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Retrofit application of heat pumps with dual heat source

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Abstract

Heat pumps (HP) are the predominant heat generator in many scenarios. Market shares in the larger capacity range, though, are still limited, in particular in existing buildings. A major restriction for larger HP capacities are suitable heat sources (HS), especially for the boiler replacement in existing buildings, where limitations of the HS by the built environment can limit installations of HP.
An option to overcome these limitations is the integration of multiple HS, in particular, if synergies among the HS can be used. The project "RenoSource" investigates the integration of the two most common heat sources used in Switzerland, outdoor air and ground probes regarding design, control and performance by system simulations and field monitoring, completed by an analysis of the cost and economy of the integration.
Two strategies for the integration have been evaluated: a peak load coverage by the ground probes and outdoor air as base load and a regeneration of the ground probes with outdoor air. Simulation results from the preceding project HP-Source confirm that for both strategies, source integration can overcome the limitations, as the ground probe field can be notably downsized. Thereby, the additional cost of the second heat source can be refunded or even overcompensated, i.e. by the synergies between the sources, and both performance and economic benefits result. Consequently, the simulation results imply, that individual heat sources can be both technically and economically inefficient compared to multi-source designs for the larger capacity range. A dual-source system was implemented in a pilot project of two multi-family houses with a heating capacity of 170 kW. This paper presents results from the evaluation of the first year of operation of the pilot project, focusing on control strategies, measured system efficiency and the regeneration of the ground. Results of the first winter period confirm that with a notably smaller design of a peak load ground probe field and air source as base load, the heat demand can be covered. Additionally, the ground source can be regenerated by the air heat exchangers.

Keywords: dual source heat pump; monitoring; simulation; borehole heat exchanger; air heat exchanger; peak load;

1. Introduction

While heat pumps have gained significant market penetration in new constructions - reaching market shares of 80-90% for smaller residential applications - their adoption in larger commercial and multi-family buildings remains limited. This is primarily due to several technical and logistical challenges associated with these settings.

One major obstacle is the availability and suitability of appropriate heat sources, especially in densely built environments. The spatial constraints often restrict the installation of geothermal systems, such as ground probes, and may also limit options like borehole depth and surface area for solar collectors or recooling units. For instance, in older districts, there is often limited outdoor space, which complicates the installation of traditional geothermal loops or extensive solar thermal systems. Additionally, urban noise restrictions, property owner limitations, and local regulations such as borehole drilling prohibitions or depth restrictions further hinder the deployment of conventional geothermal systems.

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Moreover, unrenovated larger buildings tend to feature higher thermal loads, which increase the complexity of designing efficient and cost-effective heat pump solutions. The high capacity demands often necessitate multiple or larger units, raising the issue of integrating such systems within existing infrastructure. These factors contribute to higher capital costs, increased technical complexity, and uncertainties regarding long-term operational performance, which collectively slow down market uptake in retrofit projects.

The project underlines the need for innovative solutions that address spatial and technical constraints while enabling sustainable heating. By combining air-source heat pumps with geothermal probes specifically designed for peak load supply, the project aims to mitigate such site limitations. This hybrid approach allows for effective heat generation without the need for extensive drilling or large surface installations, making it suitable for constrained urban environments.

Furthermore, this research aims to demonstrating the technical feasibility and economic viability of such multi-source systems through real-world monitoring. It aligns with broader energy transition goals, emphasizing reduced reliance on fossil fuels, lower greenhouse gas emissions, and increased system flexibility. The insights gained will in a next step contribute to the development of best practices, design guidelines, and regulatory frameworks that facilitate wider adoption of sustainable heating technologies in complex existing buildings. Furthermore, after the monitoring, data will be used to validate simulation models and to detailly compare the monitored system with other system configurations, also including individual heat source solutions as reference.

2. Methodology

This methodology of the entire project incorporates a multidisciplinary approach combining system design, modeling and simulation, as well as real-world monitoring to evaluate the performance of an innovative multi-source heat pump system in two existing multi-family buildings. The system design integrates indoor propane heat pumps with a hybrid geothermal heat source tailored for peak load coverage, addressing spatial and drilling depth limitations inherent in retrofit urban settings. The project is based on results obtained from the HP-source [1,2] project using dynamic models developed in Matlab-Simulink using the Carnot-Blockset [3], which provided valuable insights and validated strategies for multi-source system integration and control by system simulation. Prior to the monitoring modelling of the investigates system delivered the feasibility of the applied system configuration of the dual source systems, which is currently verified in the real operation.

