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Field Performance Of Domestic Heat Pumps For Heating And Hot Water In Switzerland Part II: Results, Analysis And Optimization

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FIELD PERFORMANCE OF DOMESTIC HEAT PUMPS FOR HEATING AND HOT WATER IN SWITZERLAND
PART II:
RESULTS, ANALYSIS AND OPTIMIZATION

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ABSTRACT

This study presents the development, the methods, and the state of the art of heat pump field trials as they are currently carried out by the Heat Pump Test Center (WPZ) in Buchs SG, Switzerland. In the current study, heat pumps for hydronic heating systems in single family houses within Switzerland have been investigated since 2016. So far, over 20 air-source and geothermal heat pumps have been added to this governmental quality assurance program (Swiss Federal authority EnergieSchweiz). For each heat pump system, more than 40 measured variables are recorded at a time interval of 10 s using calibrated sensors with very low measurement uncertainty.

The aim of this field study is to record the real system efficiency in operation and to draw comparisons with characteristic values from laboratory measurements and manufacturer data. The study presented is divided into two parts. The first part entitled "Technology, Methods and State of the Art of the field studies" focuses on the procedure and measuring technology of field studies performed at WPZ Buchs.
The second part is entitled "Results, Analysis and Optimization of current field studies" and presents meaningful results of the current field study as well as identification and optimization of possible deficiencies in the planning, installation and handling of the investigated heat pump systems.

Heat pumps installed in new and refurbished buildings have been investigated with different system boundaries. In terms of performance, the current study shows an average annual coefficient of performance (*SPF*) of 3.6 and a span from 3.5 to 3.7 for floor heating and domestic hot water production using air/water heat pumps. Geothermal heat pump systems reach an average annual coefficient of performance of almost 5.
Although the systems are running quite satisfying overall, the results also show considerable differences between the systems as well as typical mistakes in the installation and handling of the heat pumps. A controller that does not work optimally in terms of application and consumption is a frequently found cause of decreased performance.
After evaluating the baseline performance for two years, the systems are optimized to increase performance and avoid poor operation. The collected data is also used to better define guidelines for planner and installers.

1. INTRODUCTION

The first part entitled "Technology, Methods and State of the Art of the field studies" introduced the method and the technology behind the ongoing heat pump field study at the heat pump test center (WPZ) in Buchs Switzerland (Kuster, Prinzing, Berthold, Eschmann, & Bertsch, 2020). The evaluated heat pumps are installed on site after the initial calibration of the heat pump and the measuring equipment together in the laboratory. In the following two years, the heat pump performance is evaluated and analyzed by collecting data from over 40 measured variables. After this evaluation period, possible optimizations are proposed based on the collected data and executed if the customer (heat pump owner) has agreed to them.

During the ongoing study or evaluation period each customer receives an annual report about the performance of his installed heat pump. Furthermore, the evaluated performance as well as the executed analysis and optimization of each heat pump site is presented in detail in the annually released report of EnergieSchweiz (Prinzing, Berthold, & Eschmann, 2019) (Arpagaus, Berthold, & Eschmann , 2018). In addition to the reports mentioned above, many of the results and findings of the field study are also presented in Swiss magazines for HP-designer and installers, so that new knowledge can be directly implemented. This paper is a summary of the most important results and findings from all installations of the current study.

2. OVERVIEW OF THE RESULTS OF THE FIELD MEASUREMENTS 2017-2019

The results presented in this section include measurements taken in the heating period of 2017/18 and 2018/19 (two years) respectively. In total 13 heat pump devices have been analyzed and compared within the current study, out of which 7 are air/water heat pumps (AWHP) and 6 are brine/water heat pumps (BWHP) with vertical boreholes. Overall 9 out of 13 devices are operated as variable speed compressors. The data was evaluated from standard heat pump devices that have not yet been optimized based on these field studies.

