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Renosource – Simulation and monitoring of propane heat pumps using integrated air- and ground-heat source for retrofit application

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Abstract. In particular in existing buildings with higher heat loads the market share of heat pumps is still limited. In a previous study it was confirmed that limitations of individual heat sources can be overcome by dual source integration of the ground and outdoor air and both performance and economic benefits can be achieved. The integration is applied in a P&D project of a boiler replacement in two larger multi-family houses with restriction of the ground source. Monitoring results of the first winter period confirm that the source capacity can be delivered to the heat pump despite a significantly smaller design of the borehole heat exchanger field, if it is only used as peak load coverage and the air source is used as base load and for the ground regeneration which confirms the simulations. It is also confirmed that temporarily higher capacities can be extracted from the ground in peak load situation, if a longer regeneration time is foreseen. Results will further be used to validate the simulation models, test control strategies as well as perform system comparison and derive design recommendations.

1. Introduction

For climate protection reasons heat pumps (HP) are seen as future heating systems in many scenarios and countries, e.g. [1]. In Switzerland, the number of HP shall grow by a factor of 5 until 2050 according to the energy perspectives 2050+ [2]. With growing number of HP also adequate heat sources (HS) are important for a high performance, which can be a challenge especially in the larger capacity range and dense urban environments often found for boiler replacements. In previous research a multi-source integration was investigated by simulations combining most common HS outdoor air and vertical ground probes. It was found that obstacles like noise restrictions for the air-source and drilling depth and space limitations for the ground-source can be mitigated and also performance and economic benefit due to synergies between the HS could be evaluated [3].

This follow-on P&D project “Renosource” aims at verifying the simulation results of an integrated air- and ground-source in a real HP installation, which encountered the same restrictions as investigated in the simulations. The original concept combined a deep Borehole Heat Exchanger (BHX) of 300 m probes with regeneration by an Air Heat Exchanger (AHX) due to space restrictions for the number of probes by the steep environment. This concept was no longer possible with artesian water found at 130 m. Therefore, the BHX was changed to peak load operation and the AHX was extended to cover the base load and regenerate the BHX. The pilot plant is shown in Figure 1 and consists of two larger multi-family houses (MFH) with 28 apartments each and an energy reference area (ERA) of 2357 m^2 of the MFH K6 and 1833 m^2 the MFH K8, respectively. The MFHs are built in 1972 and were only slightly renovated in the 1990s.

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Figure 1. Pilot object of two MFH K6 (pink, back) and K8 (blue, front) with boiler replacement (source: Lägern Wohnen)

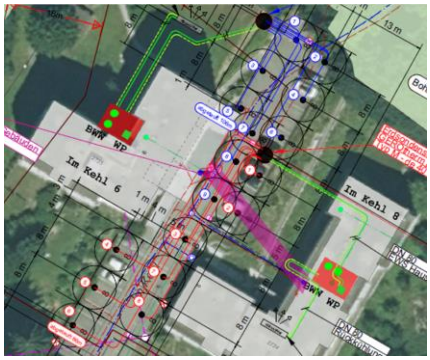


Figure 2. Ground probes installed on the parking lot between the buildings (source: modified from A+W Zurich)

The existing heat generation system composed of two oil boilers was placed in the basement of the MFH K6 with a pipe connection to the MFH K8. The oil consumption over the last 14 years was evaluated to 60,000 l/yr or 600 MWh/yr on average. For the boiler replacement one indoor installed propane HP per building of 90 kW for K6 and 70 kW for K8, respectively, with a dedicated fraction of a common BHX field, i.e. 9 probes of totally 906 m for K6 and 7 boreholes for K8 of totally 786 m, see Figure 2, was planned. Due to the advanced state of the planning, the HPs were each integrated with the respective fraction of the BHX and the connected AHX by an intermediate brine cycle, see Figure 3.

