Evaluation of Two Ground Source Heat Pump Systems in Nearly Zero Energy Buildings

Caroline Haglund Stignor[1], Ola Gustafsson[1] and Jon Persson[1]

[1] RISE Research Institutes of Sweden, Box 857, 501 15 Borås, Sweden
Caroline.haglundstignor@ri.se*
Ola.gustafsson@ri.se
Jon.persson@ri.se

Abstract. In the future, most buildings will be nearly Zero Energy Buildings (nZEBs). Heat pumps are frequently used as heating system in Swedish single family buildings, but in most cases they are used in buildings with higher heating demand than the nZEBs of tomorrow. In this study, operation parameters such as heating water and brine temperatures were analyzed in real operation in two different nZEBs. The results show that the measured supply temperatures coincide in some cases well with what is described in the standard developed to be harmonized with the ecodesign and energy labelling regulations - EN14825, but in some cases they were higher. However, the brine temperatures were often considerably higher than the test conditions described in EN14825. The results also show how interconnection of a tank affects the operating parameters of a heat pump system. Another finding was that in order to reach the highest overall energy performance the heat pump and the heating system must be optimized together and not separately, which often is the case today.

Keywords: Heat pump, nZEB, Energy Labelling

1 Introduction

1.1 Background

The updated Energy Performance of Buildings Directive, 2010/31/EU (EPBD2) requires very low energy consumption in all newly or re-constructed buildings from year 2021 and onward. Across Europe there are a number of Nearly Zero Energy Buildings (nZEB) that meet the requirements of the EPBD2, but the concept is still in the pilot or demonstration stage according to Wemhöner and Kluser [1]. Previous research [1-3] has shown that heat pumps are an attractive solution for these buildings seen from energy point of view. Also, in these buidlings heat pumps are often used because of the flexibility they offer - they allow for greater freedom in designing the building envelope, since nZEB defintions are in many cases based on bought energy, and they can provide both room heating/cooling and domestic water heating[2,3].

Moreover, heat pumps can be effectively linked to various heat sources and sinks and they can provide load balancing in a future smart grid. Wemhöner and Kluser [1] concluded that heat pumps are both an energy-efficient and cost-effective system technology for nZEBs. However, one conclusion from the same study was that there are no commercially available products that are of the right capacity. It was shown by Persson et al. [2] that a liquid/water heat pump was the most efficient heating option from both an energy and cost perspective in a nZEB under Swedish circumstances. Since the total heating demand in the nZEB is small, the cost of the heat pump system can not be too high for the system to have a competitive LCC. A heat pump system in combination with some form of heat storage is also an attractive alternative in future smart energy systems where intermittent renewable energy sources (e.g. wind and solar) are becoming more common. Therefore it is very important to increase the knowledge of how the heat pump's operating parameters (e.g. flow temperature, brine temperature, efficiency etc.) in actual operation in a nZEB are affected by speed control, by the connected storage tank, the choice of heating system etc.

Heat pumps are frequently used as heating system in Swedish single family buildings, but in most cases they are used in buildings with higher heating demand than the nZEBs of tomorrow. In the European Union there are mandatory eco-design and energy label requirements for heat pumps for hydronic heating systems from 2015. These requirements will have a large influence on the design of heat pump systems. Due to these reasons we should learn more about real operation conditions for heat pumps in nZEBs. This is important, first of all to be able to optimize the design of such heat pump system, but also to know how well their operation is reflected by the performance data for the labelling, in order to be able to influence a revision of the regulations if so needed.

1.2 Scope

The scope of this study was to:

- increase the knowledge of how different operation parameters are affected by the type of control (inverter-controlled compared with on-off), the different types of distribution system, to thereby provide data on how well the energy label correspond to reality for a heat pump in a nZEB building
- increase the knowledge of how the interconnection of a tank affects the operating parameters of a heat pump system, in order to obtain data for guiding how heat pump systems can be developed for future smart grids and use of electricity produced on-site (since the latter is important for nZEB definitions in several countries)

2 Method

2.1 Evaluated Objects

This study is based on evaluation of two different heat pump systems in two almost identical nZEBs in Sweden. One of the heat pump systems consists of an on/off controlled heat pump with an extra storage tank (see Fig 1) and the other nZEB has a heating system with an inverter controlled heat pump. More information about the houses and their heating systems is found in Table 1**.**