Thus, the key component of the methodology involves extensive on-site monitoring over two heating seasons to collect operational data on system performance, energy consumption, and temperature profiles. The paper shows results from measured data of the first year of operation. The monitoring also facilitates the assessment of dynamic control strategies, especially concerning the control of geothermal probes as peak load source despite their reduced lengths.

In a next step the real-world data also serve to validate the accuracy of the simulation models and improve the model exactness. Subsequently, the validated models will be employed to evaluate the economic and technical feasibility of the proposed system, including lifecycle costs, efficiency gains (e.g., seasonal performance factor improvements), and greenhouse gas reductions. Comparative analyses with conventional heating solutions (e.g., fossil fuel boilers, monovalent heat pumps) will also be performed to highlight potential advantages.

This integrated approach enables optimized system design tailored to site-specific constraints, provides insights into operational behavior, and supports the development of best practices for multi-source heat pump applications in retrofit projects.

This paper only comprises the analysis of the monitoring results of the first year of operation and does neither include the prior simulation work nor the subsequent model validation and system comparison.

2.1. Pilot project

The pilot system consists of a multi-source indoor heat pump installation designed to supply two larger multi-family residential buildings located in Baden, Switzerland. The buildings, constructed in 1972, each have approximately 28 apartments and a total living area of 4190 m^2. They were slightly renovated in the 1990s, but predominantly retained their original structural and infrastructural features.

The former heating infrastructure relied on centralized oil boilers, with one building denoted as K6 equipped with its own boiler room, while the other denoted K8 is connected via a pipe to the central heating system in

K6. The age of the buildings, combined with their original state, posed opportunities for energy retrofit, in particular due to the high heating oil consumption averaging about 600 MWh annually.

Initially, the retrofit concept of the heating system was planned using 12 ground probes, each 300 m deep, combined with an air heat exchanger (AHX) for ground regeneration. The depth was chosen due to spatial constraints limited to the parking lot due to the steep surrounding terrain (Figure 1). During the installation process, though, unforeseen drilling limitations occurred, since artesian water was encountered at 130 m depth, which led to a permitted borehole depth of 120 meters set by the cantonal authorities and required a reconsideration of the planned borehole design.

Figure 1. left: K6 (higher building) and K8 (lower building). Middle and right: AHX and HP in K8

The adapted system incorporates a dual heat source approach due to the drilling limitations. Instead of relying solely on borehole heat exchanger (BHX), the system was redesigned to include a hybrid configuration with a BHX and supplementary AHX that serves as a baseload and regeneration heat source. In each of the buildings, K6 and K8, a separate system, containing a BHX field, an AHX and a two-stage inverter heat pump with propane as refrigerant has been installed. The difference of the two systems is in the capacity of the heat pumps and the BHX field. The AHX has the same size for both systems. This means, compared to the heating capacity, the sources are slightly larger in K8 than in K6, see Table 1.

Table 1: Dimensioning of the heat pumps and the heat sources in absolute terms and relative to heating capacity

Building		K6		K8	
	unit	total	per kW	total	per kW
Heating capacity	kW	94	-	73	-
No. of probes	-	9	-	8	-
Total BHX probe length	m	906	9.6	786	10.8
AHX capacity (according to EN 1048: $T_{air,\,in} - T_{fluid,\,in} = 15$ K)	kW	94	1.0	94	1.3

The measurement concept depicted in Figure 2 includes heat meters (HM) for the individual heat sources (HM AHX, HM BHX) of the air source and the ground probes as well as for the heat emission side (HM H, HM DHW), an electricity meter (EM) for the HP (EM1, including all auxiliaries including the BHX pumps) and an extra electric meter for the fan (EM2).