Figure 1 shows the connection between the annual coefficient of performance (*SPF*) and different design temperatures (Prinzing, Berthold, & Eschmann, 2019). The data is displayed as a function of the heating curve pre-set in the controller of the heat pump. It can be seen that brine/water heat pumps in new buildings (supply temperature of approx. 30 °C at the design point) achieve an annual efficiency (*SPF)* of more than 6 in pure heating operation. In combination with domestic hot water (DHW) production, the *SPF* drops to approx. 5.2. In contrast, air/water heat pumps achieve an efficiency of about 4.0 for heating, and 3.7 for heating+DHW production.

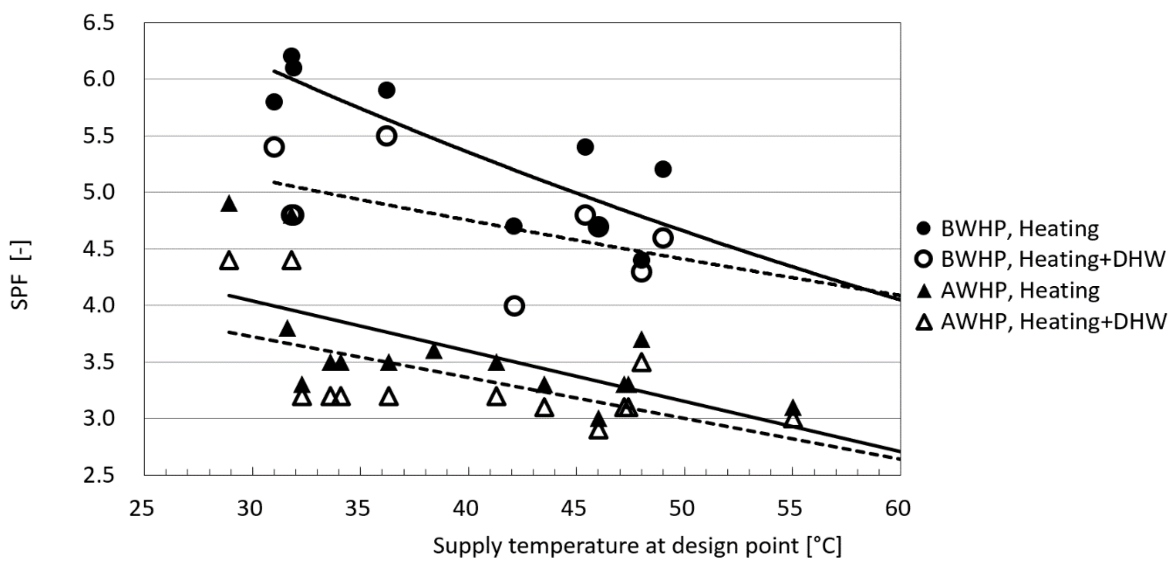


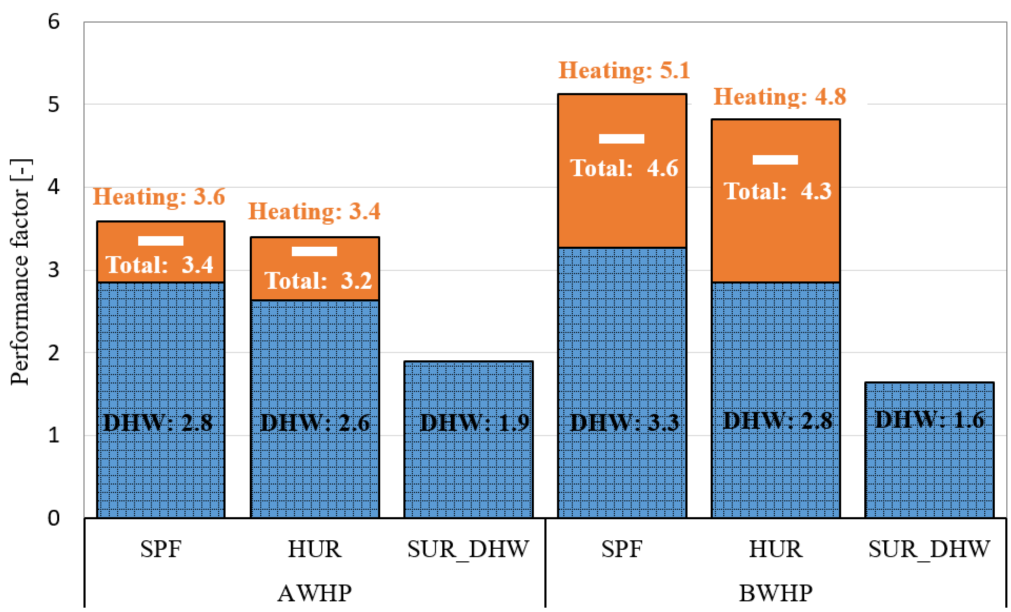
Figure 1: Efficiency (SPF) of air/water heat pumps (AWHP) and brine/water heat pumps (BWHP) depending on supply temperature at the design point