Table 1. Technical information about the two different nZEBs and their heating systems evaluated in this study

Place	Borås	Varberg
Size	• 166 m^2, 22 $kWh/m^2/yr$ (projected-space heating and DHW demand)	• 166 m^2, 20 $kWh/m^2/yr$ (projected space heating and DHW demand)
Ventilation	• Balanced ventilation system with heat recovery	• Balanced ventilation system with heat recovery
Heating source	• Ground source heat pump (4.5 kW, on/off controlled) • Storage tank 150l. • Borehole 90 m (81m active) • Dimensioning temperature: 0°C	• Ground source heat pump (6 kW, inverter controlled) • Borehole 90 m (71m active) • Dimensioning temperature: 0°C
Heating system[a]	• Floor heating on upper and 1st floors • Dimension temperature: 36°C at dimensioning outdoor winter temperature	• Low temperature radiators, upper floor • Floor heating, 1st floor
Solar	• PV-panels 3000 kWh/yr	• PV-panels 3000 kWh/yr
Habitants	• Simulated family	• Real family

[a]Controlled by an outdoor sensor and selected heat curves

2.2 Measurement Plan and Equipment

Operation parameters such as heating water temperatures, brine temperatures, heating water flow, electric power and outdoor temperature were analyzed in real operation in the two different nZEBs. Sensor type used for each parameter and the estimated expanded measurements uncertainty for the corresponding parameter (including sensor accuracy, sensor mounting, sensor stability, etc) is listed in Table 2 below, together with expanded uncertainties for calculated parameters.

The results from the two systems were compared to see differences and similarities of the systems with an inverter controlled heat pump and a system with on/off controlled heat pump. The relevant measurement equipment is shown in Fig. **1** including schematic representation of placement of flow meters and temperature sensors. This study presents data evaluated over measurement periods of a year but also presents some examples of specific time events (from hours to days) to show upon cases where the differences of the systems becomes clear.

Table 2. Technical information about the different measurement parameters

Parameter	**Sensor type**	**Expanded measurement uncertainty**
Supply temperature, heat pump to tank, $t_{w,hp\text{-}tank}$	Pt100[a]	±0.5K
Return temperature, tank to heat pump, $t_{w,tank\text{-}hp}$	Pt100[a]	±0.5K
Supply temperature to heating system, $t_{w,s,hs}$	Pt100[a]	±0.5K
Return temperature from heating system, $t_{w,r,hs}$	Pt100[a]	±0.5K
Brine temperature out from heat pump, $t_{b,out}$	Pt100[b]	±0.5K/±1.0K
Brine temperature in to heat pump, $t_{b,in}$	Pt100[b]	±0.5K/±1.0K
Heating water flow rate, heating system, q_{hs}	Armatec AT7500C	±1%
Electric power used by heat pump system, P_{hps}	Velleman EMDIN03 kWh meter	<±4%
Outdoor temperature, $t_{outdoor}$	Pt100	±1.0K
Specific heat, c_p	Tabulated value	<±0.5%
Density, ρ	Tabluated values	<±0.1%
Cold water temperature $t_{w,DHW,c}$	Pt500	±0.5K
Hot water temperature $t_{w,DHW,h}$	Pt500	±0.5K
Domestic hot water flow, q_{DHW}	Armatec AT7080	±1%
Heat losses, water tanks, Q_{losses}	Estimated value	±20%

[a] The Pt100 sensors were placed in thermowells to obtain lowest possible measurment uncertainty

[b] In the research villa in Borås there were both sensors placed in thermowells as well as surface mounted sensors. In the villa in Varberg, there were only surface mounted sensors.

