power and energy.

In the decentralized heat pump systems, the combined electrical power consumption of the heat pump, source pump, storage charging pump as well as the auxiliary power consumption, and the power consumption of the HE are measured with an electric power meter. Due to its specific load profile, the electricity demand of the HE can be isolated from the total electricity demand.

The flow and return temperatures, volume flows, and the resulting thermal energy and power at the output of the heat pumps are determined via heat meters. The stationary measurement technology is supplemented by mobile ultrasonic flow meters and clamp-on temperature sensors, which are used to measure the flowrates as well as the flow and return temperatures of some heat pump sources for selected time periods. The system measurement data is supplemented by automatically generated error and status messages from the heat pumps and by weather data from the German Weather Service for the location. In fig. 3 all sensor positions can be seen.

Also shown in fig. 3 is the boundary for the energy balance and the performance assessment of the heat pump systems. The cut off-point for the heat supply lies directly behind the heat meter at the outlet of the heat pumps. For technical reasons, the electric heating elements are located behind the heat meter in the buffer storage tanks but could be allocated to the energy balance as heat generators according to their electricity consumption. (An electricity-to-heat conversion rate of 100% is assumed). Heat losses in the buffer storage or in the DHW circulation pipes or, are not considered in the balancing.

The key evaluation parameter for a heat pump system is the coefficient of performance (COP). It describes the ratio of electrical energy used to heat generated. The annual average coefficient of performance is also called seasonal performance factor (SPF).

Typically, two different balance sheet limits are used. For COP1 electrical power consumption of the heat pump, the source pump, the storage charging pump and other auxiliary power consumption for control systems etc. is taken into account (eq.1). The HEs are not considered here. COP2 also includes the electricity demand and heat generation of HEs (eq.2)

$$\mathrm{COP1} = \frac{Q_{HP}}{E_{hp}+E_{pump,source}+E_{pump,sink}+E_{aux}} \quad \text{(eq.1)} \qquad \mathrm{COP2} = \frac{Q_{HP}+Q_{HE}}{E_{hp}+E_{pump,source}+E_{pump,sink}+E_{aux}+E_{HE}} \quad \text{(eq.2)}$$

4. Assessment of the wastewater heat exchanger

In 2023, a total of 160 MWh of wastewater heat was extracted from the sewer and fed into the heating network, see fig. 4. The low/absent heat extraction between April and July is due to a network outage caused by a heat exchanger leakage. Therefore, the total heat energy delivered does not correspond to a typical operating year. The high measurement uncertainty is mainly caused by the thermal flow velocity sensor.

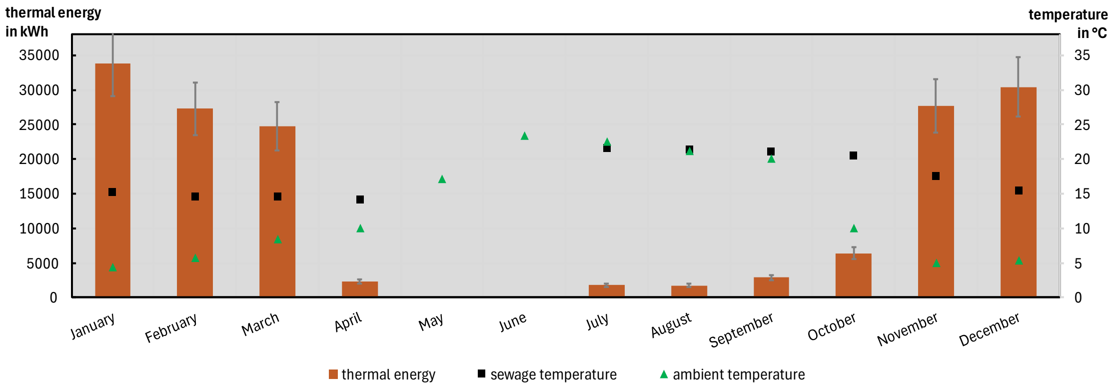

Fig. 3. Monthly heat extraction from the wastewater heat exchanger and average monthly ambient air and wastewater temperature (right y-axis)