As expected, the efficiency decreases with higher supply temperatures. Especially refurbished buildings need higher supply temperatures due to their radiator heating system. However, with a *SPF* of over 4.0, BWHP systems are still very suitable for such renovated buildings. Even compared to new variable-speed AWHP, BWHP still show a significant efficiency advantage of approximately 30 %.
Table 1 provides a more detailed overview of the evaluated performance of AWHP and BWHP by heating and heating+DHW application.

Table 1: Annual Coefficient of Performance (*SPF*) for different AWHP and BWHP applications (Prinzing, Berthold, & Eschmann, 2019)

Supply temperature at design point	35 to 30°C (New building)	45 to 40°C (Renovation)	55 to 50°C (Old building)
Heating AWHP	3.7	3.3	2.9
Heating BWHP	5.7	5.0	4.4
Heating + DHW AWHP	3.5	3.1	2.8
Heating + DHW BWHP	4.9	4.6	4.3

As already mentioned, it is essential to use comparable system boundaries in practice when investigating systems. Significant differences can be identified between the efficiency of heat production and the heat actually used especially when it comes to DHW production. This is partly caused by the use of electric heating elements (e.g. Legionella circuit), but mainly due to storage losses. Figure 2 shows a comparison of the average annual coefficient of performance *(SPF)*, heat utilisation ratio *(HUR)* and system utilization ratio (SUR_{DHW}) for AWHP and BWHP systems (Prinzing, Berthold, & Eschmann, 2019). It can be seen that the efficiency of DHW production is 17.5 % to 19 % lower than the overall efficiency for heating+DHW production due to the higher sink temperatures.
For BWHP this difference is much bigger (28 % to 35 %) because of higher source temperatures compared with AWHP in wintertime. It is also remarkable that the *HUR* is 0.1 or 0.3 points lower than the *SPF*. This is mainly due to the electric heating elements for legionella control and the circulation pump (sink) which were not included in the *SPF*. In this context it is also worthy to mention that no electric heating element had to be used to support the heating system of any heat pump investigated during the period under consideration. This also applies to the cold period at the end of February, beginning of March 2018 which showed outside average temperatures between -6 to -9 °C and up to 2 K below the design temperature.



The system utilization ratio *(SUR_{DHW})* (figures will be covered in more detail in chapter 3) is only determined for DHW production and it is considerably lower than the *HUR*. This is primarily caused by storage losses, especially for buildings with a low DHW demand. When it comes to single-family houses the overall system efficiency suffers particularly when a DHW circulation is used to keep the distribution lines warm. Therefore, hot water circulation is clearly not recommended for such applications from an energetical point of view.

3. DHW-PRODUCTION, AUXILIARY EQUIPMENT

Hot water production is becoming increasingly important compared to the heating operation of a water heating system, also due to the continuous improvement of the building fabric (insulation). Therefore, its partial aspects (also with regard to the key figures) are explained in more detail below.