2. Scientific Methodology

The feasibility of the configuration as outlined above have been evaluated by system simulation. In order to verify the simulations and get experience of the real-world operation, HP and HS system are equipped with more the 90 measurement sensors to derive key performance indicators (KPI) for the system behaviour and performance, in particular the Seasonal Performance Factor (SPF). Figure 4 shows the additionally installed sensors in the systems, other measurements can be extracted from the HPs. In parallel, simulations of the plant will be performed to study the system control for optimized HP performance. The plant shall be measured for three heating periods, also including the summer and the transitional periods to monitor and simulate the regeneration of the BHX by the AHX. Based on the results an economic evaluation and comparison with standard systems is derived. This paper focuses on the monitoring results of the first heating period.

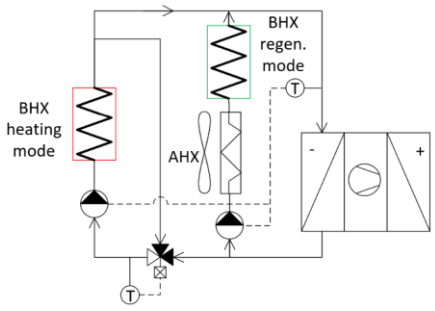


Figure 3. Hydronic sketch of the integration of the HS

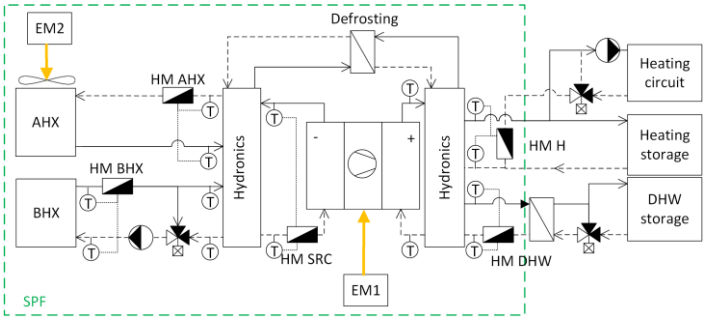


Figure 4. Measurement scheme of the HPs and installed measurement equipment

3. Simulation results of the retrofitting

To approve the feasibility of the dual source concepts, parameter variations and test of respective control concepts have been performed by simulations for the combined strategies of peak load coverage by the BHX and regeneration with the AHX. Figure 5 and Figure 6 summarize the simulation results. A BHX-only source would require 14 ground probes of 400 m depth to keep the SIA 384/6 [4] criteria not to surpass the lowest permissible average fluid temperature of –1.5 °C as depicted as black line in Figure 5.

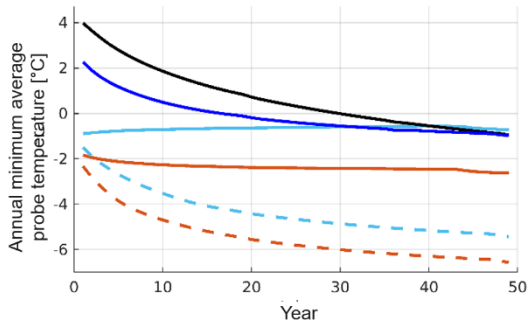


Figure 5. Simulated source over 50 years for varied BHX depths, probe number and control