Wastewater temperatures

The average monthly wastewater temperature and the average outdoor temperature are plotted on the secondary axis in fig. 4. In July to September, the average wastewater temperature is almost identical to the outdoor temperature. However, the seasonal variations in wastewater temperature are much less pronounced than the variation of the ambient air temperature. During the heating period from 1st October to 30th April, the average wastewater temperature is 9 °C higher than the outdoor temperature. The average monthly wastewater temperature ranges from 14.5 °C in February to 21.6 °C in July. The average wastewater temperature over the entire observation period is 16.2 °C.

A more suitable approach for examining the wastewater temperature than the average temperature over time is the average temperature level at which the thermal energy is actually extracted. The histogram in 5 shows what proportion of the total thermal energy is extracted at certain temperature level of the wastewater.

The largest proportion of the extracted energy, just under 90 % or 141 MWh, is extracted at temperatures between 12 °C and 18 °C. Especially low temperatures of <10 °C are extremely rare, with a share of < 1 % of the extracted energy. Around 5 % of the energy is transferred at particularly high temperatures of >18 °C. Both, very high and very low temperatures can cause problems with heat pump operation.

The energetic average temperature level is 13.7 °C, this is significantly lower than the time average temperature. This is of course due to the fact that periods with above-average heat demand correlate with below-average wastewater temperatures.

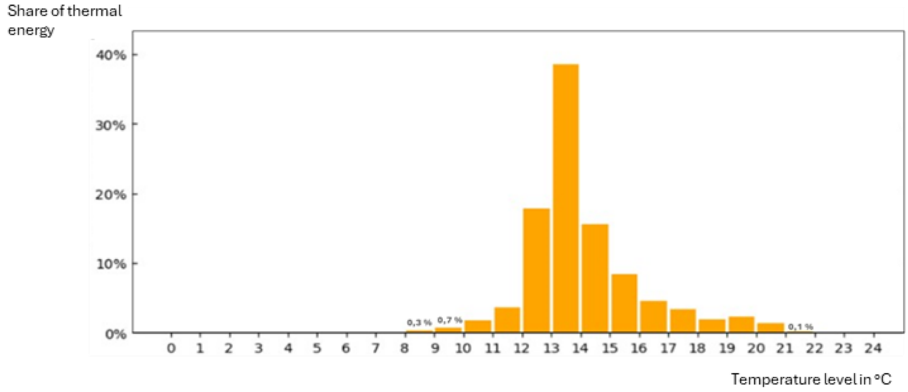

Fig. 4 Distribution of the temperature level of waste heat utilisation

<u>Precipitation-related temperature drop in the wastewater temperature</u>

Normally, the wastewater temperature is relatively stable and is subject only to slow diurnal and seasonal changes. However, sudden drops in the otherwise relatively constant wastewater temperature could be observed sporadically. Fig. 6 shows an exemplary representation of this behavior. The wastewater temperature (brown) drops from 15.6°C to 7.4°C within a short period of time. This behavior is due to the design of the local sewer, which is a mixing sewage system. During heavy rainfall, rainwater and wastewater are discharged together through the sewer. Very high precipitation (blue) leads to a sharp increase in the wastewater level (purple) due to the inflow of cold surface water. In combination with low outside temperatures (green), this leads to a significant drop in the wastewater temperature. After the end of the precipitation, the temperature normalizes again within a day. The minimum observed wastewater temperature can drop to 7.2 °C in similar cases. Very pronounced drops in wastewater temperature, cause some of the decentralized heat pump systems to repeatedly experience outages.