On the one hand, the domestic hot water is heated by the heat pump. The ratio of this amount of heat to the electrical energy required for compressor and circulation pump (heatsource) is called the annual performance factor SPF. Since some heat pumps cannot reach temperatures of 60 °C only with the compressor, an electric auxiliary heating element is used in many cases to carry out the legionella programme. This additional electrical energy input as well as the heatsink circulation pump energy, are included in the heat utilization ratio HUR, which is therefore lower than the *SPF*. Finally, the thermal energy of the hot water usage can also be put in relation to the total electricity requirement. From this, the system efficiency SUR_{DHW} is calculated. Besides the heat pump and auxiliary heating element this key figure also includes the performance of the storage buffer tank and any hot water circulation. Table 2 shows these three parameters for several heat pump systems built-in single-family houses at different sites (A-M) (Prinzing, Berthold, & Eschmann, 2019). It can be seen that the SPF of AWHP for domestic hot water production reaches 3.0 on average. The expenditure for the electric heating element is usually small and leads to a HUR that is about 0.2 below the annual performance factor. With BWHP, a higher *SPF* of 3.5 is achieved on average. However, the heat utilization ratio is on the same level as with air/water heat pumps. This is mainly due to the more frequent use of the direct electrical heating element for the legionella circuit.

Table 2: Performance of DHW-production for different HP sites

HP Type	Site	SPF	HUR	SURDHW	Vol. [m^3]	Temp [°C]	AHR
BWHP	D	4.38	4.06	0.25	5	38	5%
	I	3.39	2.84	1.78	26	48	22%
	F	3.24	2.63	1.58	39	55	25%
	B	3.07	2.90	1.59	62	46	2%
AWHP	K	3.43	3.32	2.17	39	40	0%
	C	2.99	2.93	2.32	79	55	0%
	E	2.82	2.70	2.13	66	49	16%
	A	2.81	2.77	2.42	94	49	0%
	M	2.68	2.00	1.33	27	49	48%
	L	2.67	2.52	1.36	54	49	8%
	H	2.52	2.22	1.53	45	50	19%
DHW-HP	J	*not evaluated*		1.25	50	56	74%
	G			2.28	44	51	0%

The system utilization ratio (SUR_{DHW}) is significantly lower for both air/water and brine/water heat pumps. There are several reasons for this.
The BWHP system at site D in the top line of Table 2, for example, provides a good example of how hot water circulation can affect system efficiency. Due to the permanent circulation of DHW, the storage tank cools down rapidly and significantly reduce the efficiency of the system (SUR_{DHW} end up well below 1 although the *HUR*>4 and the auxiliary heating rod share (AHR) is small) (Prinzing, Berthold, & Eschmann, 2019).

As noted above, the circulation DHW in a single-family house should be avoided whenever possible. This can be achieved, for example, by short discharge pipes.
Furthermore, even a low hot water supply quantity can have a negative effect on the SUR_{DHW}, which can also be observed at HP-site D ($Vol. \approx 5\ m^3$). In this case, the amount of heat drawn is small in relation to the heat losses of the storage tank. A similar picture can be observed with the AWHP system at site M with a relatively low DHW demand ($Vol. \approx 27\ m^3$) (Prinzing, Berthold, & Eschmann, 2019). For this reason, an assessment only by the SUR_{DHW} should be viewed with caution if the amount of hot water drawn is massively below the design capacity. The last two HP-sites (J, G) in Table 2 are heat pump boiler systems (DHW-HP) in which no heat flows can be measured within the system. Hence, only the system utilization ratio is given. Site G is a version installed in the cellar, which stands out due to the highest system efficiency of all systems. A very positive effect here is the low power draw during charging, which leads to small temperature differences in the system. In addition to hot water production, a closer look at the energy consumption of the auxiliary equipment of the evaluated heat pump systems is also revealing.