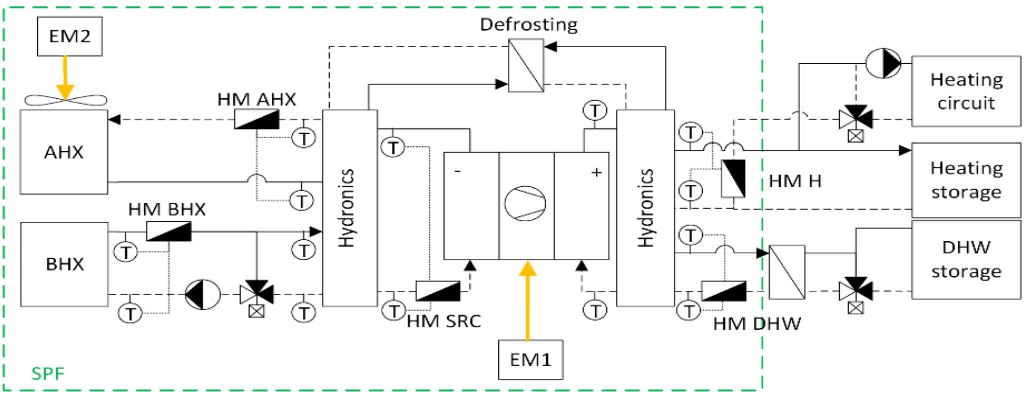

Figure 2: Hydraulic scheme and measurement points for monitoring

In addition, the operating states in terms of the compressor speed and pump status as well as the valve positions and refrigerant data (temperatures, pressures) are recorded. The seasonal performance factor (SPF) is calculated according to Eq. (1).

$$SPF = \frac{Q_{h,heating}+Q_{h,DHW}}{E_{el,HP}+E_{el,aux}+E_{el,fan}} \quad (1)$$

2.2. Control strategies

The system uses advanced control strategies to dynamically switch between the air and ground source based on outdoor conditions and system loads. Sensors and automation facilitate real-time operational adjustments, optimizing performance and energy consumption.

Figure 3 shows a simplified hydraulic scheme of the installed system and the highlighted flow for each operation mode.

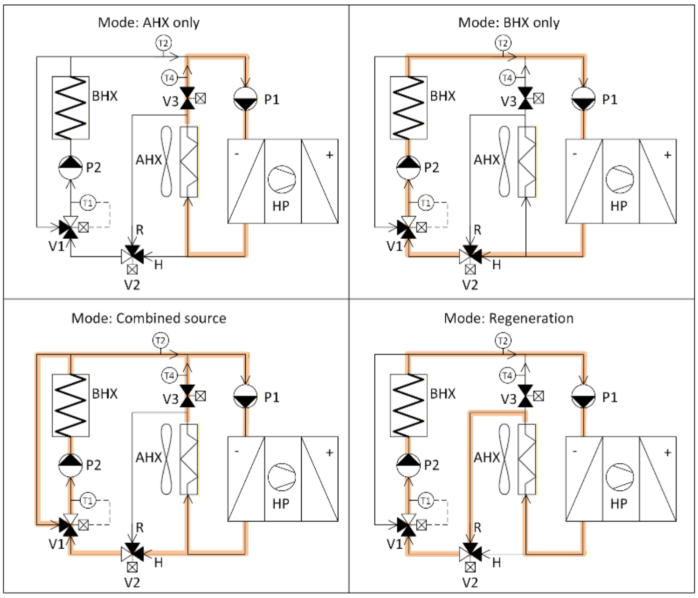

Figure 3. Simplified hydraulic scheme with highlighted flows for each operation mode

Table 2 shows an overview of the two control strategies that have been tested during the first year of operation, each with the available operation modes and activation conditions.

C1 applies the air source in cases of outdoor air temperatures higher than 6 °C. From temperatures lower than 6 °C both sources are operated, with a BHX fraction depending on the set point for the borehole inlet temperature. At lower inlet temperature, higher source capacity is extracted from the BHX.