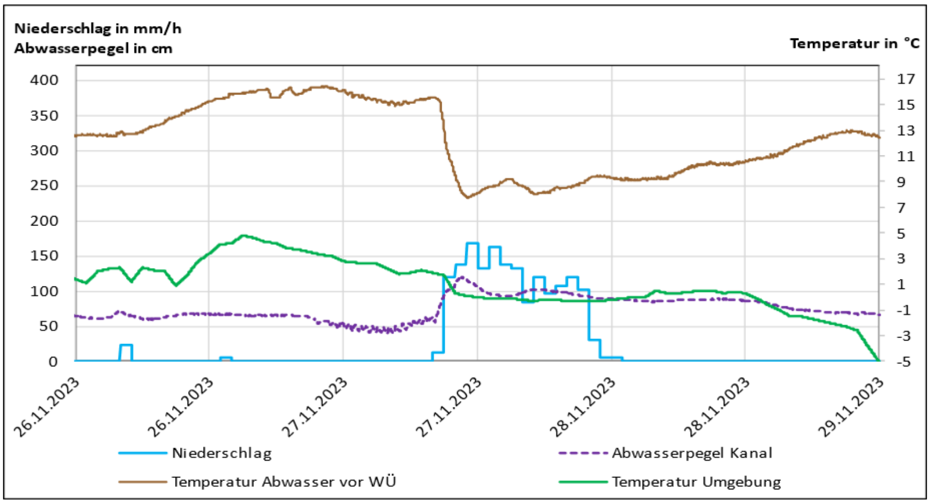

Fig. 5 Temperature drop in wastewater - correlation between precipitation, wastewater level and outside temperature

<u>Heat exchanger operation</u>

The heat extraction rate from the heat exchanger is rather fluctuating, as the network flow rate varies greatly. Depending on the operation of the decentralized heat pumps the flow rate is between 16 m³/h (for one active heat pump) and approx. 102 m³/h (for all active heat pumps). The average network flow rate during operation is 20 m³/h. The average heat extraction rate during operation is 54 kW, with a maximum stationary extraction rate of 390 kW in peak conditions. The average temperature reduction of the wastewater during operation is only 0.2 °K (within the measurement uncertainty range of the sensors). The same applies to the coarseness of the heat exchanger (temperature difference between the wastewater and primary side at the heat exchanger outlet). with 0.3 °K during operation. This means that the flow temperature in the cold local heating network is essentially identical to the wastewater temperature.

Typically, sediments and the development of a biofilm (fouling), can lead to a significant reduction in the thermal conductivity of a wastewater heat exchanger surface. However, due to the very small temperature differences (in the range of the measurement uncertainty), no significant reduction in the heat transfer coefficient/heat transfer capacity (UA-value) could be determined.

Network outage caused by heat exchanger leakage

In early April 2023, an unexpected pressure drop occurred in the local heating network, accompanied by a simultaneous malfunction of all heat pump systems. The cause was identified as a leak in the channel heat exchanger, which led to an outage of the entire heating network. The manufacturer's investigation suggested that the most likely cause for the damage were concrete drilling debris from an unknown construction site upstream. Extensive repairs were required after locating the fault. Since the damage was below the water level, the wastewater channel had to be dewatered without disrupting wastewater transport. In coordination with the local authorities, a dam plate was installed and a bypass line was laid within the channel. Subsequently, damaged modular heat exchanger components were replaced. The network was fully operational again by mid-July. The total network outage lasted 91 days. During this period, the heating demand of the connected buildings (primarily for domestic hot water preparation) was met using the HEs

5. Operational assessment of heat pump systems

In this section, the operating behavior of the heat pump system is presented. Fig. 7 shows the typical operation over 24 hours for a selected sample system. In the top panel the electrical power consumption (green) and the thermal power output (yellow) of the heat pump could be seen. The source temperature of the heat pump (flow temperature of the cold heating network) is plotted in blue on the right y-axes. The flow temperature of the heat pump is shown in red. In the bottom panel the current operating mode of the heat pump is shown.