Figure 3 shows the electrical energy consumption of the HP-sites broken down to the individual auxiliary consumers (Prinzing, Berthold, & Eschmann, 2019). While the energy consumption of the circulation pumps (source/sink) is in the lower percentage range, the share for the electric heating elements is quite significant. Plant M in particular stands out with a heating rod share of almost 50 % of the total energy consumption. This is because the system in question runs the legionella programme completely without support of the compressor.

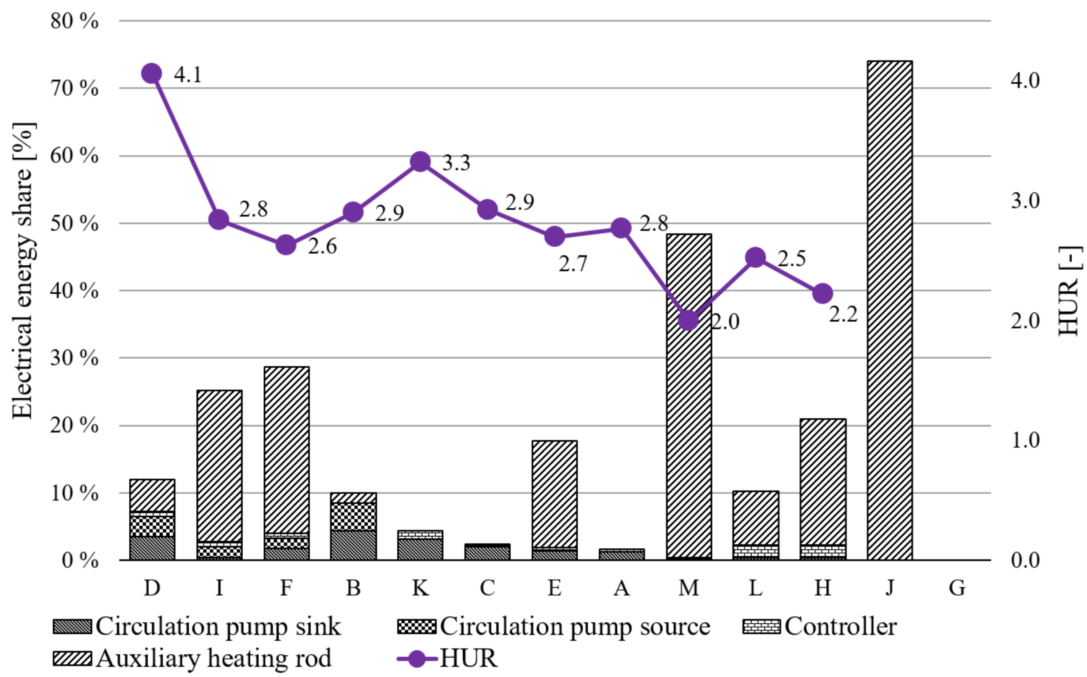


Figure 3: Electrical energy share of auxiliary equipment

The very high proportion of auxiliary heating energy at site J is caused by a compressor damage, which is why only the heating rod could be used. At the other sites with activated legionella control (once a week), the heating element accounts for approx. 20 % to 30 % of the total electrical power requirement.
In practice, there is still a significant potential for improvement here. For example, in most systems, the auxiliary heating element used for the legionella circuit is not controlled by the heat pump but is activated directly with a timer. This means that the heating element is often used when the storage tank is not fully charged. Ideally, the heat pump would be used first to preheat the DHW-storage as much as possible, so that the heating element only has to raise the temperature slightly. However, this requires direct control by the heat pump.

4. OPTIMIZATION

A considerable optimization potential can be found in DHW production. AWHPs benefit greatly from a larger charging timeframe at midday with a previous charging delay caused by a reduced design temperature. Since temperatures at noon can be over 10 K higher than in the morning, charging efficiency can be increased by 10 to 20 % (Prinzing, Berthold, & Eschmann, 2019). Although this optimization measure seems obvious, only in one HP-system controller out of 13 this measure was implemented to make use of a smaller temperature-lift at noon.
Around 50 % of the investigated heat pump systems use only electric auxiliary heating (heating rod) to perform their weekly Legionella program by heating up the water tank to over 60 °C. Three systems first make use of the compressor to support charging, which would be an obvious method to reduce the electric energy demand. In a typical example, 180 kWh electric energy can be saved annually by implementing this simple software modification to always preheat the domestic hot water using the compressor before switching to auxiliary heating, with no further costs. Where variable speed compressors are installed, an increase in efficiency can also be achieved by reducing the heating capacity when preheating domestic hot water.