Table 2: Control strategies and available operation modes

Building	K6	K8
Control Strategy	CS1	CS2
Mode: AHX only	Tamb > 6°C	Tamb > 0°C
Mode: BHX only	Off	Tamb < 0°C
Mode: combined source (AHX and BHX activated)	Tamb < 6°C, dynamic BHX capacity	off
Mode: Regeneration	Tamb > 10°C	off

In combined source mode, pump P2 is controlled dynamically by a PI controller (process variable: BHX return T2, setpoint: T4 – 3 K). Valve V1 controls the BHX supply temperature (T1) as frost protection for ground probes by mixing the colder BHX supply temperature with the warmer BHX return. The evaporator inlet temperature T3 results from the mixture of the output from the two sources. This control strategy ensures that the return temperatures from both sources are as similar as possible. This maximizes the utilization of the air source while accounting for the temperature increase provided by the BHX without unnecessarily stressing it. For example, if the BHX outlet temperature T2 is higher than the AHX outlet temperature T4, the mass flow through the BHX is increased. Consequently, the heat extraction from the BHX is enhanced, causing the temperature T2 to decrease. At the same time, the capacity of the AHX decreases, and the AHX return temperature T4 rises until the two temperatures are approximately equal.

CS2 was not planned from the beginning. This strategy could only be tested in K8, as the BHX and AHX source capacity relative to the heating capacity is higher in K8 compared to K6 (see Table 1). The regeneration has been deactivated in K8.

The pilot project was commissioned in May 2024. The detailed monitoring system could only be put into operation in October 2024, so limited data are available prior to that date. In the meantime, a full year of detailed monitoring data has been collected and analyzed. The following results focus, in addition to the comparison between the two control strategies in K6 and K8, on the regeneration of the ground, which was only active in K6.

3. Results and Discussion

In the first heating season 2024/25 focused on general tests of the functionality and the control strategies described above. The first operating winter did not have an extensive cold spell with temperatures in the higher negative range below -5 °C. However, in the second winter, in the beginning of January 2026, several very cold days with temperatures less than -10 °C occurred.

3.1. Heating mode

Figure 4 shows source temperatures for K6 and K8 from December 1st 2025 to January 7, 2026. In K6, the BHX is in operation most of the time. The evaporator inlet temperature as a mix of the AHX and BHX return temperatures, is around 1-2 K below ambient temperature. With decreasing ambient temperature, the evaporator inlet temperature follows the ambient temperature, dominated by the low AHX return temperature. In K8, until December 29, AHX is the only heat source, and the evaporator inlet temperature is generally lower than in K6, except for the period of higher ambient temperatures around December 9. The source is switched from AHX to BHX on December 29 due to the decreasing ambient temperature, which results in a significantly higher evaporator inlet temperature (BHX return) and SPF.

