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Field Performance Of Domestic Heat Pumps For Heating And Hot Water In Switzerland – Insights And Analysis

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FIELD PERFORMANCE OF DOMESTIC HEAT PUMPS FOR HEATING AND HOT WATER IN SWITZERLAND: INSIGHTS AND ANALYSIS

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ABSTRACT

This study presents recent results, analysis, and optimization of heat pump field trials as they are currently carried out by the Heat Pump Test Center (WPZ) in Buchs, Switzerland. In the current study, heat pumps for hydronic heating systems in mainly single-family houses within Switzerland have been investigated since 2016. So far, 24 air-source and geothermal heat pumps have been added to this governmental quality assurance program (SFOE). For each heat pump system, approximately 40 measured variables are recorded at a time interval of 10 s with calibrated sensors with very low measurement uncertainty.

This field study aims to record the real system efficiency in operation and to draw comparisons with characteristic values from laboratory measurements and manufacturer data. This work presents meaningful data and results of the current field study as well as a detailed analysis of the investigated heat pump systems. Due to digitalization and short sampling intervals, temporal processes in heat pump systems can be investigated in detail, enabling comprehensive analysis and comparison.

More than 70 % of the installed heat pumps in Swiss households are air-sourced. Thus, the performance of most heat pumps in Switzerland is strongly influenced by the outside temperature. Geothermal heat pumps, on the other hand, benefit from a more stable source temperature. Geothermal heat pumps show a 4 K higher average source temperature (8.1 °C) during operation compared to air-source heat pumps (4.3 °C) for heating and DHW production. Remarkable differences in source temperature and thus performance were also found between existing and newly installed geothermal systems. Besides installation issues also control concepts have been evaluated based on the measurement data. Such control concepts allow air-source heat pumps to be advantageous compared to geothermal heat pumps in some examples.

The comparison of variable speed systems to conventional on/off heat pumps shows a significant difference in efficiency and controls strategies, but for example, the standby power consumption of inverter systems must be considered quite critical, since several heat pump systems show unnecessarily high losses. In one example, a detailed analysis of the measurement data revealed a permanently high standby power loss of about 50 W, which resulted in lower system efficiency.

1. INTRODUCTION

The use of domestic heat pumps (DHP) in Swiss households for heating and domestic hot water production is advancing. The number of heat pumps sold in Switzerland in 2021 increased by 20 % compared to 2020, 40 % compared to 2019, and almost 70 % during the last 5 years (2017-2021) (Fachvereinigung Wärmepumpen FWS 2021). Approximately 73 % are air-/water heat pumps (AWHP), 26 % are brine-/water heat pumps (BWHP, geothermal) and around 1 % are groundwater heat pumps (GWHP). Almost 56 % of these sold DHPs are in the range between 5-13 kW_{th} and over 86 % are below 20 kW_{th} of heating capacity (Fachvereinigung Wärmepumpen FWS 2021).
Please note that this paper refers to geothermal heat pumps with vertical boreholes using brine as a heat transfer medium as brine-/water heat pumps (BWHP).

Along with increasing DHP sales, the estimation of the field performance of such heat pump systems is gaining importance since the efficiency of heat pumps reacts sensitively to their integration into the heating system and the settings of the heat pump controller. Such performance gaps cannot be determined by measuring the system in the laboratory, but only by taking measurements at the actual place of use over a certain period of time.

The heat pump test center WPZ at the Eastern Switzerland University of Applied Sciences in Buchs, is an EN 17025 certified inspection authority. It offers a comprehensive testing service in the field of heat pumps and refrigeration technology. Field measurements from the extended monitoring period between 2016 and 2022, which were commissioned by EnergieSchweiz, are currently being evaluated (Prinzing, Berthold und Bertsch, et al. 2021)
The main objective of the monitoring study was to identify suitable indicators based on the data measured and evaluated over the period of two years. Subsequently, comparisons should show the optimization potentials of the systems, which can then be implemented. Each year, approximately five new heat pumps are included in the series of measurements. The ongoing study, which was later extended until 2024, currently comprises 24 heat pump systems mainly located in the German-speaking lowlands of Switzerland (Kuster, Prinzing, et al. 2020, Part I).

Compared to former studies in the 1990s and early 2000s like FAWA (field analysis of heat pump installations) (Erb, Hubacher und Ehrbar 2004), the measurement methodology and data acquisition technology have changed considerably. Nowadays, thanks to digitalization, much more data is available. Short recording intervals (10 s) can be used to describe temporal processes in heat pump systems in detail, enabling easier detection of defects such as bad parametrization or unwanted circulation. The data acquisition systems used in the field study are quite sophisticated. Between 30- and 40 sensors are installed in each heat pump system. The goal is an overall uncertainty of the target values of <5 %. To reliably achieve this target, a temperature measurement uncertainty of ±0.1 K (absolute) and ±0.02 K (relative) must be maintained (Kuster, Prinzing, et al. 2020, Part I).

