13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Field Performance of Domestic Heat Pumps for Heating and Hot Water in Switzerland

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Abstract

This study presents the development, the methods, and the state of the art of heat pump field tests as they are currently carried out by the Heat Pump Test Center (WPZ) in Buchs. Since 2016, heat pumps for hydronic heating systems in single-family houses in Switzerland have been investigated. So far, nearly 20 air-source and geothermal heat pumps, primarily located in the lowlands have been added to this governmental quality assurance program. For each heat pump system, calibrated sensors record approximately 50 data points at 10 seconds intervals, which ensures very low measurement uncertainty.

The aim of this field study is to record the efficiency of the real systems in operation and to draw comparisons with characteristic parameters from laboratory measurements and manufacturer data. Further goals are the identification and optimization of possible deficiencies in planning and installation as well as in the controls of the heat pump devices. The results of field measurements show the importance of careful design and installation of these systems. The optimal integration in retrofit systems (building renovations) is also a major challenge.

Heat pumps installed in new and refurbished buildings have been investigated with different system boundaries. The results show significant differences between the systems as well as typical installation faults. After a year of baseline performance evaluation, the systems are optimized to determine the potential of such measures and better define guidelines for planners and installers. An overview of such measures is also presented.

Selection and/or peer-review under responsibility of the organizers of the 13th IEA Heat Pump Conference 2020.

Keywords: heat pump field tests; seasonal performance factors; annual coefficient of performance; domestic hot water, state of the art

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 2018 increased by almost 10 % compared to 2017 and almost 19 % compared to 2016 [1]. 70 % of the heat pumps are air/water heat pumps (AWHP), 28 % brine/water heat pumps (BWHP) and 2 % are groundwater heat pumps (GWHP).

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. Therefore, 25 years ago, a comprehensive field study of DHP in Switzerland, called FAWA (field analysis of heat pump installations) was launched [2], which was commissioned by the Swiss Federal Office of Energy (SFOE) and carried out with the support of industrial and academic partners.

Between 1996 and 2003, a total of 221 heat pumps with a maximum heating capacity of 20 kWth were measured, mainly in new single-family houses. According to the defined system boundary (Seasonal performance factor SPF (JAZ)) [2] an average coefficient of performance (COP) of 2.7 for AWHP-systems

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and 3.5 for BWHP-systems were recorded. At that time, data was still recorded manually, at best once a week.

Outside of Switzerland, DHP-field studies were performed in several other countries starting in 2005 with the Frauenhofer (ISE) studies [3] [4]. The first ISE study showed average seasonal performance factors (SPFH3) of 2.7/3.5 (AWHP/BWHP) whereas the second study in 2009 revealed slightly increased factors for both AWHP (2.9) and BWHP (3.9) systems.

In contrast to the SPF definitions used in Switzerland, many European studies are based on the harmonized systems boundary definitions (SPFH1 to SPFH4) introduced during the SEPEMO project (SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector) in 2011 [5] [6].

Gleeson et al. [7] investigated eight different European studies and the respective system boundaries or key figures used (Table 1).

Table 1. Overview of key figures in European field studies [7]

Field study	No. of units	*SPF1 (JAZ1)*	*SPF2 (JAZ2)*	SPF_{hps}	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	DHW share
FAWA [2]	221	-	221	-	-	-	-	-	50%
Frauenhofer 2009 [3] [4]	74	-	-	-	74	74	74	74	100%
Frauenhofer 2005 [3] [4]	70	-	-	-	-	-	70	-	100%
DTI	150	-	-	-	-	-	-	150	100%
LAHR [8]	25	25	25	-	-	-	-	-	unknown
SPTRI 2007	5	-	-	5	-	-	-	5	100%
SPTRI 2010	6	-	-	-	6	-	6	-	86%
EST	71	-	-	-	-	-	-	-	77%
Total	622	25	246	5	80	74	150	229	

Apart from the FAWA study, only the Lahr field trials (2006 to 2014) [8] performed in Germany used the SPF definitions, which makes direct comparison difficult. In fact, performance figures of field test studies are only meaningful in combination with their respective boundary conditions. All further results presented in this work will use the performance figures and the system boundaries defined by the Swiss Federal Office of Energy (SFOE).