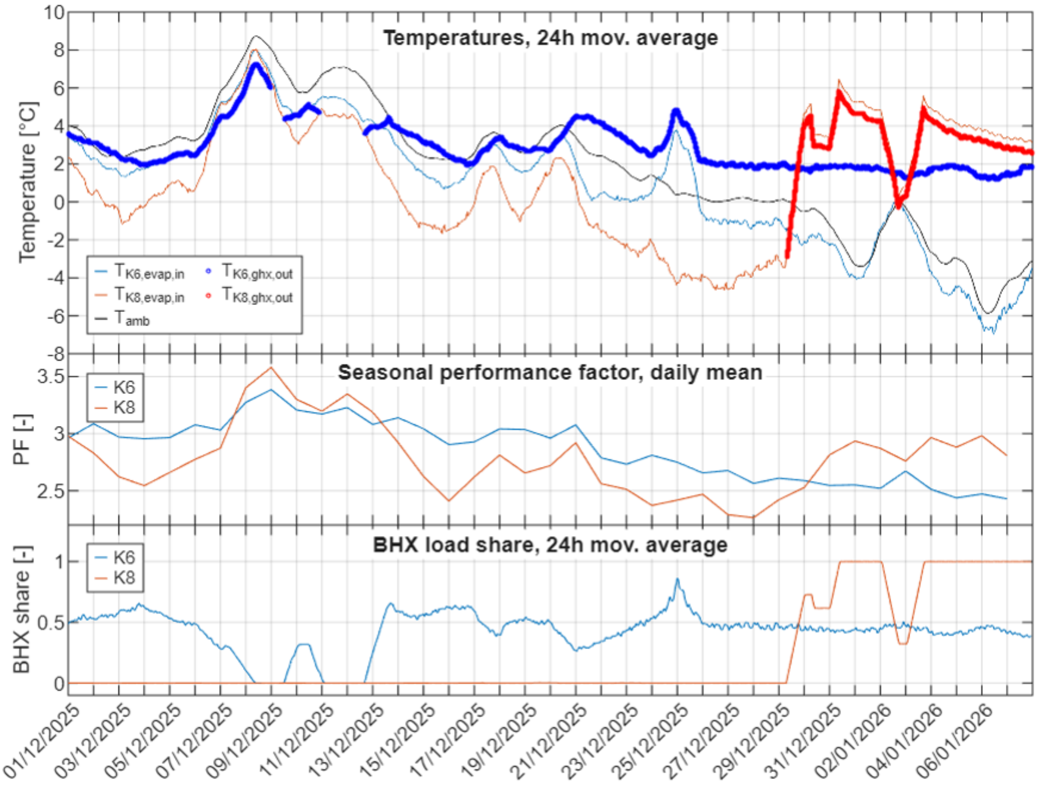

Figure 4. Borehole shares, Performance Factor (PF) as well as evaporator inlet temperature, BH outlet temperature and ambient temperature for the winter evaluation period 25/26.

Figure 5 on the left side and in the middle shows the evaporator inlet temperature in relation to the ambient air temperature for K6 and K8, respectively. In AHX-only mode (blue), the evaporator inlet temperature is approx. 3-4 K below the air temperature due of the temperature difference of the heat exchanger. In dual source mode, the evaporator inlet temperature increases up to the ambient air temperature or even more as a result of the mixing with the warmer BHX outlet. In BHX-only mode in K8, source temperatures between 5 and 10 °C can be reached, although its significantly less hours in operation (348 h/a) compared to dual source mode in K6 (1068 h/a).

Figure 5 on the right shows the length-specific heat extraction from the probes. In K8 up to almost 100 W/m has been measured in BHX only mode. However, in K6, thanks of the dual source mode, the specific capacity extraction could be limited to around 60 W/m, but is mostly below 40 W/m.

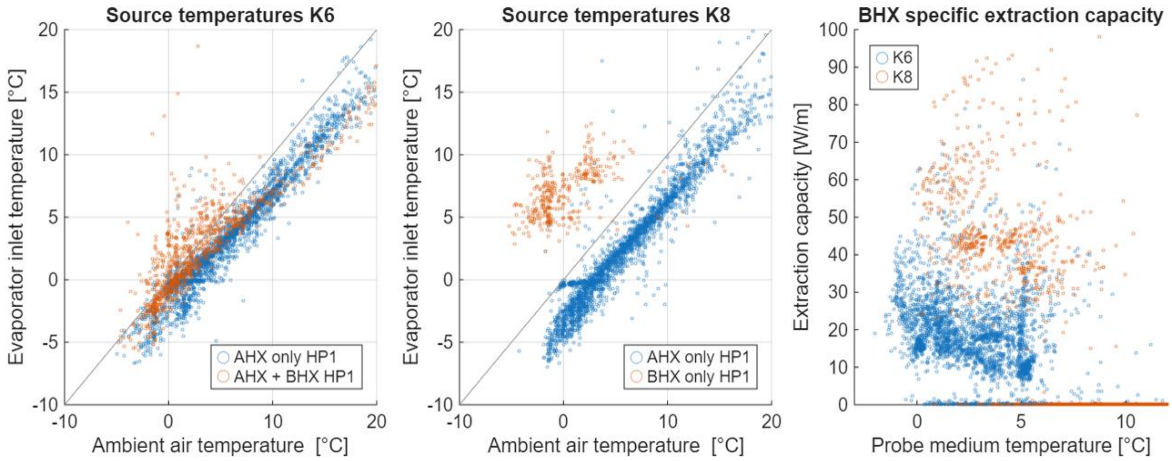

Figure 5. left and middle: Evaporator inlet temperatures in relation to ambient air temperatures for the first and the second heating period in K6 and K8. Right: BHX length-specific extraction capacity for K6 and K8 (hourly average values)

Figure 6 shows the performance depending on the ambient temperature, on the one hand as COP (right), and on the other hand with the specific electricity demand per energy reference area (left). During the coldest days with temperatures below 0 °C, the BHX in K8 deliver a higher source temperature and thus significantly better efficiency than in K6, where the source temperature is reduced by mixing of the two sources (marked by blue and red circles for K6 and K8, respectively).