Results of the ongoing field study, presented at the 18th Purdue conferences (Kuster, Prinzing, et al. 2020, Part II) clearly show the expected dependence of the annual performance factor (SPF) on the supply temperature and the selected heat source. Therefore air/water heat pumps in new buildings achieved an average SPF of 3.7 with underfloor heating (35 °C), while brine/water heat pumps achieved an average SPF of 5.7. At higher supply temperatures, such as about 50 °C in old buildings with radiator heating, average SPF values of about 2.9 for AWHPs and 4.4 for BWHPs are measured. Combined systems for heating and domestic hot water production showed 3 to 9 % lower coefficients of performance (e.g. SPF) due to their increased supply temperatures (Kuster, Prinzing, et al. 2020, Part II).

In summary, the examined heat pumps functioned well overall, but there was still further potential for improvement identified, especially in the production of hot water (DHW), as well as in proper control settings.

2. HEATING DEMAND

In 2021 almost 75 % of heat pumps sold in Switzerland were air-/water heat pumps (AWHP), while brine-/water heat pumps (BWHP) accounted for around 25 %. Since 2010 the share of sold AWHPs increased almost by 25 % (Fachvereinigung Wärmepumpen FWS 2021). In the current field study, AWHPs share of 54 % (13 of 24 objects) is significantly lower than the Swiss market average (Prinzing, Berthold und Bertsch, et al. 2021). Nevertheless, the performance of the majority of heat pump systems in Switzerland is decisively influenced by the outside temperature or the climatic conditions. This is most evident during cold periods, such as in February 2021. At very low outside temperatures, BWHPs only have to provide the higher heating demand with a higher supply temperature. The source temperatures of the geothermal probe drop only slightly. AWHP, on the other hand, must also operate at significantly lower source temperatures. This reduces their maximum heating capacity, which is thus contrary to the higher heating demand of the building. However, the collected data demonstrates the impact of such extremely cold days on the annual heat demand of AWHP is small. Figure 1 shows the mean supply temperature (Y-axis left) and the annual thermal heat share (right axis) of the AWHP object No. 16. It is located at an altitude of approx. 540 m above sea level in the Swiss midlands and represents well the average AWHP with variable speed compressor.
The upper plot shows data from the heating season 2019/20 which was quite average. It can be seen, that most of the thermal heat demand (approx. 73 %) was needed between 0-10 °C outside temperature. The particularly cold days below 0 °C account for only about 5 % of the annual heat demand (Prinzing, Berthold und Eschmann, et al. 2020).

In Figure 1, a cold period of the 2020/21 heating season is well recognizable. Significantly lower daily mean temperatures were reached than in the previous heating season. Nevertheless, the share of heat demand required at outdoor temperatures below 0 °C is still low at around 10 %. Around 71 % of the annual thermal heat demand was still needed during outside temperatures between 0-10 °C. It can be noted that AWHPs in particular are designed for very cold days with daily mean temperatures below 0 °C (heating capacity), but only a minimal proportion of the annual heating energy is generated during these cold days. Only at very low outside temperatures (below -10 °C) do the investigated heat pumps begin to reach their performance limits and the electric auxiliary heating has to support. This was the case for a small number of HP systems during the February 2021 cold period and is unique in the history of the current field study (2016-2022). Also interesting is the share of heating demand above 10 °C. In the 2019/20 heating season, about 23 % thermal heat was required, and in the 2020/21 season only 20 %.

