Purdue University

Purdue e-Pubs

International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2021

Field Performance Of Domestic Heat Pumps For Heating And Hot Water In Switzerland Part I: Technology, Methods And State Of The Art Of The Field Studies

Ralph R. Kuster
Eastern Switzerland University of Applied Sciences, ralph.kuster@ost.ch

Manuel Prinzing

Berthold Matthias

Mick Eschmann

Stefan S. Bertsch

FIELD PERFORMANCE OF DOMESTIC HEAT PUMPS FOR HEATING AND HOT WATER IN SWITZERLAND PART I: TECHNOLOGY, METHODS AND STATE OF THE ART OF THE FIELD STUDIES

Ralph KUSTER[1]*, Manuel PRINZING[1], Matthias BERTHOLD[1], Mick ESCHMANN[1], Stefan S. BERTSCH[1]

[1] OST Eastern Switzerland University of Applied Sciences, Institute for Energy Systems, Werdenbergstrasse 4, 9471 Buchs, Switzerland

* Corresponding Author: ralph.kuster@ost.ch, +41 58 257 31 82

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 with calibrated sensors with very low measurement uncertainty.

The aim of this field study is to record the real heat pump 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 that is entitled "Technology, Methods and State of the Art of the field studies" focuses on the procedure, system boundaries and measuring technology of past and current field studies at WPZ Buchs and provides an insight to the state of the art of field performance measurements of domestic heat pumps carried out in Switzerland. The second part is entitled "Results, Analysis and Optimization of current field studies" and concentrates on various measured figures and the improvement potential of the investigated heat pump systems.

Compared to the former studies made in the 1990s and early 2000s, the measurement methodology and data acquisition have changed considerably to date. Nowadays, thanks to digitalization, much more data is available. Short sampling intervals are used to describe temporal processes in heat pump systems in detail, enabling an easier detection of defects such as heat losses and unwanted circulation.

Thanks to carefully defined system boundaries like *JAZ*, *WNG* and *SNG* heat pump systems can be compared and optimized effectively.

Great importance is attached to the measurement of temperature because of its major influence on the overall uncertainty. Therefore, temperature is measured with an uncertainty of ±0.1 K/±0.02 K (absolute/relative) using directly immersed PT-100 sensors and four wire technology. Together with the prior calibration of the whole measuring equipment in the laboratory, an overall uncertainty of the target values *(COP, JAZ)* of 10% was achieved.

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 2019 increased by almost 10 % compared to 2018 and almost 20 % compared to 2017 (Fachvereinigung Wärmepumpen FWS, 2019). Over 70 % are air/water heat pumps (AWHP), 28 % brine/water heat pumps (BWHP) and around 1 % are groundwater heat pumps (GWHP) (sold in 2019). Almost 52 % of these sold DHPs are in the range between 5-13 kW_{th} and 84 % are below 20 kW_{th} of heating capacity. 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 University of Applied Sciences of Technology in Buchs, Switzerland is an EN 17025 certified inspection authority (Prinzing, Berthold, & Eschmann, 2019). It offers comprehensive testing service in the field of heat pump and refrigeration technology. Field measurements from the extended monitoring period between 2016 and 2019, which were commissioned by EnergieSchweiz, 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 WPZ in Buchs is carried out in cooperation with the ENERGIESCHWEIZ and pursues the following strategy:

- Investigation of the real-life performance of heat pump systems.
- Identification of optimization potenzial.
- Annual addition of five heat pumps to the campaign.
- Reliable measuring data through pre-calibration of each 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, which was lately extended beyond 2020, currently comprises over 20 heat-pump systems mainly located in the German speaking lowlands of Switzerland.

2. PREVIOUS STUDIES IN EUROPE

25 years ago, a comprehensive field study of DHP in Switzerland, called FAWA (field analysis of heat pump installations) was launched (Erb, Hubacher, & Ehrbar, 2004), which was also commissioned by the EnergieSchweiz 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 kW_{th} 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 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 (Miara, Günther, Kramer, Oltersdorf, & Wapler, 2011) (Miara, Günther, Langner, Helmling, & Wapler, 2014). The first ISE study showed average seasonal performance factors *(SPF_{H3})* 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 total 144 heat pump facilities have been investigated.