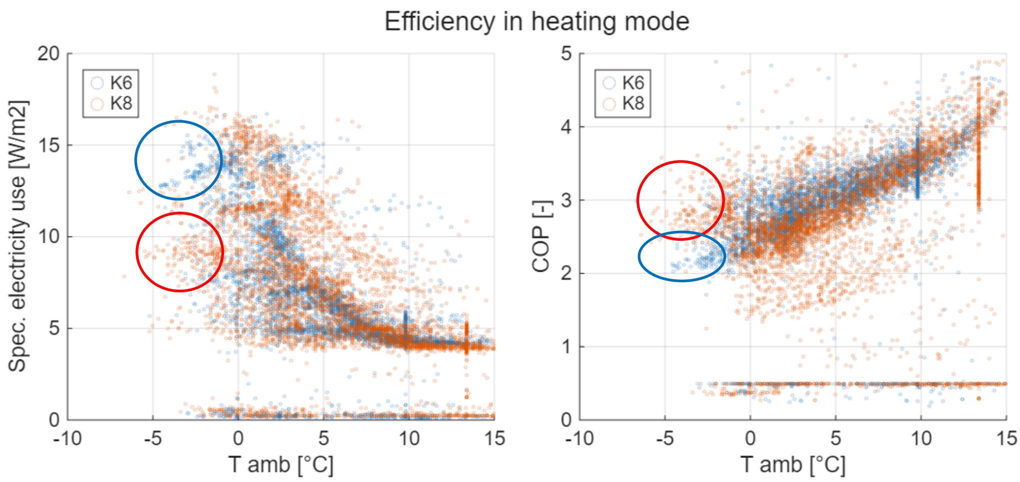

Figure 6: Specific electricity use and COP in heating mode (hourly values)

3.2. Regeneration mode

Regeneration was deactivated for K8 from the beginning. In K6 regeneration started in May 2024.

Figure 7 left shows the daily net-regeneration (regenerated energy minus extracted energy) for three time periods. The first time period (blue) contains the first summer in operation 24/25.

As the initial commissioning of the system was in May 2024, there was no energy extracted from the undisturbed ground which resulted in lower daily regeneration yields. The second period (red) encompasses the first winter season, where regeneration is low, but nevertheless, some energy could be regenerated. The third period (yellow) comprises the summer 2025 and shows significantly higher daily regeneration yields due of the lower ground temperatures, caused by the energy extracted in winter 24/25.

In Figure 7 right, the monthly regeneration yield is shown for 2025. There is a peak of the regenerated energy as well as for the ambient temperature in June. But although, the ambient temperature in July was not much lower, the regeneration yield dropped significantly.

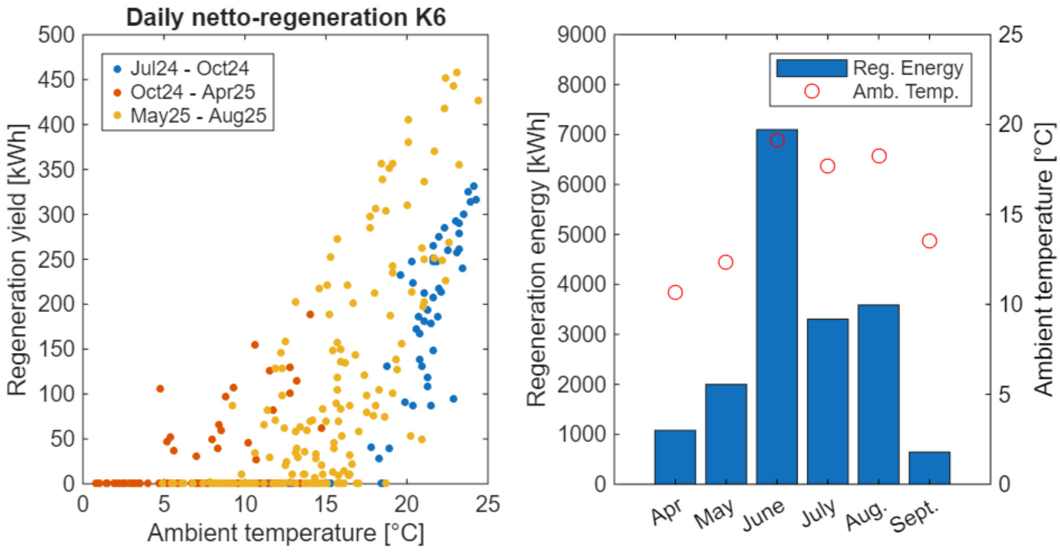

Figure 7 left: Daily net-regeneration in K6 for three time periods. Right: monthly net regeneration yield and ambient temperature in K6.