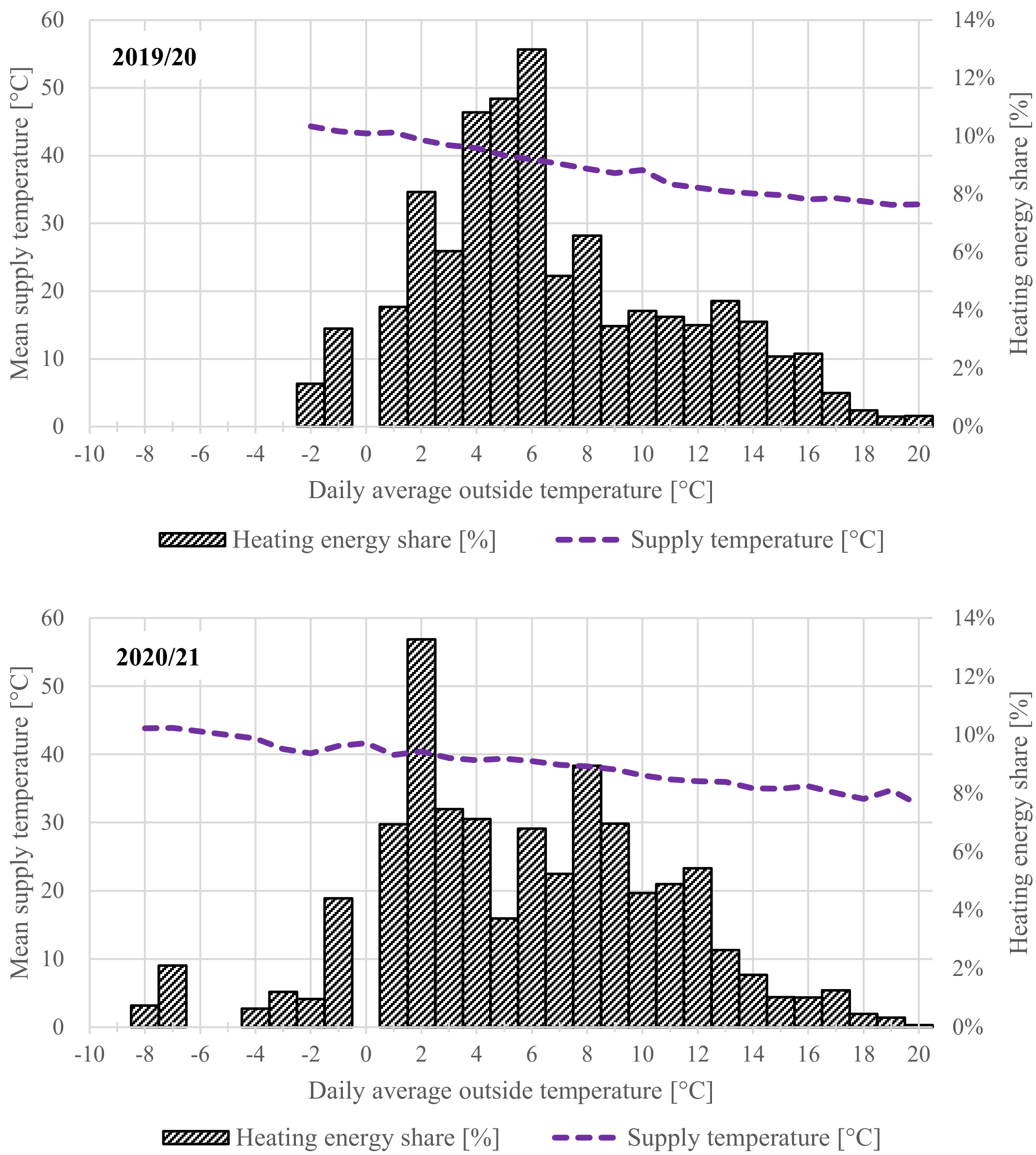

Figure 1: Annual heating demand of object No. 16 in heating season 2019/20 (top) (Prinzing, Berthold und Eschmann, et al. 2020) and 2020/21 (bottom) (Prinzing, Berthold und Bertsch, et al. 2021)

3. HEAT SOURCE INFLUENCES

It is well known that brine-/water heat pump (BWHP) systems are considerably less dependent on the outside temperature. These systems benefit from relatively stable ground temperature during the year. This is illustrated in Figure 2 where the average annual source temperature of every evaluated HP object is shown. The upper plot refers to the season 2019/20 and the lower plot to the season 2020/21. AWHP plants are located on the left side of each plot, and BWHPs is on the right. The source temperature is listed separately for mode only "Heating" and the combination "Heating & DHW". The dotted and the dashed line show the average source temperature overall facilities.