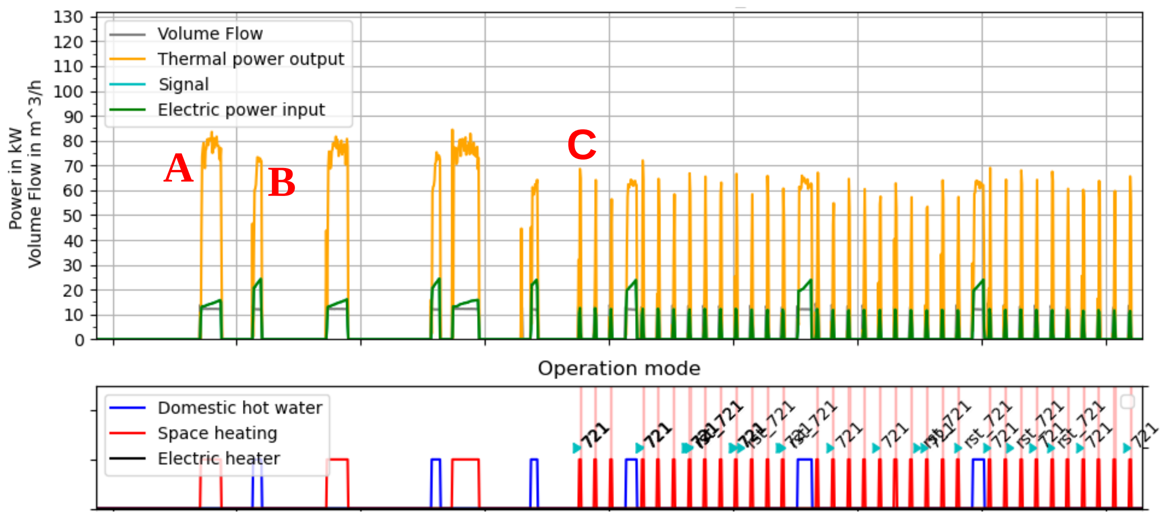

Fig. 6 Heat pump operation. Top: Electrical and thermal power
Bottom: Operation mode

Space heating and drinking hot water preparation

Marking A flags a typical heating operation phase of the heat pump. With the start of the compressor, the electrical power consumption (green) rises to approx. 15 kW. At the same time, the thermal output power (yellow) rises to around 75 kW. The flow temperature increases till the target temperature is reached (heating curve dependent on the outside temperature) and the heating buffer storage tank is fully charged.

For all heat pump systems in 2023, the average flow temperature in space heating operation is 42°C. In steady state space heating operation, without consideration of the start-up and shut-down process the heat pump systems reach a $COP1_{Space\ heating}$ of 5.1

In a DHW-preparation phase (marking B), the flow temperature rises to the fixed target temperature of 65°C degrees. Due to the higher temperature difference between the source temperature and the sink temperature, a higher compression rate and therefore a higher electrical power demand of the heat pump compressor is required than in space heating mode. For all heat pump systems, the average $COP1_{DHW}$ for DHW preparation in steady state conditions is 2.6.

<u>Operating faults - aborted operating phases:</u>
From 09:00, there is a significant drop in the flow temperature of the cold district heating network (blue). This was caused by a strong reduction in the temperature of the wastewater due to heavy precipitation as described in the previous chapter. This drop in source temperature triggers an abnormal behavior of the heat pump. The heating operation phases last only a few minutes without reaching the target flow temperature.

The operation is aborted due a low-pressure fault status of the heat pump (code 721). A low-pressure fault or a low-pressure cut-out is an operating pressure shortfall on the low-pressure side (evaporator/heat source) in the refrigerant circuit of a heat pump.

Individual low-pressure faults are typically not considered critical. The fault does not necessitate an immediate response from the plant operator and typically has no significant impact on the operation of the heat pump. The heat pump restarts after a brief blocking period. However, a more concerning issue is the occurrence of a heavy clustering of faults over an extended duration. This can result in the heat pumps being unable to maintain normal heating operations over an extended period. In order to prevent an undersupply, the electrical backup heating element must then be activated.