Another study carried out in Germany that used similar performance factor definitions as FAWA (*SPF* or *JAZ*) was the Lahr trial, which was part of the Local Agenda 21 program. 33 AWHP, BWHP, and GWHP all used exclusively for space heating have been investigated (Auer & Schote, 2012). In addition, five heat pumps for domestic hot water production were also part of the study. BWHP showed an average seasonal performance factor *(SPF, JAZ)* of 3.4 directly after the heat pump and 3.1 including heating buffer tank and DHW-production.
During the study a *SPF* of 2.8 was found for AWHP using floor heating systems and 2.2 for radiator heating respectively. For GWHP average *SPF's* of 3.2 for the heat pump itself and 2.9 for the whole system performance was evaluated.

In contrast to the *SPF (JAZ)* definitions used in Switzerland, some European studies are based on the harmonized systems boundary definitions (SPF_{H1} to SPF_{H4}) introduced during the SEPEMO project (SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector) in 2011 (SEPEMO-Build., 2012) (Nordman, Andersson, Axell, & Lindahl, 2010).

Between May 2010 and July 2011, the boundary definitions according to SEPEMO were also used in a field study of the Danish Technology Institute (DTI). With 150 investigated HP-facilities this study was one of the biggest performed in Europe. This study included 138 ground sourced and 12 air sourced heat pump systems. The seasonal performance factors according to SPF_{H4} resulted in average values of 3.03 for BWHP and 2.33 for AWHP: As the outermost boundary defined by SEPEMO the SPF_{H4} includes both, backup heater and circulation pump. (Gleeson & Lowe, 2013).

Apart from the European mainland a major study which was performed in the United Kingdom was entitled "UK Energy Saving Trust (EST) trials". During a period of 12 months (April 2009-April 2010) a total of 83 heat pumps in residential properties across Great Britain have been investigated (Dunbabin & Wickins, 2012). The study involved a big variety of different installation types and both air-sourced and ground-sourced DHP. Compared to the other mentioned field trials, the EST study used a unique boundary definition by including the hot water draw off within the overall SPF heating system boundary.

Different definitions of system boundaries and performance factors are a well-known challenge, when it comes to the comparison of different field studies. Gleeson and Lowe (Gleeson & Lowe, 2013) performed a meta-analysis of European HP-field trials. The investigation of the used system boundaries and key figures was also part of their work. The following table shows a summary of used boundary-definitions in European field trials.

Table 1: Overview of key figures in European field studies (Gleeson & Lowe, 2013)

Field study	No.of units (DHP)	*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	

The studies can roughly be divided into two groups when it comes to performance factor definitions and their boundaries. Except from the EST-study all mentioned trials used either the *SPF (JAZ)* definitions introduced by FAWA or the harmonized boundary definitions according to SEPEMO.

3. KEY FIGURES AND SYSTEM BOUNDARIES

Performance factors out of heat pump field trials are only meaningful by considering their respective boundaries.
It must be clearly defined which energy parameters are taken into account and also how long the observation period is. As mentioned, the EnergieSchweiz sets its own guidelines for key figures and system boundaries. In terms of energy figures, they are defined as follows (Prinzing, Berthold, & Eschmann, 2019):

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

$$HUR = \frac{Q_{SH}+Q_{DHW}}{E} \quad (2)$$

$$SUR_{DHW} = \frac{Q_{DHWU}}{E_{DHW}} \quad (3)$$

$$Q_{HD} = \frac{Q_{SH}}{E_{RA}} \quad (4)$$

$$THR = \frac{Q_{SH}+Q_{DHW}}{E_{RA}} \quad (5)$$

$$HR_{DHW} = \frac{Q_{DHW}}{E_{RA}} \quad (6)$$

$$\eta_{DHW} = \frac{Q_{DHWU}}{Q_{DHW}} \quad (7)$$

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), where no internal measurements are possible.

Figure 1 shows the corresponding system boundaries (Prinzing, Berthold, & Eschmann, 2019). It can be seen, that the SEPEMO boundaries SPF_{H1} and SPF_{H2} match with *COP, SPF* according to EnergieSchweiz (Arpagaus, Berthold, & Eschmann , 2018). 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 in Figure 1. (SEPEMO-Build., 2012)

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 (room) temperature is not recorded for any of the investigated objects 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) (Prinzing, Berthold, & Eschmann, 2019). The $HGT_{20,12}$ applies to new buildings whereas the $HGT_{20,16}$ is considered for refurbished buildings.