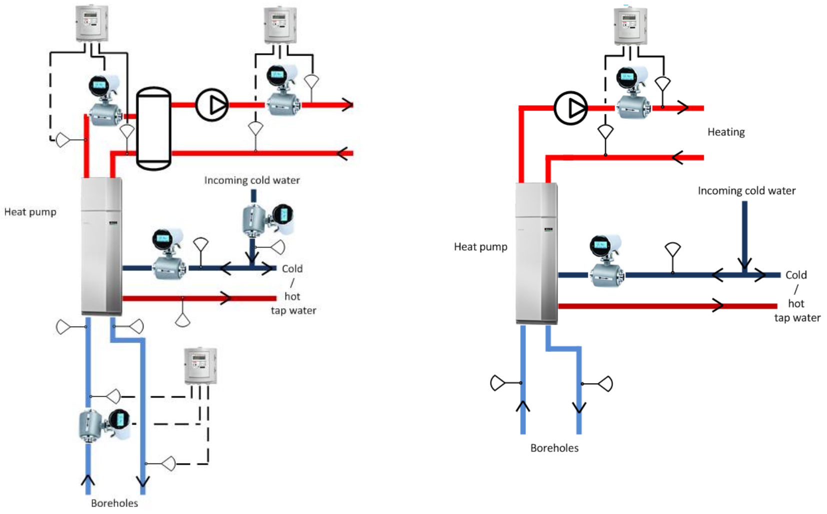

Fig. 1. Schematics of the measurement equipment in the two heating systems. To the left the system with an on/off heat pump and an extra storage tank is shown (Borås). On rhe right the system with the inverter controlled heat pump is shown (Varberg).

For the heating system with the on/off heat pump the supply temperature to the tank was also compared to the supply temperature out to the floor heating system to evaluate the efficiency impact of an extra storage tank and the on-off operation.

The evaluation done in this study is based on measurements performed from May 2015 to the April 2016 for the research villa in Borås and from March 2016 to February 2017 for the villa in Varberg. The reason for differing evaluation periods is that the houses were completed at different times. Even though the houses in many ways are identical, there are differing circumstances. First of all, the Varberg villa is placed in a somewhat milder climate. The yearly average climate is 8.0°C compared to 6.6°C in Borås according to SVEBY [4]. But the largest difference is that there is a real family living in the Varberg villa, while it is a simulated one in the research villa in Borås. During the evaluated periods this has resulted in large differences in ventilation air flow (by choice) and use of domestic hot water. Nevertheless, since the heating systems have many similarities the study stills offers many interesting comparisons.

3 Results and Discussion

In figure 2 and figure 3 the heating demand for space heating and domestic hot water is shown together with the electric power consumption for the two houses. Also the average "SCOP" per month is shown. SCOP (system COP) is calculated according to equation 1 below.

$$SCOP = \frac{\Sigma\big((t_{w,s,hs}-t_{w,r,hs})\cdot q_{hs}\cdot c_p\cdot \rho+(t_{w,DHW,h}-t_{w,DHW,c})\cdot q_{DHW}\cdot c_p\cdot \rho\big)+Q_{losses}}{\Sigma P_{hps}} \quad (1)$$

As can be seen the SCOP is relatively stable throughout the heating season in both nZEB houses (Fig 2 and Fig 3) and is only lower during the summer months when the heating demand is very low. The bars for DHW energy include the losses from the DHW tank, Q_{losses} during the months with heating demand and for those months the losses have been included in the SCOP. However, during the months with very low heating demand (May-August), the losses have not been included in the SCOP, since they have been considered as not useful (and for those months they are neither included in the bars for DHW energy). The domestic hot water use varies over the year in the Varberg house, but only moderately. In the research villa in Borås the domestic hot water consumption is very low (almost only losses). Q_{losses} is not measured, due to difficulties in installing sensors for that, but is instead based on manufacturer data. It constitutes 5-10% of the total, so even if the uncertainty for the value itself is high, it has small effect on the overall uncertainty.

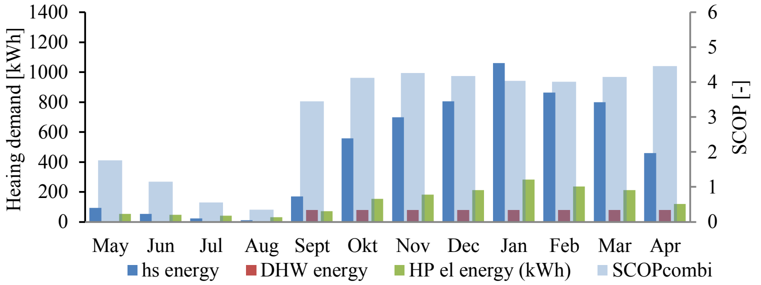

Fig. 2. Measured heating demand and electric power (left axis) and average SCOP per month (right axis) for combined operation in the research villa in Borås. The electricity to the heating system water pump is not included.