The heat pump test center WPZ at the University of Applied Sciences of Technology in Buchs, CH is an EN 17025 and EN14511 certified inspection authority [9]. It offers comprehensive testing service in the field of heat pump and refrigeration technology. Field measurements from the extended monitoring period between 2015 and 2019, which were commissioned by the SFOE, are currently being evaluated.

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 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 current heat pump field study at the Heat Pump Test Center (WPZ) in Buchs is carried out in cooperation with the Swiss Federal Office of Energy (SFOE) and pursues the following strategy:

- Investigation of the real-life performance of heat pump systems.
- Identification of optimization potential.
- Annual addition of five heat pumps to the campaign.
- Reliable measuring data through pre-calibration of the field measuring system.
- Meaningful measuring data thanks to high sampling rate and accurate measuring devices.
- Implementation of suggested optimizations after two years of recording and evaluation.

The ongoing study currently comprises nearly 20 heat-pump systems mainly located in the German speaking lowlands of Switzerland.

2. Technology, boundaries and methods of the field tests

Compared to the earlier studies in the 1990s, 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 an easier detection of defects such as heat losses and unwanted circulation. Based on the collected data series, it is also possible to investigate the following processes deeper, which was not feasible with manual readings [9]:

- starting behavior,
- defrosting,
- on/off cycling,
- detailed breakdown by different levels of utilization,
- measurement at the different system boundaries,
- value of the building/structural condition, and
- effect of auxiliary devices on efficiency (circulating pump, heating elements, etc.).

Due to the short sampling time and the high-resolution data, processes can be viewed not only energetically but also in terms of performance over time. Thus, the measured values can be assigned to a clear chronological sequence. For example, the efficiency of domestic hot water generation and heating water charging can be considered separately.

It is also possible to categorize processes in which the compressor is switched off and only the auxiliary heater is active (standby power consumption analysis) [9]. Such temporal differentiation is becoming increasingly important for the calculation of meaningful key figures. Another advantage of having high-resolution data is the ability to distinguish between the heating and cooling modes of a heat pump. This is particularly interesting for BWHP systems, as no reversible compressor and cycle is required and the excess heat can be fed into the ground. Due to global warming and the resulting hot summers, the demand for heat pump systems with cooling function has significantly increased already in Switzerland.

As mentioned, the SFOE sets its own guidelines for key figures and system boundaries. In terms of energy figures, they are defined as follows [9]:

$$SPF = \frac{Q_{SH}+Q_{DHW}}{E_{tot}-E_{CP,Sink}-E_{ext,HE}} \tag{1}$$

$$HUR = \frac{Q_{SH}+Q_{DHW}}{E} \tag{2}$$

$$SUR_{DHW} = \frac{Q_{DHWU}}{E_{DHW}} \tag{3}$$

$$Q_{HD} = \frac{Q_{SH}}{E_{RA}} \tag{4}$$

$$THR = \frac{Q_{SH}+Q_{DHW}}{E_{RA}} \tag{5}$$

$$HR_{DHW} = \frac{Q_{DHW}}{E_{RA}} \tag{6}$$

$$\eta_{DHW} = \frac{Q_{DHWU}}{Q_{DHW}} \tag{7}$$

The annual performance factor *SPF* mainly determines the efficiency of the heat pump. Only the electrical energy of the compressor, fan (AWHP), source pump (BWHP) and the control electronics of the heat pump are considered in this indicator. The heat utilization ratio *HUR* also includes the electrical energies of the heat sink circulating pump and all auxiliary heating elements. This way the efficiency of the complete heating integration is illustrated and made comparable to other heating systems. The third parameter, the SUR_{DHW} (system efficiency of domestic hot water use), shows the hot water efficiency with respect to usage, including all storage and distribution losses. In addition, this key figure can also be used to assess domestic hot water heat pumps (DHWHP).

Fig. 1 shows the corresponding system boundaries [9]. It can be seen, that the SEPEMO boundaries SPF_{H1} and SPF_{H2} match with *COP, SPF* according to the SFOE [7] [9]. However, the SPF_{H3} does not include the circulation pump and the auxiliary heating of the DHW tank like *HUR* does. In contrast to the outermost boundary SUR_{DHW} the SPF_{H4} does include the entire HP-System with both DHW and space heating buffer tank and is therefore not included in the schematic below.