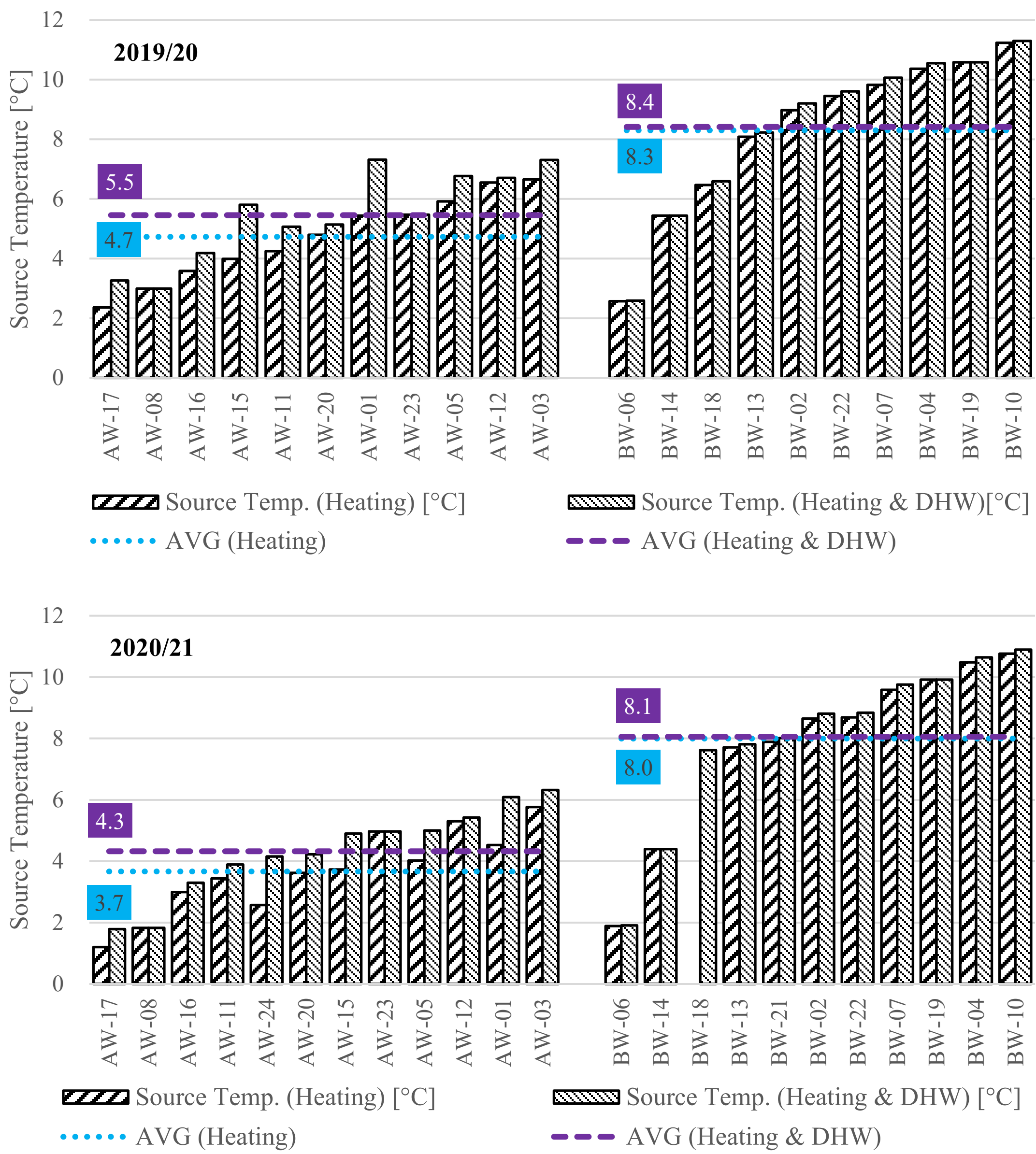

Figure 2: Annual average source temperature of AWHP and BWHP of season 2019/20 (top) (Prinzing, Berthold und Eschmann, et al. 2020) and 2020/21 (bottom) (Prinzing, Berthold und Bertsch, et al. 2021)

The significantly more stable source temperature of the BWHPs is observed in the comparison between the values for "Heating" and "Heating & DHW". The differences are marginal, also the average values over all plants hardly differ. In contrast, the influence of the typically higher average source temperatures (i.e. outside temperature) due to the hot water production is clearly apparent for the AWHPs. Especially object No. 15 benefits from the significantly warmer outside temperature during hot water production shortly after noon. It is understood that the production of hot water in the warm months of the heating season also leads to an increase in the average source temperature of AWHPs. Therefore, the source temperatures for "Heating & DHW" are always higher than those for "Heating" only. Object 1 also has a very high source temperature for "Heating & DHW". In this case, this is due to the relatively high demand for hot water compared to the required heating energy. Cases like this will occur more frequently in the future, with better insulated new buildings in combination with increasing global warming. It is also instructive to compare the 2019/20 heating season with the 2020/21 season, with the cold period in February 2021. While the average source temperature of all BWHP systems for "heating" fell by only about 0.3 K in the 2020/21 season, the average source temperature of all AWHP was 1 K lower in the colder season of 2020/21. This corresponds to an average reduction in SPF of about 2.5 % for the AWHPs.

Differences in source temperatures among AWHP objects are primarily due to geographic differences in altitude. The 24 objects are mainly located in the German-speaking part of Switzerland between 393 to 834 meters above sea level (Prinzing, Berthold und Bertsch, et al. 2021). In contrast, source temperatures for BWHP objects are highly dependent on the condition and age of the particular borehole(s). This is apparent in a comparison of object BW-06, which uses existing boreholes with a new heat pump, and BW-22 with a completely new installed HP system. Figure 3 shows that the newly installed BWHP of object 22 provides over 8'000 kWh more thermal heating energy per year with less electrical energy than object 6 (dashed oval). In this context, it is interesting to know that geothermal probe wells in Switzerland were designed with higher specific power extraction rates (watts per meter) until 2010. These days, significantly lower (approx. half sized) guide values are used (SIA 384/6). In addition, the old boreholes of object 6 are further stressed by the newly installed heat pump, as the increased efficiency (HP) requires even more heat source capacity than before for the same heating capacity. These facts but also high investment costs due to greater construction effort can be disadvantages of BWHPs. Nevertheless, Figure 3 also shows the major efficiency advantage of BWHPs. For example, for thermal heating energy of 20'000 kWh per year, approx. 2'000 kWh less electrical energy was required than with an average AWHP (horizontal arrow) (Prinzing, Berthold und Bertsch, et al. 2021).