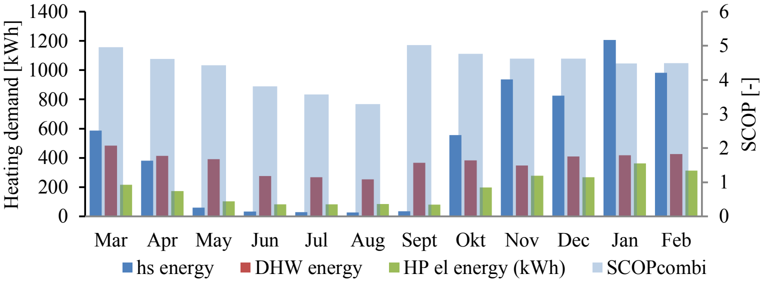

Fig. 3. Measured heating demand and electric power (left axis) and average SCOP per month (right axis) for combined operation in the villa in Varberg.

In figure 4 the space heating demand is plotted versus outdoor temperature (the measurement interval is 5 minutes and all values have been backwards averaged for a 24 hour period to reduce the scatter in the graph. The same apply for Fig. 5). As can be seen there were no days that are as cold as the coldest hours of the cold climate defined in EN14825, -22˚C during the evaluation periods. The heat demand scatter is relatively large in the Borås villa. However, in the Varberg villa, where there is a real family living in the house, the scatter is much larger. The data points that spread the most are probably a result of adjustments in heating settings made by the family. What also can be seen is that the space heating demand is larger in the Varberg villa compared to the Borås villa, it varies around 55 kWh/day compared to 35kWh per day at an outdoor temperature of 0˚C, which is due to a higher ventilation air flow (compared to what is stated as minimum constant value in the building regulations) was selected by the family living in the house (observed by monitoring the fan power). The space heating demand approaches zero around an outdoor temperature of 14˚C, which is lower compared to the standard EN14825 [5] which assumes heating demand up to 16˚C, which is the calculation standard that the ecodesign and energy labelling regulations are based on.

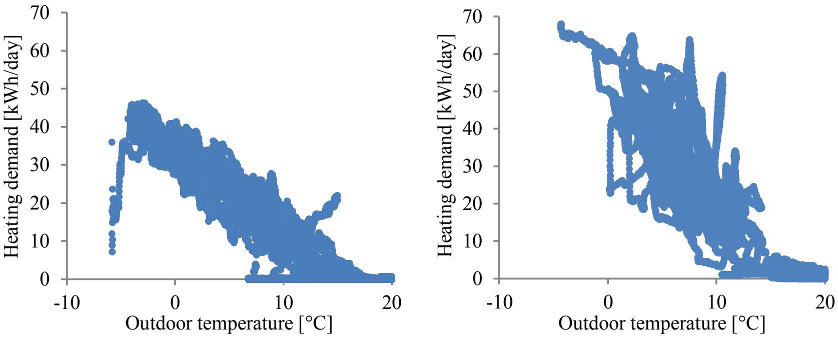

Fig. 4. Space heating demand for the research villa in Borås (left) and in the villa in Varberg (right) as a function of outdoor temperature.

In figure 5 the supply water temperatures for the two houses are displayed as a function of outdoor temperature. In the left graph there are two sets of values. The upper one is the temperature of the water that is flowing from the heat pump to the tank (see figure 1 for schematic drawing) and the lower set of values are the temperature of the water from the tank out to the (floor heating) system. This is partly due to the on-off operation of the heat pump, which forces the heat pump to operate at a higher temperature during its on-periods to compensate for that there is no temperature-lift at all during its off periods (see also Fig. 6) . In addition, it is partly due to some extent of mixing in and losses from the tank. In the inverter controlled heat pump system there is no tank and hence only one set of values are shown. The large temperature deviation between the two villas is because different heating systems are used in the houses. In the Borås villa floor heating is used on both floors and in the Varberg villa radiators are used on the upper floor which need a higher supply temperature. The lines in the graphs represent the heating curves in EN14825 [5]. In the Borås house with the on/off controlled heat pump the supply temperature to the heating system coincides well EN14825 heating curve for a cold climate and a low temperature application. In the standard there is an equation correcting for that the heat pump work at a higher supply temperature during the on-periods, so performance data are taken from these higher temperatures when SCOP is calculated, which seems to be adequate according the measurements. In the Varberg house with the inverter controlled heat pump the heating curve coincides with the EN14825 heating curve for a cold climate and a medium temperature application for the colder part of the measurement period (except for some scatter), but is higher at the higher outdoor temperatures measured values are higher. The reason is probably that the heat pump system has a variable liquid flow operation and lowers the flow rate at lower capacity and the heating curve of the standard assumes constant liquid flow.