In order to assess the influence of the building itself or the user behavior and its location, the characteristic values Q_{HD} and *THR* are determined and displayed. However, since the interior temperature is not recorded for any of the 13 measurement the determination of user influences is limited. The heating degree days $HGT_{20,12}$ are determined by a heating limit temperature of 12 °C and a target internal temperature of 20 °C. The $HGT_{20,12}$ is then calculated from the difference between the average daytime temperature and 20 °C. The $HGT_{20,12}$ are only counted if the average daytime temperature is lower than the heating limit (here 12 °C) [9].

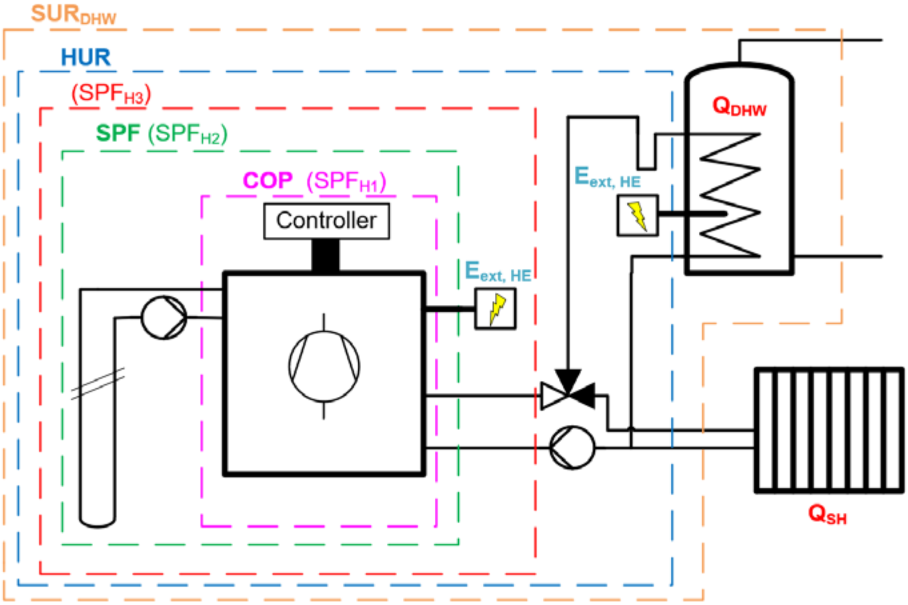

Fig. 1. System boundaries and key figures (*SUR*, *HUR*, *SPF*, *COP*) based on the SFOE [9] and SEPEMO definition [7]

Thermal and electrical energy numbers are measured as numerical integration of several power sensors with a sampling interval of 100 ms. With this approach low sensor costs were combined with high accuracy and the ability to gather rapid changes in the system. The values are then recorded every 10 s, leading to an averaging of 100 datapoints and a small statistical error.

Of course, a discretization error cannot be avoided. This can cause problems if the measured variable changes abruptly. However, it has been shown that for the majority of measurement series a recording interval of 30 s would already be sufficient, since thermodynamic systems tend to change at a slow pace.

The performance values themselves are formed from the effective measured variables according to the established methodology.

By using a volume flow sensor and temperature measurements, the mass flow is determined via the density, where $\rho_w = f(T)$. The heat output for example is then calculated as follows:

$$\dot{Q}_{heat,i} = \dot{m}_w \cdot c_{p,w} \cdot \Delta T = \dot{V}_w \cdot \rho_w\left(T_{supply}\right) \cdot c_{p,w}\left(T_{supply}\right) \cdot \left(T_{supply} - T_{return}\right) \qquad (8)$$

The volume flow is measured in the supply pipe. The temperature difference between supply and return flow is determined from two temperature measurements. The formula (9) shows that the temperature measurements are included several times in the calculation. This means that the measurement error of the temperatures has a strong effect on the overall measurement uncertainty of the heat output. For this reason, great importance is attached to temperature measurement that is as accurate as possible. The aim is an overall uncertainty of the target values of <10 %. To reliably achieve this goal, a measurement uncertainty of the temperature measurement (absolute) of ± 0.02 K has to be met. Calibrated PT-100 sensors with four-wire technology are immersed in the flow and thermally decoupled. For redundancy reasons, important temperatures points are measured twice and the sensors are calibrated and immersed in the flow. The basic placement of the sensors in the system can be seen in Fig. 2. However, the real positioning can be slightly different for each case depending on the type of HP-system or building.