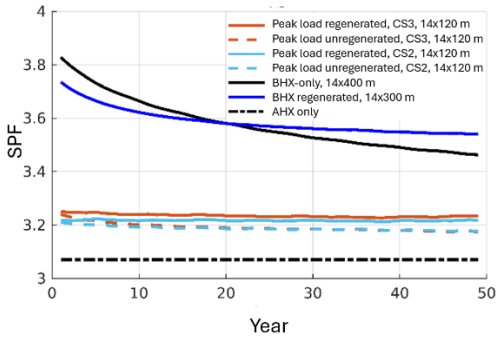


Figure 6. SPF for the respective design variations of the pilot plant

For the initial planning with a BHX of 14 ground probes at 300 m depth, a regeneration with the AHX would be required to meet the criteria. However, by the regeneration, the BHX is not as much exhausted (dark blue curve) and yields a slightly higher SPF than the original design (black curve) as seen in Figure 6. For the depth of 120 m and only peak load operation of the ground, two control strategies have been tested, a conservative control strategy CS2 (light blue), which only uses the BHX when the AHX-only cannot provide the entire required source capacity. CS3 (red) denotes a more progressive control strategy, which has higher shares of BHX use to optimize the SPF. It is clearly visible that without regeneration, the SIA criterion cannot be met independent on the control strategy (dashed red and light blue curves). With regeneration, however, the criterion can be kept with the conservative control strategy CS2 (light blue curve), while it is not reached with the progressive control strategy CS3 (red curve). Moreover, due to the peak load operation, the BHX is operated colder than the deeper probes at 300 m, which decreases the SPF by about 0.4 points to 3.2 (compare light blue and red curve to dark blue curve). The temperature decreases right from the beginning, which is due to a higher capacity extraction for the short-term peak load operation. For CS2 (light blue curve), the temperature slightly increases before levelling off. In comparison, an air-source, however, would only reach an SPF of slightly above 3 and would be problematic to realize due to noise issues by a strongly extended AHX.

4. Monitoring results of the first heating period

The two HP were installed and commissioned in February 2024. During the summer period, the borehole field has been slightly regenerated by the AHX, but since little heat of the ground has been extracted, the effect of the regeneration is limited. The simulation results are currently verified in the P&D project described above. The focus of this evaluation is set on the first heating period 24/25, which was characterized by December temperatures generally in line with the 1991–2020 average, while in January 2025, an average temperature of -0.8 °C was recorded, which is 1.4 °C above average, marking one of the warmest Januarys on record. For the monitoring period of Oct. 1 to Jan. 31, 2025, the space heating (SH) and domestic hot water (DHW) shares evaluated reflect typical fractions for existing buildings with 77% for SH and 23% for DHW, respectively. The SH is operated at supply temperatures up to 60 °C in the considered period, and the DHW is charged to 65 °C. The heat source energy was mainly covered by the AHX with a share around 90% and only 10% by the BHX, which is on the one hand due to the mild January and on the other hand due to the conservative control strategy which only activates the BHX heat source when the AHX is at its capacity limit. Figure 7 shows the temperatures and Figure 8 the source capacity for K6 with combined source control in more detail for a four-day period in January. On Jan 21, the minimal inlet temperature to the BHX is set from 0 to -2 °C as can be seen in Figure 7. The BHX source power increases from around 15 kW to around 25 kW while the AHX source power decreases from around 40 kW to around 20 kW. The evaporator inlet temperature, a mixture of both flows from BHX and AHX, increases from around 2 K below the ambient temperature to a value close to the ambient temperature. The "AHX in" daily peaks are due to defrosting of the AHX. Due to the slightly different design of the source capacity in the MFH K8 an alternate source control has been tested, i.e. either the AHX or the BHX is operated. This strategy could only be tested in K8, because the heat load is lower than in K6 whereas the AHX has the same capacity as in K6.

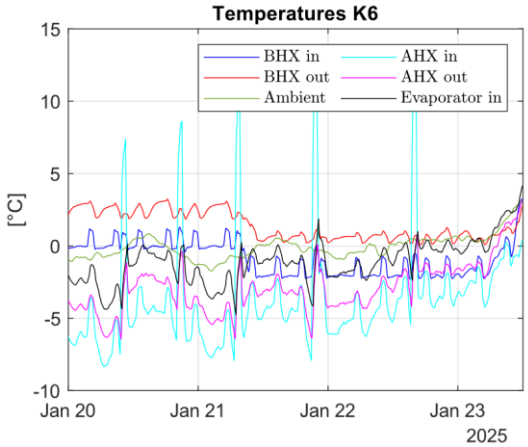


Figure 7. Source of the heat sources in the building K6, evaporator inlet and ambient air