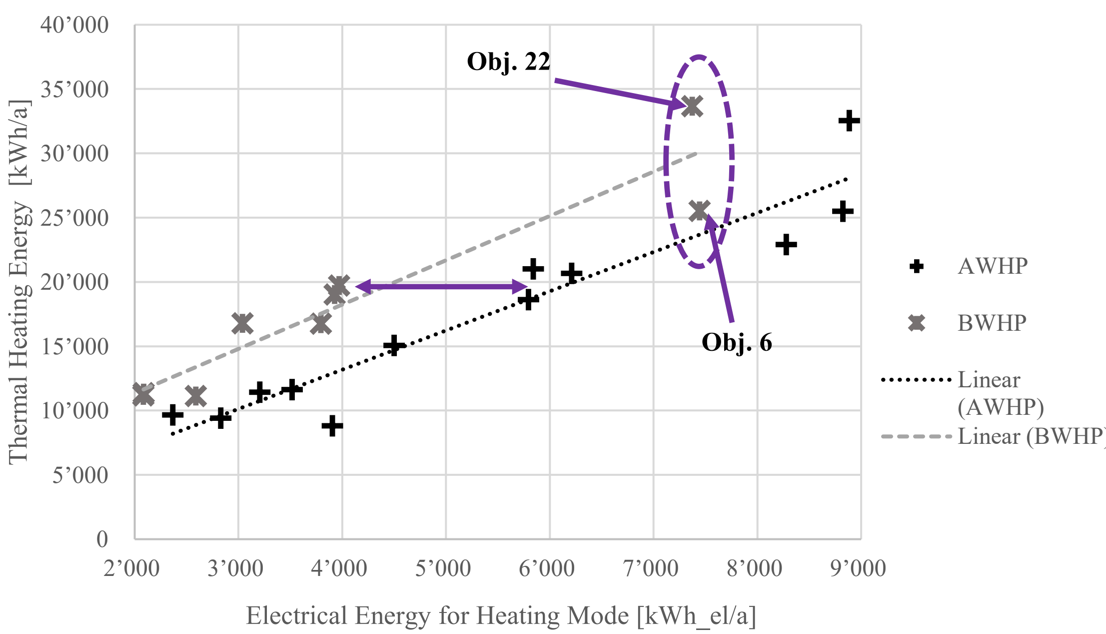

Figure 3: Electrical energy consumption and provision of thermal heating energy for AWHPs and BWHPs **(Prinzing, Berthold und Bertsch, et al. 2021)**.

4. FIXED AND VARIABLE SPEED COMPRESSORS

In the ongoing field study, it was found that over 90 % of the required annual heating energy is needed above an outside temperature of 0 °C (Chapter 2). Nevertheless, the maximum heating capacity of the heat pumps is designed for an outside temperature between -9 °C and -7 °C (Prinzing, Berthold und Eschmann, et al. 2020). Therefore, the compressors are active most of the time in reduced power operation and/or cycling mode. Compressors with fixed speed (without inverter) are significantly more susceptible to early failure due to the frequent compressor starts (cycling) (ASHRAE 2012, 38.4).

Important key figures in this context are the number of compressor starts in one heating season and the total annual compressor operation time, which is depicted in Table 1. On average, fixed speed systems start 62 % more often than variable speed systems. The average operation time of the variable speed compressors on the other hand is more than doubled. With 57 % AWHP in both categories (inverter/fixed speed), the comparability of the averaged values in Table 1 with respect to the heat source is satisfactory.

Table 1: No. of compressor starts and compressor operation time (heating mode) averaged over all objects**.**

Type	No. of objects [-]	Average no. of comp. starts [-]	Average comp. operation time [h]
Inverter	14	2’131	3’315
Fixed speed	7	3’454	1’513

The data in Table 1 confirms what was already expected. On average, variable-speed compressors can perform part-load operation significantly better and with less material stress. Nevertheless, it must be noted that many variable speed compressors are individually oversized or poorly parameterized, resulting in an unnecessarily large number of compressor starts and short running times.
Figure 4 shows both key figures for each of the 21 examined objects. These are sorted in descending order by number of starts and grouped by fixed speed (“Fix”) and variable speed (“Inv”). In the current field study, variable-speed compressors are significantly more common, accounting for 66 % of the installations. At first glance, the large differences in the numbers of compressor starts in both categories are striking. The eight highest values for the compressor running time in heating mode (>3’000 h) are achieved by only inverter machines. The same applies to a particularly low number of compressor starts (<1000). As mentioned, some variable speed compressors show high numbers of compressor starts (>2000).