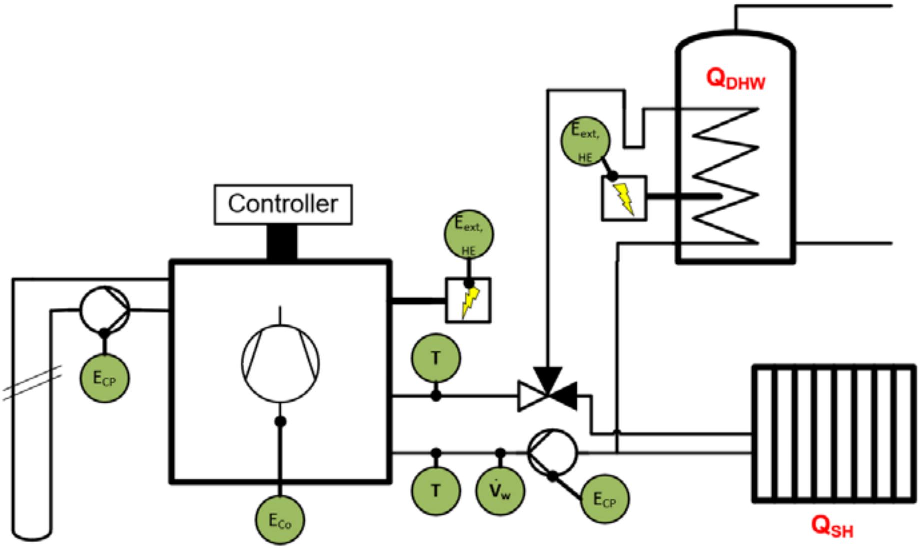

Fig. 2. Basic placement of sensors in a typical heat pump system according to the WPZ [10]

After measurement, the data is automatically read and stored daily on a server in Switzerland for further processing. The storage structure includes 5 different databases and is relational. That means each piece of information is only stored once in one of the five databases. This makes it very easy to keep the data up-to-date and consistent [10].

For data protection reasons, the link to the personal data is made via specially generated ID's, whereby the personal data are stored in the other databases and not apparent in plain language. Furthermore, the database system is also designed to evaluate external measurement data.

As mentioned, every year approximately five new installed heat pump systems are added to the ongoing field study. Arpagaus et al. [10] explained the sequence of a complete measurement and evaluation cycle for a new installation of a system:

1. Application of a customer (who wants to install a heat pump system privately).
2. Calibration of the heat pump with field measuring equipment at the WPZ in Buchs under laboratory conditions.
3. Comparison of laboratory measurements with manufacturer's specifications.
4. Installation of the heat pump system on site, whereby the intended field measuring equipment is also installed.
5. Commissioning of the heat pump system in the presence of an employee of the WPZ.
6. Ongoing measurement of the heat pump system.
7. Comparison and analysis of measured data with laboratory and field test data.
8. Recommendations for optimization and improvements after one year of data collection.
9. Implementation of the proposed optimization in coordination with the customer.
10. Control measurement to record improvements of the heat pump system.
11. Field measuring equipment remains on site with the customer, and data recording is continued.

Inadmissible defects and weaknesses of the heat pump itself are usually detected during laboratory measurements. On the construction site of the building, it should be noted that the installation of the heat pump system as well as its commissioning and handover to the customer is the responsibility of the planning office and the heating installer. The WPZ staff only coordinate the installation of the necessary sensors and data acquisition. Possible errors or defects of the HP systems caused by the installation or commissioning are detected with the help of the data during the measurement phase. Suitable improvement measures or optimizations are suggested to the customer, which then can be carried out under the responsibility of the HP installer.

3. Results, analysis and optimization of current field studies

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.

Fig. 3 shows the connection between the annual coefficient of performance (SPF) and different design temperatures [9].