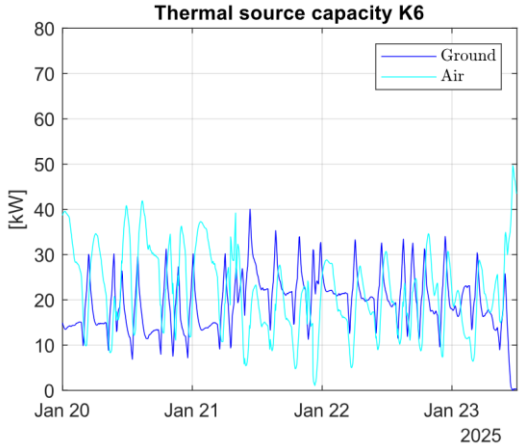


Figure 8. Thermal source capacity in the building K6 by the AHX and the BHX

In K6, operating only with AHX at very cold ambient temperatures leads to evaporator inlet temperatures that fall below the minimum permissible temperature limit for the HP. Figure 9 and 10 show the temperatures and the thermal source power for K8. In BHX-only operation, the evaporator inlet temperatures are significantly higher than in combined operation in K6, whereas they are significantly lower in AHX-only operation. In BHX operation, the outlet temperature is decreasing due to cooling down of the ground (Fig.7 and Fig.9). When reaching the minimal temperature of 2 °C, the source is switched to air. The difference in temperature between BHX outlet resp. AHX outlet and evaporator inlet during operation of BHX occurs from different positions of the sensors and can be neglected. Temperatures above 10 °C occur when the individual sources are not in operation or AHX is in defrosting mode and can therefore also be ignored.

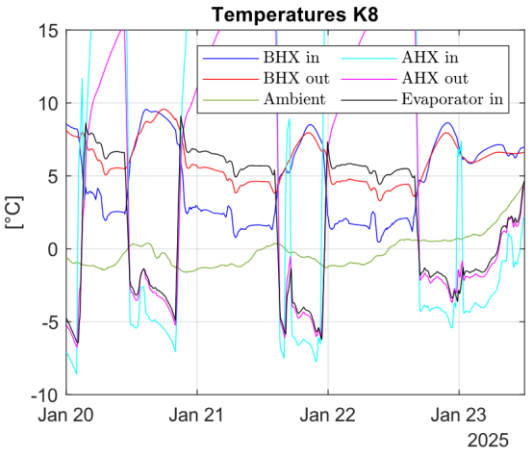


Figure 9. Source temperatures of the heat sources, evaporator inlet and ambient air

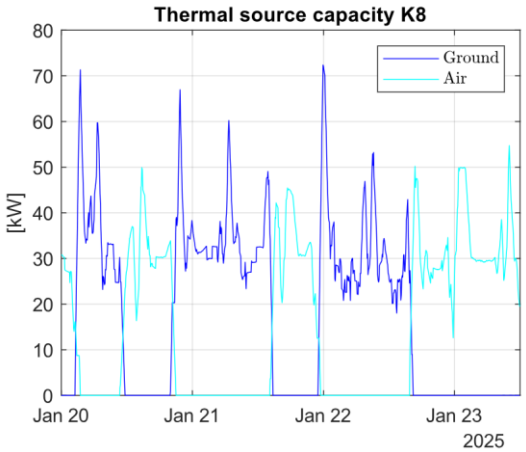


Figure 10. Thermal source capacity by the AHX and the BHX in the building K8

Figure 11 shows the evaporator inlet temperature as a function of the outdoor air temperature for the different control strategies. Compared to AHX-only control depicted in red, the evaporator inlet temperature can be increased in combined source strategies depicted in blue. The separate source strategy compensates the lower air temperature with significantly higher temperatures in BHX-only mode depicted in orange. Figure 12 shows the hourly moving averaged BHX specific thermal source capacity. The source capacities are notably lower in the combined operation in K6 depicted as blue dots, since additionally the the air is contributing to the total capacity required. In K8, however, the BHX-only operation reaches extracted capacities above 90 W/m at maximum as shown in Figure 12 due to the alternate operation of the sources, which confirms that short-term extraction of higher capacities are possible without damaging the BHX, since BHX operation is maintained as shown in Figure 14.