Compared to the high-resolution time series in Figure 8, it is noticeable that the ambient temperature in August was sometimes as high as in June, yet the regeneration performance was significantly lower. However, the variation across the BHX is higher. The data also shows that the flow rate through the BHX has been reduced after the first week of July. The cause of the reduction has not been identified, yet. However, it is likely that the reduction in flow rate is the main cause of the decreased regeneration.

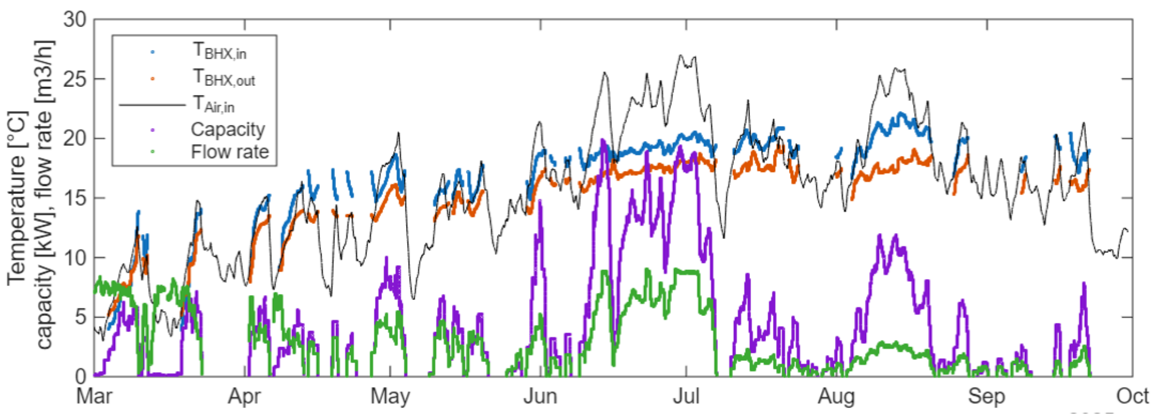

Figure 8. BHX and AHX air inlet temperatures, capacity and flow rate. The BHX temperatures are only displayed when the capacity exceeds 2 kW.

3.3. System performance

Table 3 shows the seasonal performance for the sources as well as the seasonal performance factor for the whole system, calculated as total heat energy produced per electric energy input (compressor, auxiliary and fan). In K6 around 20% of the source energy in winter is extracted from the BHX field, while in K8 it is just about 12%. In K6, the SPF is noticeably higher in winter than in K8.

Although the BHX field and the AHX in K8 are slightly larger relative to the heating capacity than in K6 - resulting in higher source temperatures and potentially a better SPF - the SPF in K6 during winter remains noticeably higher than in K8. The proportion of source energy derived from the BHX is significantly higher in K6 than in K8, suggesting that the dual-source control strategy leads to better system performance compared to the alternating operation of the two sources. However, it should be noted that in K8, a refrigeration cycle issue caused a substantial reduction in the SPF from February to March over a period of six weeks. Additionally, the AHX fan in K8 was operated at maximum speed for three weeks in April due to a controller problem, which increased electrical energy consumption. The impact of these incidents on the SPF has not yet been investigated. Defrost energy for the AHX is around 4% of the overall heat gain from AHX in heating mode. Regeneration efficiency is calculated as the rate between thermal energy input into BHX to electrical energy use for fan and auxiliary.

Table 3. Seasonal energy performance indicators for the source balance.