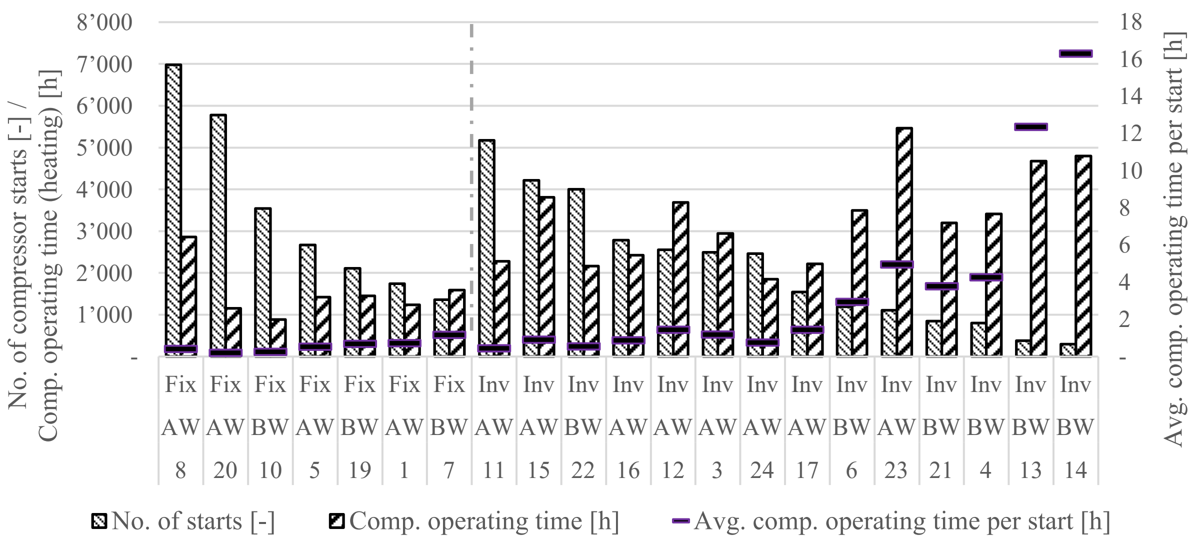

Figure 4: No. of compressor starts, seasonal compressor operating time and operating time per start of 21 examined objects.

There might be several reasons such as heat pump oversizing or bad parametrization of the system. This is indicated by a large number of compressor starts in combination with a low total runtime in heating mode. This is best visualized by the compressor operating time per compressor start (related only to the heating mode), which can be read on the second Y-axis on the right side of the diagram. Object 22, for example, is remarkable, since it is a BWHP, and the frequent starts cannot be partially attributed to defrosting. Furthermore, this object is a heating system with a 500 l buffer tank, which should also tend to lead to fewer compressor starts (Prinzing, Berthold und Bertsch, et al. 2021). In contrast, BWHP objects 13 and 14 are good examples of very long run times per compressor start. Both are direct heating circuits (without buffer storage) and, therefore more susceptible to frequent cycling. These examples demonstrate that variable speed compressors do not generally perform better than fixed-speed devices. An optimal operating behavior can only be achieved with a suitable design (dimensioning) and correct parameterization.

Significant differences between these fixed and variable speed compressors can also be found in the noise-reduced operation mode (silent-mode) of AWHPs. With the increasing replacement of fossil heating systems, especially in inner-city areas, this low-noise mode of operation is becoming more and more important, particularly at night (Dott und Afjei 2014). Fixed speed compressors have a disadvantage in this regard, as the compressor cannot also be operated with the fan at reduced speed (noise minimization). As a result, the evaporating temperature automatically decreases with lower fan speed. This, in turn, results in lower efficiency and heating capacity, as well as more frequent defrosting and the additional compressor starts. The topic of silent mode and power reduction at night is a highly topical issue in Switzerland since the majority of heat pumps are AWHP (Chapter 1) and the reduction of noise emissions is becoming increasingly important (Cercle Bruit 2022).

This is another reason why the efficiency of heat pumps in the partial load range is an interesting topic in the ongoing field study. A detailed comparison of AWHP with fixed and variable speed in the outdoor temperature range between 0-10 °C (more than 70 % of the annual heating demand, Chapter 2) was made in terms of efficiency. Figure 5 shows the seasonal performance factor (SPF) (Kuster, Prinzing, et al. 2020, Part I) of 12 AWHPs depending on the temperature lift (sink supply temperature minus source temperature). As mentioned, the SPF was determined and plotted for four fixed speed AWHPs and eight variable speed AWHPs in the outdoor temperature range of 0-10 °C. Each circle or triangle represents one daily averaged SPF value.