A recently more often implemented optimization of the self-consumption of photovoltaic systems through the exclusive use of electricity (DHW-production, legionella program) must be strongly questioned from an energy point of view. The recommendation for a good legionella circuit is therefore heating the storage tank by means of using the compressor to the maximum possible temperature during a time without demand (night), then reheating with the auxiliary heating element.

Another important optimization scope of heat pump systems is the proper adjustment of the heating curve and the heating limit respectively. Considerable differences were found between properties within the same building standard. New buildings in particular, were found to have a heating curve that is too high with respect to the outside temperature. Nevertheless, only three heating curves out of 13 monitored objects were adjusted downwards whereas two were increased. This is because many residents were satisfied with the current setting and no adjustment was desired. By integrating an intelligent heating curve with averaged outside temperatures, the annual heating energy demand can be reduced distinctly. One of the monitored new buildings shows theoretical potential savings of 6 % of the annual energy demand by solely adapting the upper heating limit without affecting comfort (Prinzing, Berthold, & Eschmann, 2019). The upper heating limit is defined as the outside temperature at which heating is automatically turned off.
Figure 4 shows the thermal energy (heat) used for heating and DHW production of a refurbishment object (household with approx. 6 persons) from 2017 (Arpagaus, Berthold, & Eschmann , 2018).

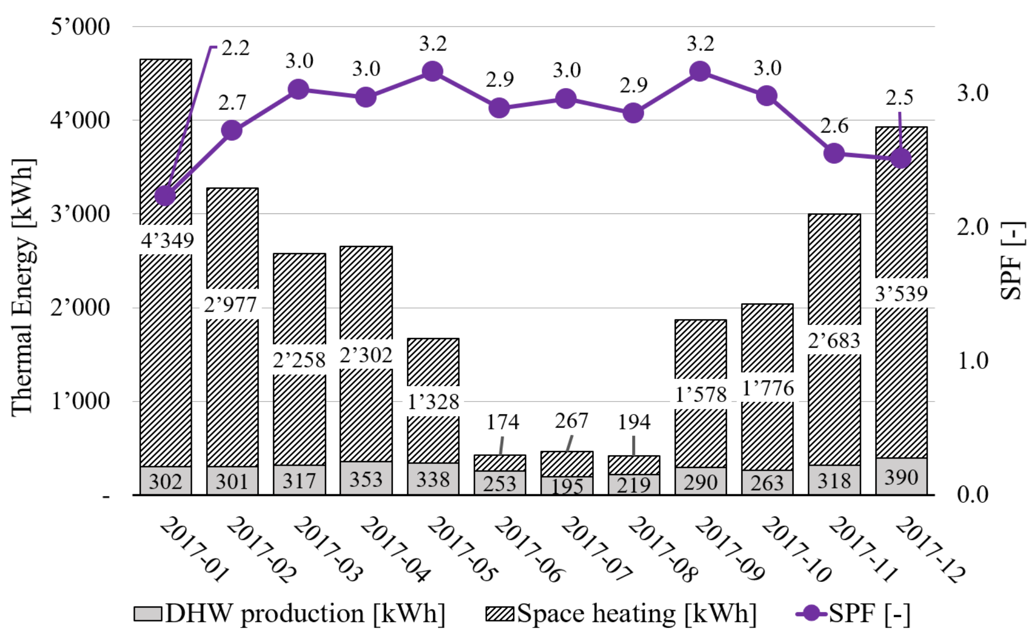


Figure 4: Annual development of the thermal energies and the SPF of an evaluated object