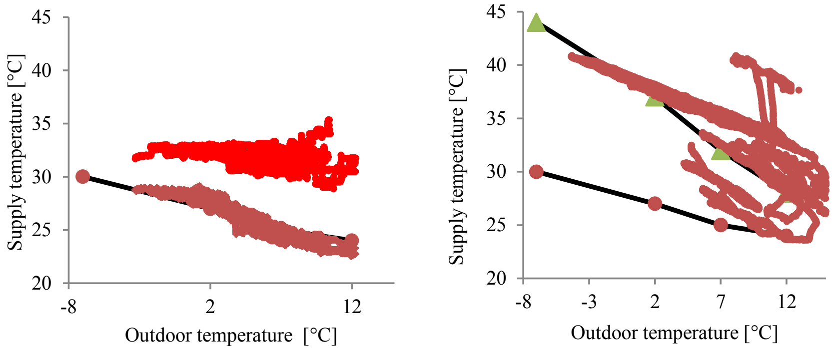

Fig. 5. Heating curves, i.e. supply temperatures (to heating system and to space heating water tank) for the research villa in Borås (left) and the supply temperature to the heating system in the villa in Varberg (right) as a function of outdoor temperature. Also heating curves as described in EN14825 at cold climate and low and medium temperature application is shown.

Figure 6 shows the on-off operation in detail for one operation cycle. As can be seen the supply temperature from the heat pump to the tank is somewhat higher than the temperature of the water that is leaving the tank out to the heating system during. The difference is shown in detail by the green dotted line and the average difference is 1.2 K. The fluctuations in the difference coincide with fluctuations in the return temperature from the heating system, which probably in turn is caused by closing and opening of the room thermostat valves. During the complete cycle, the average temperature out to the heating system was 28.8°C while the average temperature from the heat pump to the tank was 31.9°C, which means that the heat pump has to work at 3.1 K higher temperature compared to what is delivered to the heating system.

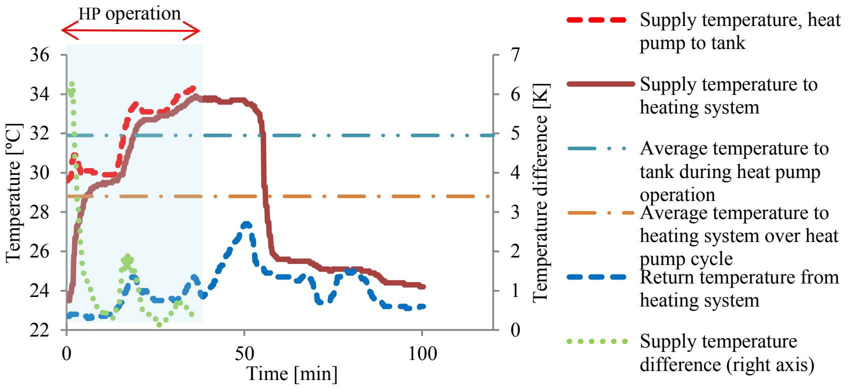

Fig. 6. Supply (and return) temperatures to the tank and to the heating system during an on-off cycle in the research villa in Borås (left) during a period with an outdoor temperature of 2°C.

Figure 7 below shows two on-off cycles. The measured temperatures out from the heat pump and out from the tank, measured every 5 minutes,is displayed together with the inlet brine temperature to the heat pump. In addition, the instantaneous measured COP value, the “Carnot” COP and the ratio between those two COP values are shown. As can be seen, the measured COP seems to be instantaneously related to the temperatures of the outgoing heating water and incoming brine. Therefore, it would be beneficial for the efficiency of the heat pump system if the variations of the temperatures of the flows could be dampened. This proves that the heat pump and the heating system should be optimized together and not separately, which often is the case today.