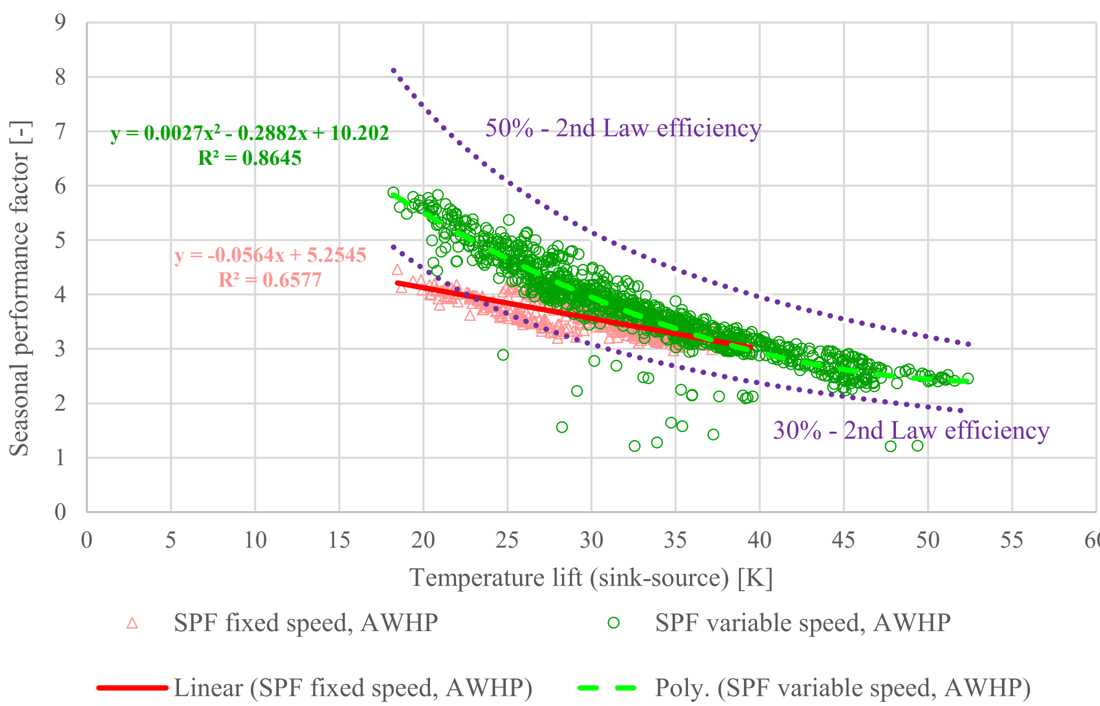

Figure 5: Efficiency (SPF) vs. temperature lift of both fixed and variable speed AWHPs in the outside temperature range of 0-10 °C. Daily averaged values for the SPF.

For orientation and better assessment, the 2nd law efficiency of 30 % and 50 % was additionally plotted corresponding to the measured temperatures. Likewise, a polynomial fitting line has been added for each of the fixed speed and variable speed compressor groups. The increasing difference in average efficiency with decreasing temperature lift between fixed and variable speed compressors is immediately noticeable. At a temperature lift of 25 K, the investigated AWHPs with inverter (SPF = 4.67) are on average almost 22 % more efficient than HPs with fixed speed compressors (SPF = 3.85). At a temperature lift of approx. 40 K variable and fixed speed compressors of the examined AWHPs work equally efficient on average. This can be expected since the temperature differences inside the heat exchangers are smaller during partial load operation with a variable speed compressor. Furthermore, the type of compressor used can also have an influence. Variable speed rotary piston compressors usually work more efficiently at small temperature lifts than scroll compressors with fixed speed (ASHRAE 2012). Below the temperature lift of 23 K, an object with fixed speed compressor falls below the 2nd law efficiency of 30 %. This is an AWHP with below-average efficiency, which differs significantly from the other three fixed-speed systems investigated. In summary, variable speed HPs are especially suited for new residential buildings with lower supply temperatures (e.g. floor heating).

In addition to significant differences in operating behavior and efficiency, there are also revealing differences in standby losses between fixed-speed and variable-speed compressors. The heat pumps consume electricity even when the compressor, including the auxiliary heater, is not in operation. In the field study, these are referred to as standby losses and they vary considerably in quantity depending on the object. The two main causes of standby losses are the heat pump control and typically also an inverter. Figure 6 shows the average standby power (Y-axis left) and the annual standby losses (Y-axis right) of 24 investigated heat pump systems. It is apparent that heat pumps with inverters show significantly higher standby power values compared to systems with fixed-speed compressors. The average standby power of all objects is approx. 22 W, whereas the five worst objects (all variable speed comp.) show an average standby power of approx. 49 W. The highest values for standby power occasionally perfectly reach the consumption of an evaporator fan (AWHP).
The annual standby losses qualitatively show a very similar picture to the standby performances. On average, the share of electrical standby losses amounts to approx. 3 % of the total annual electrical energy demand (Prinzing, Berthold und Bertsch, et al. 2021). However, these values have to be compared with foresight. The losses are strongly dependent on the respective running times or standby times of the heat pump. This is observed in a comparison of objects 11 and 12 (both AWHP with inverter). Although Object 11 has approximately 10 W (17 %) less average standby power than object 12, the annual standby losses of object 11 are approximately 5 % higher than those of object 12. The average running time is influenced by many factors such as type of heating system, DHW-production, dimensioning of heating capacity, integration into the hydraulics, parameterization, and, last but not least, user behavior. In principle, low standby power is no guarantee for low standby losses, especially if the heat pump is oversized, and has been poorly parameterized or integrated.