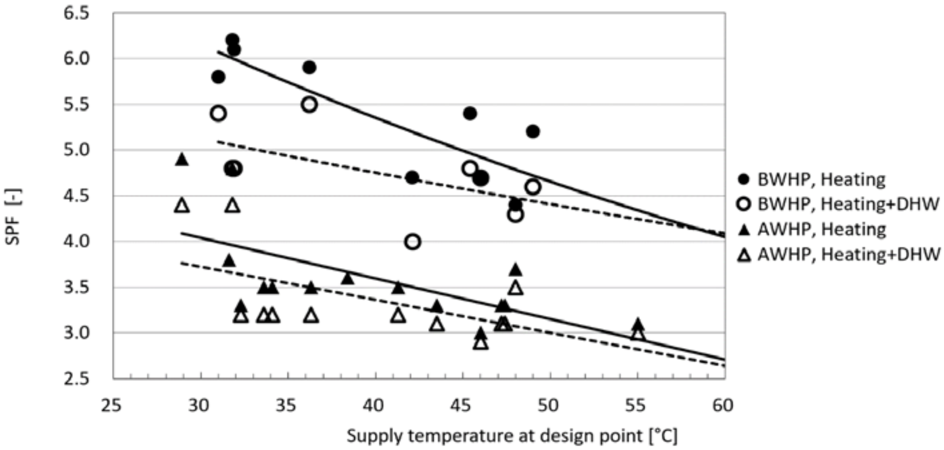

Fig. 3. Efficiency (*SPF*) of Air/Water heat pumps (AWHP) and Brine/Water heat pumps (BWHP) depending on predefined heating and heating+DHW curves.

The data is displayed as a function of the heating curve pre-set on 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.

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 2 provides a more detailed overview of the evaluated performance of AWHP and BWHP by heating and heating+DHW application.

Table 2. Annual Coefficient of Performance (SPF) for different AWHP and BWHP applications [9]

Supply temperature at design point	35 to 30°C (New building)	45 to 40°C (Renovation)	55 to 55°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 matching 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. Fig. 4 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 [9].

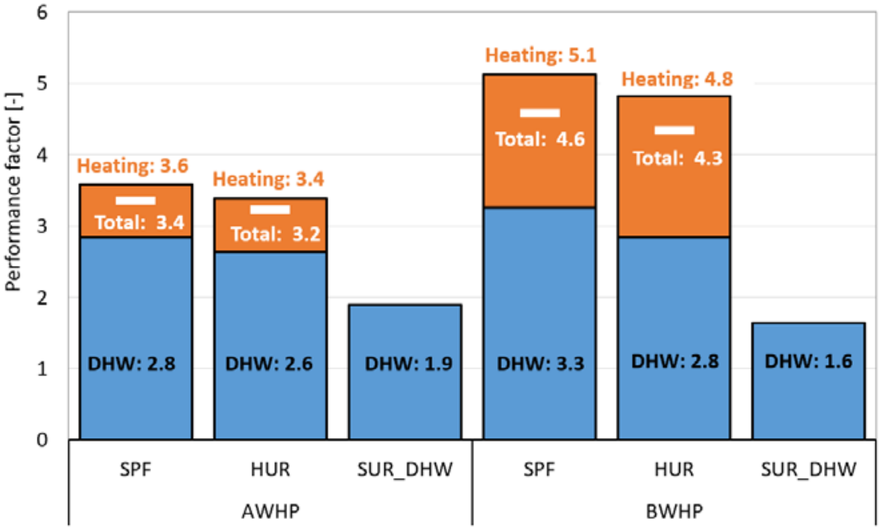

Fig. 4. Comparison of averaged *SPF*, *HUR* and SUR_{DHW}

As expected, 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 lower source temperatures compared with AWHP in summertime. 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 pumps. 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 periods 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.

For conceptional reasons, the system utilization ratio (SUR_{DHW}) can only be 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.

The detailed data recording of several measured variables during more than one heating period offer the determination of various optimization possibilities and the comparison of different objects with regard to the heating settings.

An 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 [9]. The upper heating limit is defined as the ooutside temperature at which heating is automatically turned off.

In a concrete example of an implemented heating curve adjustment, a rather low *SPF* of 2.6 at a daily mean temperature of 7 °C in the period from 10/01/2017-12/17/2017 was successfully increased to *SPF*=3.7 (42 %) in the second recording period until 10/31/2018.