In total, over 1,000 operating phases of the five heat pump systems were aborted due to faults in 2023. In 10 cases, the HE had to switch on to providing backup heat generation for several days at a time.

In addition, one heat pump had a breakdown due to a defect in the evaporator and had to be substituted with the backup HE for over two months. Overall, the five backup HE were required to operate for over 800 hours due to direct faults/breakdowns of the five heat pump systems (not including the outage of the district heating network from April-July)

The underlying cause of the many aborted operation phases of the heat pumps is still under investigation. While the temperature drops in the wastewater play an important role, they are not considered the sole cause. Particularly because only some of the heat pump systems are affected by a high number of low-pressure faults. Other systems show no conspicuous behavior. Although all heat pump systems have identical hydraulics and share the same network temperature. The issues also arise despite the source volume and temperatures being within the permitted operating parameters for the heat pumps.

Possible causes that are under consideration are: Deposits on the evaporator that reduce heat transfer, insufficient refrigerant quantity or malfunctions in the refrigeration circuit control of the heat pumps, and air or undissolved gases in the heating transfer fluid of the cold district heating network. Deposits on the evaporator that reduce heat transfer, malfunctions in the refrigeration circuit control of the heat pumps, insufficient refrigerant quantity and air /undissolved gases in the heat transfer fluid of the cold district heating network.

<u>Operating time and cycle behaviour</u>
The number and length of the operating cycles and thus the number of compressors starts is an important parameter for evaluating heat pump operation. Frequent instationary operating states (start-up and shutdown processes) have a negative influence on the efficiency of heat pumps. Experimental and simulation-based research indicate that frequent on/off switching can lead to efficiency losses of up to 20% an minimum operating cycle times should not be below 15 (Uhlmann und Bertsch 2010) and 20 minutes (Waddicor et al. 2016) to avoid exceeding efficiency losses. Furthermore, a high number of compressor starts could lead to a reduced service life of the heat pump.

During the observation period, the five heat pumps on average run 730 full operating hours and complete an average of 2243 operating cycles each. This equates to an average of just 22 minutes per cycle.

In Fig. 8 the typical distribution of duration cycle duration of a heat pump system for one month can be seen. In space heating operation the heat pump system have running periods of 26-60 minutes (38 minutes average for all systems). DHW preparation phases are much shorter with average cycle duration of only 14 minutes, DHW preparation is also responsible for 62 % of all compressor starts. The quite short operating cycle duration of the DHW preparation indicates that the heat pump is slightly oversized for the existing DHW buffer storage. Although not optimal, the operating cycle duration and the cycle behavior of the heat pumps in regular/fault-free operation are still within an acceptable range. Much more critical is the high number of very short operating phases that are aborted due fault conditions of the heat pumps. In some heat pump systems, these account for a considerable proportion of compressor starts (up to 18 %).

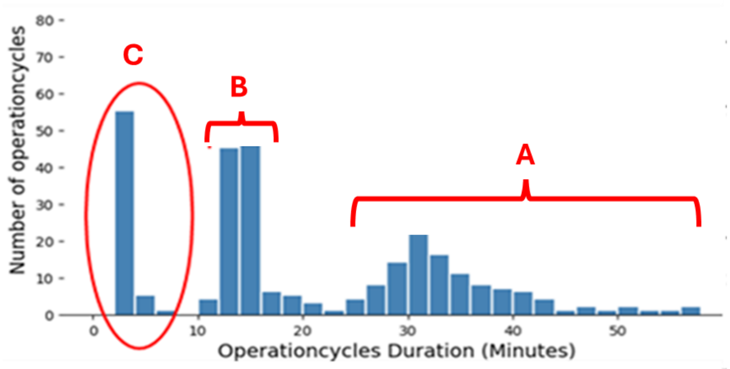

Fig. 7: Distribution of the operating cycle duration

6. Energetic assessment of heat pump systems

The five heat pump systems in the multi-family houses delivered 343 MWh of thermal energy in 2023. The average amount of heat supplied for each building is slightly varying and lies between 55 and 72 MWh. Fig. 9 shows the monthly distribution across the individual buildings.