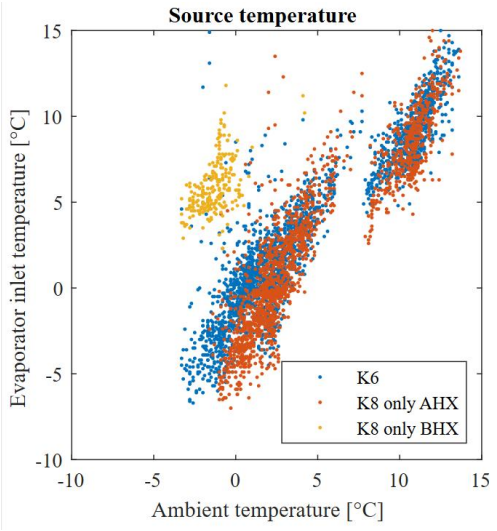


Figure 11. Source temperature in K6 and in K8;

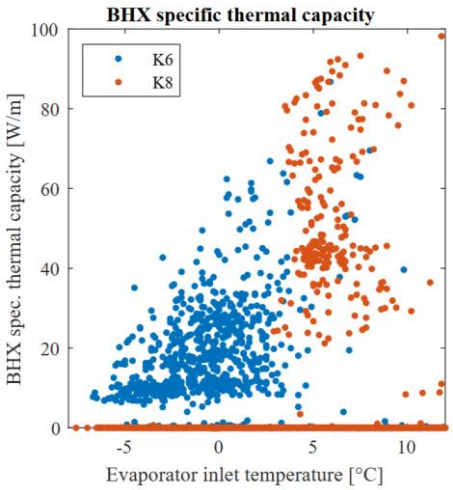


Figure 12. Specific thermal capacity extracted from the BHX in K6 and K8

Figure 13 shows the ambient temperature and the evaporator inlet temperature (24 h moving average), the SPF and the BHX share on source power (daily average). Until Dec. 13, both systems were running on air-only, and the evaporator inlet temperature is roughly the same.

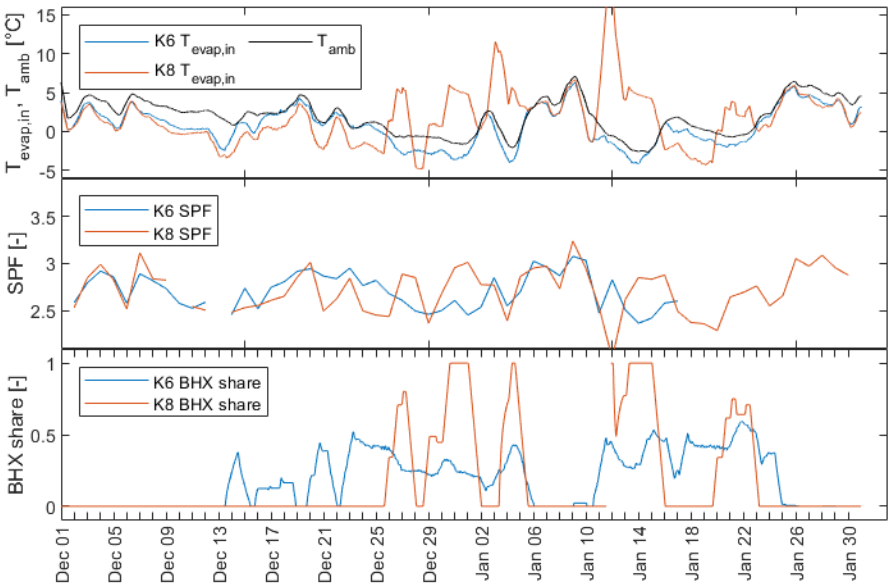


Figure 13. Borehole shares, SPF as well as evaporator inlet temperature and ambient temperature for the 2-month evaluation period