A considerable optimization potential can also be found in DHW production. AWHPs benefit greatly from a larger charging timeframe at midday with a previous charging delay that leads to a reduced set temperature. Since temperatures at noon can be over 10 K higher than in the morning, charging efficiency can be increased by 10 to 20 % [9]. 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.

4. Conclusions

Between 1996 and 2017 more than 600 heat pump systems, mainly in single-family houses, were investigated in the field in Europe. On average, slightly more (approx. 60 %) brine/water heat pump (BWHP) systems were recorded than air/water heat pump (AWHP) systems. Although the amount of data collected over these years is important, it can only be used in part for comparison, due to different definitions of key figures and system boundaries or long sampling intervals.

Detailed analyses of temporal processes are possible by recording power values instead of energy values. This requires short sampling intervals (<30 s) in order to adequately map dynamic processes.

Great importance is attached to the measurement of temperature because of its major influence on the overall uncertainty. Therefore, the supply and return temperatures are measured with an uncertainty of ± 0.02 K (absolute) using PT-100 sensors and four-wire technology. Together with the prior calibration of the whole field measuring equipment in the laboratory, an overall uncertainty of the target values (*COP, SPF*) of <10 % was achieved. Of course, these measurement accuracies require relatively complex and expensive measurement equipment.

However, such precision is not always required or necessary. In the field of building performance estimation, cheaper and simpler solutions can be found recently.

Frei et al. [11] described a concept that combines a variety of different sensors for temperatures, humidity, heat flux, CO_2 etc. embedded as a wireless sensor network (WSN) with open source software platform for communication and data analysis. Although the field of application showed is different, there is common ground and some ideas may be useful for future solutions. Such an installation would help to identify major errors in the applications.

The current study, which now includes almost 20 heat pump systems in the field, clearly shows strong dependence of the annual performance factor *(SPF)* on the supply temperature and the selected heat source. Therefore, AWHPs in new buildings reach an average *SPF* of 3.7 for floor heating (35 °C) whereas BWHPs attain a *SPF* of 5.7. With higher supply temperatures of around 50°C found in old buildings average SPF values of around 2.9 for AWHP and 4.4 for BWHP were measured, respectively.

Combined systems for heating and domestic hot water (DHW) production show 3 to 9 % lower coefficients of performance (e.g. SPF) values due to the increased supply temperatures.

After investigation of the monitored heat pump systems for more than one heating period, various optimization potentials were identified, such as intelligent heating curves or Legionella routines. By implementing these simple software updates, the charging efficiency of DHW could be increased by 10 to 20 %. Typical optimization measures are:

- Adjustment of the heating curve and heating limit.
- Increased charging timeframe at midday.
- Preheating of DHW with the compressor.

In the field of refurbished buildings BWHPs are recommended. For drawing the correct conclusions when comparing heat pump systems, it is crucial to use the correct system limits and boundaries. The current field study shows, that the investigated heat pumps work well overall, but there is still potential of improvement, especially when it comes to DHW production.

Acknowledgements

The results published in this report were funded and obtained in close cooperation with the Swiss Federal Office of Energy (SFOE). The content and conclusions of this report are sole responsibility of the authors.