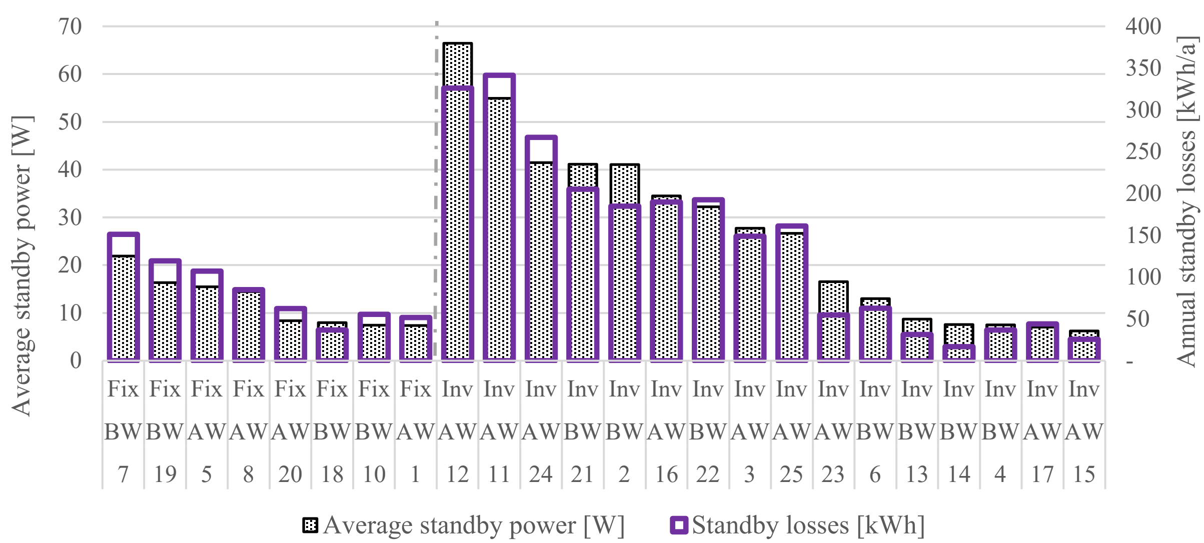

Figure 6: Average standby power and annual standby losses of all examined objects

5. CONCLUSIONS

The current study, which now comprises 24 heat pump systems in the field, shows the great influence of the outside temperature and climatic conditions on the air-sourced heat pumps which account for 54 % of the examined objects. In contrast, the collected and analyzed data also show that more than 70 % of the heating energy share is needed within the outside temperature range between 0-10 °C. Although cold periods can lead to a significant reduction in AWHP seasonal source temperatures, the impact of such significantly cold days on heating energy demand is comparatively small. Compared to the 2019/20 season, the average source temperature of an AWHP example object (no. 16) was 1 K lower in the 2020/21 season. The heating energy demand in the temperature range below 0 °C doubled from about 5 to 10 % of the seasonal heating energy demand.

BWHP objects, on the other hand, have a much more stable source temperature over the season, as expected. In addition to the significant efficiency advantage over AWHP, there are considerable differences between objects with older, existing, and new boreholes. In the presented example, a heat pump combined with new boreholes achieved nearly 8 MWh more thermal heating energy per year with slightly less electrical input than with old, existing boreholes.

As the majority of the required thermal heating energy is generated between 0-10 °C outside temperature and heat pumps tend to be designed too large in relation to the heating capacity, the partial load operation is of great importance. Variable speed compressors are in principle better suited for this operation since the compressors do not have to cycle due to speed reduction. This leads to fewer compressor starts and longer compressor running times, which clearly extends its lifetime. The measurement data from the field study show that fixed-speed compressors start 62 % more often on average and are in operation for only half as long per year. However, variable speed compressors are not consistently better in performance and operational behavior. Some variable speed objects show significantly more starts and shorter run times per start than necessary due to oversizing and/or poor parameterization.

In terms of efficiency, the analyzed air-/water heat pumps with variable speed compressors perform better on average than fixed speed models at a temperature lift below 40 K. Around 25 K temperature lift, the advantage of inverter heat pumps in the seasonal performance factor (SPF) is approx. 22 %.
However, in standby operation, the picture is less positive. Almost 32 % of the investigated heat pumps with inverters have a standby power of more than 40 W, which easily corresponds to the input power of the evaporator fan. In combination with low compressor runtime (dimensioning, parameterization), the system efficiency can suffer significantly from the high standby power of the inverter.

In summary, an air-sourced heat pump with a variable-speed compressor is well suited as a heating system for the conditions in Switzerland and is also the most frequently selected heat pump type. However, correct dimensioning, integration, and parameterization are the key to the efficient and long-lasting operation.

NOMENCLATURE

AWHP	Air/water heat pump
BWHP	Brine/water heat pump, Geothermal HP-system with vertical boreholes
DHW	Domestic hot water
EnergieSchweiz	Federal authority on behalf of the Swiss Federal Office of Energy (SFOE)
FAWA	Field analysis of heat pump installations
GWHP	Groundwater/water heat pump
HP	Heat pump
OST	Eastern Switzerland University of Applied Sciences, Campus Buchs
SPF	(JAZ) Seasonal performance factor according to the definition of ENERGIESCHWEIZ [-]
WPZ	Heat pump test center (Buchs, CH), German: Wärmepumpen Test Zentrum

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