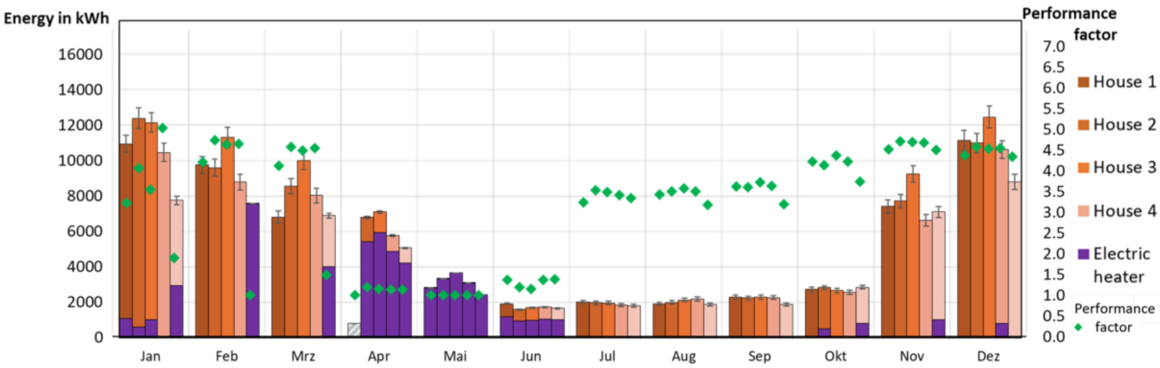

Fig. 8 Monthly heat quantities provided by the heat pumps and electric heating elements (shaded). Monthly average COP (right y-axes)

The heat requirement for DHW-preparation is similar for all houses and averages 26 MWh (39% of the total heat supply) From June to September, the heat requirement can be fully allocated to DHW preparation.

The purple area of the bars represents the amount of heat that had to provided by the backup electric heating elements. In the months of April-June, the electric heating elements had to take over a large part or all of the heat supply due to the described outage of the cold district heating network. During the outage period from 04/13/2023 to 07/12/2023, the electric heating elements produced 42 MWh of heat There were also several occasions when the HE had to provide the load due to problems directly related to the heat pumps. From mid-January to March, the heat pump in house 5 failed due to a defect in the evaporator. The other HE operation cases were caused by a cluster of heat pump operation faults, as described in the previous section. Over the year 59 MWh of heat hat to be provided by the backup HE (17% of the total heat supply)

A total of 128 MWh of electricity, including the consumption of the backup HE was used to generate the required heat. The right y-axis in Fig. 9 shows the corresponding monthly average COP2 for each heat pump system. Again, the heating network outage between April and June is clearly visible. During this period, heat had to be supplied exclusively by the electric HE, which convert electricity directly into heat (COP=1).

The use of HE during the heat pump related outages also has a significant impact on the corresponding COP2 of these heat pump systems. In the second half of the year, the COP is much more stable. There was only a very low usage of the HE in this time period. With the start of the heating period, the average monthly COP for all heat pumps rise from 3.4 in July to around 4.6 in November. This can be attributed to the increasing demand for space heating and the resulting decrease in the proportion of DHW preparation in the overall heating demand. Due to the lower temperature spread, the heat pumps work correspondingly more efficiently.

As a result of the various outages of the network and the heat pumps and the resulting need to use the inefficient HEs, the overall average seasonal performance factor (SPF2) for all heat pump systems is relatively low at 2.7. If the period with the heating network outage is not considered the average SPF2 rises to 3.5. If the complete HE operations are excluded the SPF1 rises to 4.1.

7. Conclusion and summary

The scientific monitoring of the cold district heating network with decentralised heat pumps and sewage water as heat source for the year 2023 illustrates the many challenges that can arise while operating an innovative and complex heat supply system.