Nomenclature

AWHP	Air/water heat pump	
BWHP	Brine/water heat pump	
$c_{p,w}$	Specific heat capacity of water	[J/kg-K]
COP	Coefficient of performance	[-]
DHW	Domestic hot water	
E_{Co}	Electrical energy of the heat pump compressor	[kWh]
$E_{CP,Sink}$	Electrical energy of the circulating pump at the heat sink	[kWh]
E_{DHW}	Electrical energy of the HP in DHW operation	[kWh]
$E_{ext,HE}$	Electrical energy of the external heating elements	[kWh]
E_{RA}	Energy reference area of the building	[m^2]
E_{tot}	Electrical energy input of the entire heat pump system	[kWh]
FAWA	Field analysis of heat pump installations	
GWHP	Groundwater/water heat pump	
$HGT_{20,12}$	Heating degree days for 20, 12 °C (heating limit)	[°C]
HP	Heat pump	
HUR	(WNG) Heat utilization ratio according to definition of SFOE	
ISE	Frauenhofer Institute for Solar Energy Systems	
NTB	University of Applied Sciences of Technology Buchs	
Q_{DHW}	Thermal energy of the HP in DHW operation	[kWh]
Q_{DHWU}	Thermal energy of domestic hot water usage (DHWU)	[kWh]
Q_{HD}	Specific heating demand	[kWh/m^2]
Q_{SH}	Thermal energy of the HP in space heating operation	[kWh]
HR_{DHW}	Specific domestic hot water heat requirement	[kWh/m^2]
SEPEMO	SEasonal PErformance factor and Monitoring	
SFOE	Swiss Federal Office of Energy (BFE)	
SPF	(JAZ) Seasonal performance factor according to definition of SFOE	[-]
$SPF1\text{-}2$	(JAZ1-2) Seasonal performance factors according to FAWA bound	[-]
$SPF_{H1\text{-}H4}$	Seasonal performance factors according to SEPEMO boundaries	[-]
SPF_{hps}	Seasonal performance factors according to SPTRI 2007 boundaries	[-]
SUR_{DHW}	System utilization ratio according to SFOE	[-]
THR	Total specific heat requirement (Heating and DHW)	[kWh/m^2]
T_{return}	Return temperature	[°C]
T_{supply}	Supply temperature	[°C]
WPZ	Heat pump test center (Buchs, CH)	
η_{DHW}	Thermal efficiency of domestic hot water usage	[-]
$\dot{m}_w$	Water mass flow	[kg/s]
$\dot{Q}_{heat,i}$	Thermal output power i	[kW_{th}]
$\dot{V}_w$	Water volume flow	[m^3/s]
$\rho_w(T)$	Density of water	[kg/m^3]
ΔT	Temperature difference	[K]

References

[1] Fachvereinigung Wärmepumpen FWS, «Statistik 2018,» FWS, Bern, 2019.

[2] M. Erb, P. Hubacher und M. Ehrbar, «FAWA Feldanalyse von Wärmepumenanlagen,» BFE, Bundesamt für Energie, 2004.

[3] M. Miara, D. Günther, T. Kramer, T. Oltersdorf und J. Wapler, «Wärmepumpen Effizienz, Messtechnische Untersuchung von Wärmepumpenanlagen zur Analyse und Bewertung der Effizienz im realen Betrieb,» ISE, Fraunehofer Institut für Solare Energiesysteme, Freiburg, 2011.

[4] M. Miara, D. Günther, R. Langner, S. Helmling und J. Wapler, «WP Monitor, Feldmessung von Wärmepumpenanlagen,» ISE, Frauenhofer Institut für Solare Energiesysteme , Freiburg, 2014.

[5] R. Nordman, K. Andersson, M. Axell und M. Lindahl, «Calculation methods for SPF for heat pump systems for comparison, system choice and dimensioning,» Technical Research Institute of Sweden, Sweden, 2010.

[6] "SEPEMO-Build.," SEPEMO, 31 May 2012. [Online]. Available: http://sepemo.ehpa.org/. [Accessed 30 September 2019].

[7] C. P. Gleeson und R. Lowe, «Meta-analysis of European heat pump field trial efficiencies,» Elsevier, London, 2013.

[8] F. Auer und H. Schote, «Schlussbericht Zweijähriger Feldtest Elektro – Wärmepumpen am Oberrhein: Nicht jede Wärmepumpe trägt zum Klimaschutz bei zumKlimaschutz bei Erdreich-Wärmepumpen mit positiver Ökobilanz Kritis-che Bewertung von Luft-Wärmepumpen.,» Lahr, 2012.

[9] M. Prinzing, M. Berthold und M. Eschmann, «Jahresbericht WP-Feldmessung 2018,» BFE, Bundesamt für Energie Schweiz, Bern, 2019.

[10] C. Arpagaus, M. Berthold und M. Eschmann , «Jahresbericht WP-Feldmessung 2017,» BFE, Bundesamt für Energie Schweiz, Bern, 2018.

[11] M. Frei, C. Deb, R. Stadler, Z. Nagy und A. Schlueter, «Wireless sensor network for estimating building performance,» Elsevier, Zürich, 2020.