Building		**K6**		**K8**	
Period	unit	Winter Nov. - Apr.	Summer Mai - Oct.	Winter Nov. - Apr.	Summer Mai - Oct.
Total source heat in the evaporator	a	166.0	72.0	111.9	44.4
Extraction from BHX (for heating)	[MWh]	32.8	0.8	13.7	0.0
Regeneration into BHX (by AHX)	[MWh]	3.5	16.8	0.0	0.0
Net extraction (entry – extraction - regeneration)	[MWh]	29.3	-16.0	13.6	0.0
Regeneration share (regeneration / extraction)	%	60.3%		0.0%	
Regeneration efficiency	[-]	32		n/a	
Proportion of BHX in source heat	%	19.7%	1.1%	12.2%	0.0%
Heat gain from AHX (without regeneration)	[MWh]	125.5	70.0	94.0	44.2
Defrost energy	[MWh]	4.7	0.2	4.0	0.5
Proportion of defrost energy relative to heat gain from AHX	%	3.7%	0.3%	4.2%	1.0%
Seasonal performance factor (SPF)	-	2.9	3.2	2.6	3.2

Efficiency losses, in addition to temperature losses in the brine intermediate circuit, are also found in the refrigeration circuit. For instance, the suction gas superheat before the subcooler is unusually large. The manufacturer has already announced a control system update to solve this issue. K6 has a better overall performance, while K8 has a better performance during the coldest days.

4. Conclusions and outlook

In the first winter season, it was demonstrated that the dual-source system with the dynamic control of the BHX generally works, even though the borehole design is massively reduced to less than 50% of the original design (regenerated BHX field) and around one third of the length needed for a BHX field without regeneration. It should be noted that the original design and the unregenerated field are based on significantly longer probes (BHX) of 300 m and 400 m, respectively, what means higher BHX temperature and thereby higher capacity per meter. This enables a monovalent heat pump operation even in situations with heat source constraints, since by the dual source design, both noise and drilling space/depth limitations can be overcome. Note that in the pilot plant, an operation of either ground- or air-source-only would not have been possible. The performance factors are not yet as high as assumed, which is partly due to technical problems and moderate ground use. However, they are well within the expected range for nearly unrenovated older building (Lämmle et al [4]) and there is still potential for increasing the SPF. In K6, a regeneration rate of 60% was achieved, with the observation that most of the regeneration occurred during the first half of the summer, with a clear peak in June. It is suspected that the regeneration share was limited by the reduced mass flow rate starting in July, indicating that a higher level of regeneration is possible.

The combined-source control strategy in K6 shows a better overall performance over the 6 months winter period, while the single-source switch strategy in K8 shows a better performance during the coldest days the core winter and a lower heat extraction from the BHX. In the second half of the winter 2025/26, a control strategy combining CS1 and CS2 will be tested.

The probe temperatures remain within the permissible range despite high heat extraction rates of up to 100 W/m. The use of the ground probes allows the evaporator inlet temperature to be increased by approximately 3 K compared to operation with the AHX-only in K8 but also allows high source temperatures in BHX-only modes for a limited amount of hours.

In the first half of winter 25/26, the proportion of heat from the BHX in K6 has been increased by raising the shutdown threshold for the dynamic dual-source control. First investigations of the monitoring data show a higher share of BHX in autumn, but also a decrease in the BHX outlet temperatures compared to K8 due to the higher BHX share.

The dual source system does not seem to offer high performance potential compared to a pure air-source heat pump, but the main goal of this system is to enable a heat pump installation at all when sources are limited. In the HP-Source project, it was already shown that the SPF is significantly closer to an air system than a BHX system, as air dominates in terms of energy supply. However, the dimensioning of both sources could be significantly reduced. For a BHX-only system, approximately four times more ground probes would be necessary (at the same drilling depth), and for an AHX-only system, the double nominal capacity of AHX. In HP-Source, a dual source system containing a direct evaporator air heat pump and a brine-to-water heat pump has also been examined and has potential for better performance. However, in this pilot project, only the system with the brine intermediate circuit could be implemented because the construction project was already far advanced when the artesian well was discovered, which led to the switch to the peak load probe system, and not many changes were possible anymore.

With the monitoring data, the simulation models will be validated and optimized. These models will be used later in the project both for testing other control strategies and for determining design parameters under various boundary conditions, such as available space or drilling depth restrictions. Furthermore, the simulations will be used to establish benchmarks, enabling a comparison with air- or ground source-only heat pump systems under the same conditions. A simple comparison based on standard-COP performance maps of an air-source-only heat pump may be premature and misleading, since also noise considerations and temperature differences in the air heat exchanger are important and vary among the systems.

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