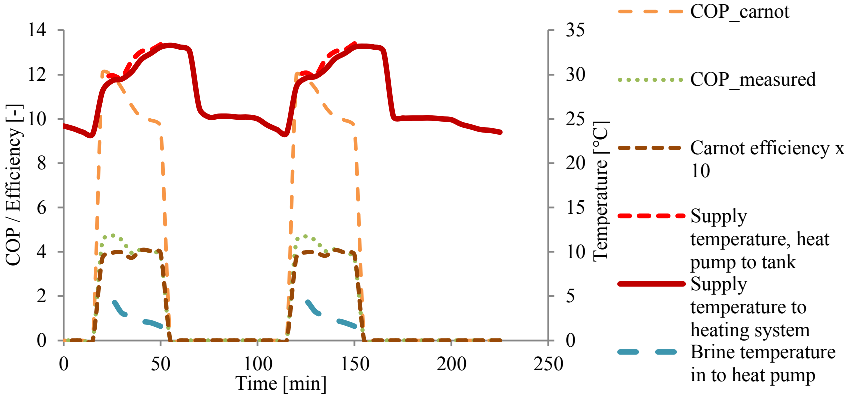

Fig. 7. Supply temperatures to the tank and to the heating system, brine inlet temperature to the heat pump (right axis) and different Coefficients of Performance (COP) and the ratio of these during on-off cycles (left axis) in the research villa in Borås during a period with an outdoor temperature of 2.5°C.

Fig 8 below shows the measured inlet brine temperature to the heat pump in the Varberg house during one year (the measurement interval is 15 minutes and all values have been backwards averaged for a 24 hour period to reduce the scatter in the graph and the same apply for Fig. 9). In EN 14825 heat pumps are tested at an inlet temperature of 0°C and as can be seen, so low temperature was never measured during the whole year. The consequence of this is that the efficiency displayed on the energy label is underestimated.

In the Borås house, the brine temperature was only measured during the last part of the evaluation period and in Fig 9 a comparison is made. Since the heating demand of the houses differed the inlet brine temperature is plotted versus electric power input to the heat pump. The on-off system has approximately 1K lower brine temperature than the other system. Considering that the borehole with the on-off heat pump has been in operation for one more heating season, this difference can be considered as small.

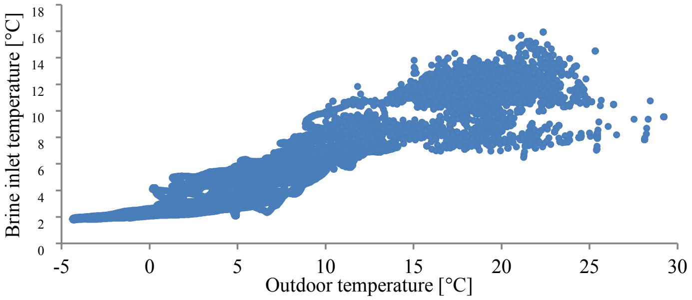

Fig. 8 Brine inlet temperatures during on-periods of the operation cycle in the villa in Varberg as a function of outdoor temperature. Data from March 2016 to February 2017.

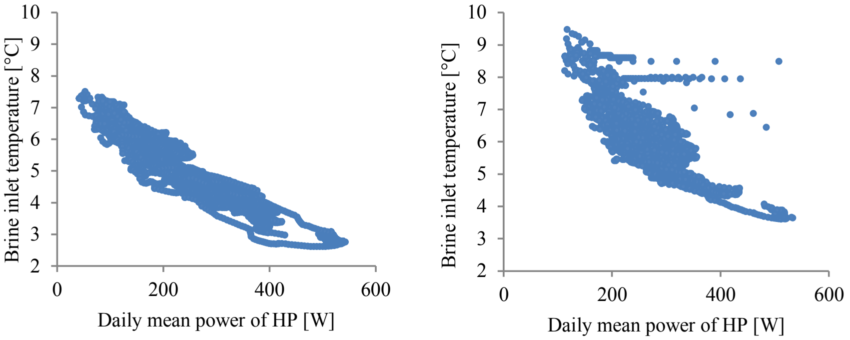

Fig. 9. Brine inlet temperatures during on-periods of the operation cycle in the research villa in Borås (left) and in the villa in Varberg (right) as a function of daily mean power input to the heat pump. Data from 15th of February 2016 to 4th of May 2016.

4 Conclusions

- The brine temperatures were often considerably higher than the test conditions described in EN14825 in the evaluated nZEB-buildings.
- On-off control and a tank in the system results in higher working temperatures for the heat pump compared to variable capacity control which must be accounted for when calculating projected use of energy, especially in “oversized” heat pumps in houses with low energy demand.
- The heating curves of the standard EN14825 coincide well with the measurements except for variable capacity and flow control in combination with low heating demand.
- The heat pump and the heating system should be optimized together for best overall efficiency

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