From Dec. 14. to Dec. 25, K6 is running on both sources while K8 is running on AHX-only. The evaporator inlet temperature in K6 is around 1-2 K higher than in K8, increasing the SPF by around 0.2. From Dec. 25 to Jan. 5, K6 is running on 30 to 50% BHX share while K8 is running mainly on BHX-only which leads to a higher SPF. From Jan. 17, data losses due of a fieldbus converter failure occurred, so no data of the electric meters in K6 were available and the SPF could not be measured and evaluated.

5. Conclusions

The P&D project investigates a dual source integration of the most common heat sources in Switzerland of the outdoor air and vertical ground probes by simulation and monitoring with the objective of verifying the benefit found in a simulation study.

The source integration shall overcome noise and space limitations found in particular for boiler replacements due to the built environment and enable a monovalent HP operation without back-up heater. Due to the smaller design of both sources, limitations both on the air-source and ground-source can be overcome. The retrofit application is also facilitated by the applied propane HPs, since besides the sustainability in terms of a low GWP refrigerant they can be operated around 70 °C avoiding thereby typical upper temperature limit of conventional HFC refrigerants. The HPs have operated smoothly in the first winter period obeying the common safety rules. Monitoring results of this first winter period confirm that the system can cover the heat load despite the smaller design of the BHX field. Due to a conservative control strategy giving preference to the air-source and a mild January, the fraction of the ground heat source is still limited and holds potentials to be used earlier and more frequently. The design of the dual source HP system is thus feasible despite the redesign in the ongoing planning process and the on-site limitations on the sources. The conservative use of the BHX also affects the SPF, which is depicted in Figure 13 and is in the range of 3 which is rather typical for AHX-only operation. Nevertheless, only the coldest month of the year has been considered in the SPF and the fraction of the BHX use is only in the range of 10% due to conservative control to prove the feasibility of the system. With optimized ground use, an increase of the SPF also in winter operation is expected.

Simulation results on the system design are thus confirmed by the first winter results. A more detailed analysis of the heat source capacity by the option to operate the building K8 in alternate mode also confirms that temporarily during peak load, higher capacities can be extracted from the ground at short term, if the BHX is reserved for peak load operation with long regeneration times, as depicted in Figure 12. This corresponds to the simulation results that only temporary use of the BHX at peak load enables significant reduction of the BHX field size and helps to overcome the source limitations encountered in retrofitting. Since only the peak capacity is extracted from the ground, but the energy is mainly delivered by the other heat source, the BHX has a long time to regenerate during the off-peak time, since peak load only occurs during the coldest period. This implies cost savings found in the simulations [3], which can compensate the investment in the second heat source for the base load and regeneration. These preliminary results will be further investigated in the following heating periods. An objective of the P&D is also to develop and evaluate monitoring measures of the ground temperature to control the extraction in the case of higher ground capacity and to prevent overuse of the ground or damage to the probes, respectively.

Future tasks are the validation of the system models by the monitoring as well as an economic comparison to the original concept and other possible options for retrofitting. This includes also cases without limitations. Furthermore, control shall be optimised by shifting the application between the heat sources, i.e. to a higher fraction of the BHX in order to evaluate potentials of the SPF.

The results indicate that individual heat sources can be economically inefficient especially for the larger capacity range due to savings in the borehole field, which can overcompensate investments for the second heat source, as found in the simulation [3]. Thereby, better system solutions regarding performance and cost can be developed using dual or multi-source integration, avoiding also fossil back-up. This shall be further investigated in order to advance knowledge for the planning process of more standardized multi-source system integration and create more reference or best-practice applications, which are currently still scarce.

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