Since the system uses an AWHP, the influence of the outside temperature on the efficiency (SPF) is clearly visible. Remarkable is the high share of heating energy compared to hot water production, so it is apparent that an optimization of the latter is hardly worthwhile. On the other hand, it is also clearly visible that heating was provided in the summer months June-August, which is not necessary. Thanks to an adjustment of the heating curve and the heating limit, a reduction of the supply temperature by over 10 K could be achieved with little effort and without affecting comfort. This led to an increase of the interseasonal *SPF*=2.7 (2017) to *SPF*=3.4 in the following year (2018), which means an improvement by 25% after accounting for climatic influences (milder winters) (Prinzing, Berthold, & Eschmann, 2019).

An important topic in connection with optimization are also findings on faulty design, e.g. oversizing of HP-systems. General oversizing of the heat pump output could not be confirmed on the basis of the 13 investigated HP-sites. Nevertheless, there are examples of a less suitable design.
One of the refurbished objects has an installed BWHP and a 1000 l parallel connected storage tank. Combined with a high hysteresis, this leads to unnecessarily high supply temperatures, large heat losses and very long operating breaks or operating times of the compressor. Reducing the hysteresis would help to lower the supply temperatures and thus can lead to more efficient operation of the heat pump without any loss of comfort for the occupants.

5. CONCLUSIONS

The current study, which now comprises almost 20 heat pump systems in the field, clearly shows the strong dependence of the annual performance factor (SPF) on the supply temperature and the selected heat source. Therefore air/water heat pumps in new buildings achieve an average SPF of 3.7 with underfloor heating (35 °C), while brine/water heat pumps achieve an average SPF of 5.7. At higher flow temperatures, such as about 50 °C in old buildings, 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 show 3 to 9 % lower coefficients of performance (e.g. SPF) due to their increased supply temperatures.
The hot water circulation and a very low hot water demand are found to be the main factors reducing the system efficiency in the use of hot water.

Apart from the compressor, the electrical energy consumption of a heat pump consists mainly of the consummation of circulation pumps, auxiliary heating rod and the controller. With up to 50%, the auxiliary heating rod accounts for the biggest share of electrical energy consumption whereas the circulations pumps are found in the lower percentage range.

After an investigation time of more than one heating period, various optimization potentials were identified, e.g. intelligent heating curves or the legionella program with heat pump control. By adjusting the heating curve using simple software updates, the annual performance factor could be increased by 10-20 % in some cases.
Typical optimization measures are:

- Adaptation of the heating curve and the heating limit.
- Charging time at noon for air/water heat pumps.
- Preheating of domestic hot water with the compressor (before legionella program).
- Improved efficiency by reducing the capacity (variable speed) of the compressor when heating domestic hot water.

Brine/water heat pumps are recommended for refurbished buildings. The current field study shows that the examined heat pumps function well overall, but there is still further potential for improvement, especially in the preparation of hot water, as well as in proper control settings.

NOMENCLATURE

AHR	Auxiliary heating rod (share)	
AWHP	Air/water heat pump	
BWHP	Brine/water heat pump	
COP	Coefficient of performance	[-]
DHW	Domestic hot water	
DHW-HP	Domestic hot water heat pump (heat pump boiler)	
EnergieSchweiz	Federal authority on behalf of the Swiss Federal Office of Energy (SFOE)	
GWHP	Groundwater/water heat pump	
HP	Heat pump	
HUR	Heat utilization ratio according to definition of ENERGIESCHWEIZ (HUR)	
OST	Eastern Switzerland University of Applied Sciences	
SPF	(SPF) Seasonal performance factor according to definition of ENERGIESCHWEIZ	[-]
SUR_{DHW}	System utilization ratio according to ENERGIESCHWEIZ (SURDHW)	[-]
WPZ	Heat pump test center (Buchs, CH), German: Wärmepumpen Test Zentrum	

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