The evaluation confirms the basic function and efficiency of the wastewater heat exchanger for supplying the cold local heating network. It was possible to extract 160 MWh of energy from the waste water at relatively high temperatures of 13.7 °C on average. The heat capacity flow of the wastewater is sufficiently large so that there is no significant cooling of the wastewater in the current state of expansion of the district heating network. Also, the heat transfer capacity is more than sufficient for the current heat requirement. No negative effects of deposits (fouling) on the heat exchanger are currently detectable. Sudden drops in temperature (~8 °C) that occur after heavy precipitation must be regarded as normal operating behaviour but could trigger unexpected faults conditions in the decentralised heat pump systems.

The leakage of the heat exchanger and the associated failure of the network must be regarded as "force majeure". The authors are not aware of any comparable incident with a similar system. However, the incident also highlights some of the fundamental challenges of wastewater heat exchanger systems. The environment of the sewer and the composition of the wastewater flow cannot be fully controlled. Work and repairs can be very time consuming. They often have to be carried out during ongoing sewer operation and must therefore be closely coordinated with the sewer operators and implemented with substantial interventions in the wastewater infrastructure.

In addition to the prolonged outage of the district heating network, a high number of direct heat pump-related faults meant that 17 % of the required heat energy had to be provided by the electrical backup heating elements. This led to an increased electricity requirement and a low overall seasonal performance factor (SPF1) of 2.7. Furthermore, an unfavourable operating behaviour of the heat pumps in the form of a high number of compressors starts and aborted operation phases caused by fault conditions in the refrigeration cycle could be observed. However, in regular operation (not taking into account the use of the backup heating elements during outages) an average seasonal performance factor (SPF1) of 4.1 could be reached.

The high efficiency values achieved during certain periods highlight the potential of the overall system. However, they also show that complex heat supply systems often require intensive monitoring and optimization over an extended period following commissioning to ensure sustained operational performance. Several optimization measures are currently under development, and their implementation will be monitored and evaluated in the next phase.

8. Acknowledgments

The authors would like to thank State Energy Agency Hessen (LEA Hessen) for funding the accompanying scientific research and the owner and operator of the monitored system ESWE Versorgungs AG for their excellent cooperation.

9. References

Calixto, Selva; Cozzini, Marco; Manzolini, Giampaolo (2021): Modelling of an Existing Neutral Temperature District Heating Network: Detailed and Approximate Approaches. In: Energies 14 (2), S. 379. DOI: 10.3390/en14020379.

Ruesch, Florian; Rommel, Matthias; Scherer, Jakob (2015): Pumping power prediction in low temperature district heating networks. DOI: 10.5075/epfl-cisbat2015-753-758. Online available: https://infoscience.epfl.ch/entities/publication/7d0eedf1-9680-4e1c-87b5-31951d94073d/conferencedetails (last checked 20.08.2024)

Uhlmann, Michael; Bertsch, Stefan (2010): Measurement and Simulation of Startup and Shut Down of Heat Pumps. In: International Refrigeration and Air Conditioning Conference. Paper 1008. Online available https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2007&context=iracc (last checked 20.08.2024)

Vetterli, Nadège; Sulzer, Matthias; Menti, Urs-Peter (2017): Energy monitoring of a low temperature heating and cooling district network. In: Energy Procedia 122, S. 62–67. DOI: 10.1016/j.egypro.2017.07.289.

Waddicor, David A.; Fuentes, Elena; Azar, Marc; Salom, Jaume (2016): Partial load efficiency degradation of a water-to-water heat pump under fixed set-point control. In: Applied Thermal Engineering 106, S. 275–285. DOI: 10.1016/j.applthermaleng.2016

Zeh, Robin; Stockinger, Volker (2022): Monitoring of a large-scale geothermal collector system and a 5GDHC in Bad Nauheim. In: European Geothermal Congress,Berlin. Online available: https://www.researchgate.net/publication/369039743_Monitoring_of_a_largescale_geothermal_collector_system_and_a_5GDHC_in_Bad_Nauheim. (last checked 20.08.2024)