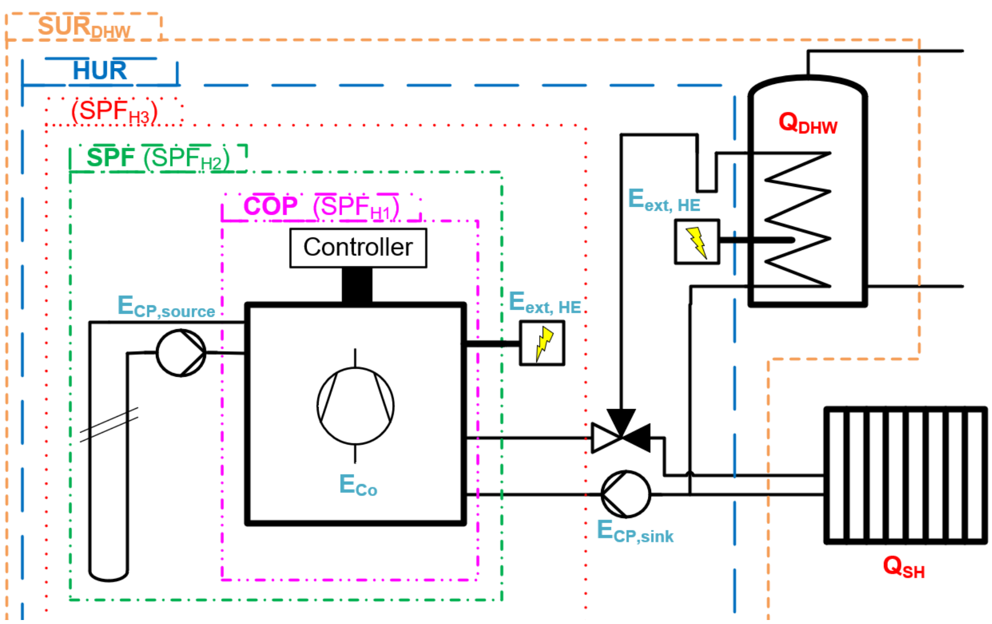

Figure 1: System boundaries and key figures (SUR, HUR, SPF, COP) based on the EnergieSchweiz (Prinzing, Berthold, & Eschmann, 2019) and SEPEMO definition (SEPEMO-Build., 2012)

4. METHOD AND TECHNOLOGY

Compared to the former studies in the 1990s and early 2000s, the measurement methodology and data acquisition technology have changed considerably. Nowadays, thanks to digitalization, much more data is available. Short recording intervals (10s) can be used to describe temporal processes in heat pump systems in detail, enabling an easier detection of defects such as heat losses and/or 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 (Prinzing, Berthold, & Eschmann, 2019):

- 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,
- 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 (standby power consumption analysis) (Prinzing, Berthold, & Eschmann, 2019). 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 compressor and reversible cycle is required, and the excess heat can be fed into the ground. Due to global warming and the resulting hot summers, the future demand for heat pump systems with cooling function will significantly increase in Switzerland.
Thermal and electrical energy numbers are measured as numerical integration of several power sensors with a sampling interval of 100 ms, which allows 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 discretization error that 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:

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

The volume flow is measured in the return pipe. The temperature difference between supply and return flow is determined from two separate temperature measurements. Equation (8) shows that the temperature measurements are included several times in the calculation. Therefore, the measurement error of the temperatures has a strong effect on the overall measurement uncertainty of the heat output as well as for various performance factors. For this reason, great importance is attached to accuracy of temperature measurement. The aim is an overall uncertainty of the target values of <10 %. To reliably achieve this goal, a measurement uncertainty of the temperature measurement of ±0.1 K (absolute) and ± 0.02 K (relative) has to be met. Calibrated PT-100 sensors with four-wire technology are immersed in the flow and thermally decoupled. For redundancy reasons, important temperature points are measured twice.
On the left picture in Figure 2 one can see a typical inline temperature measuring using two sensors and in the picture to the right the usually used volume flow sensor placed in one of the pipe lines.

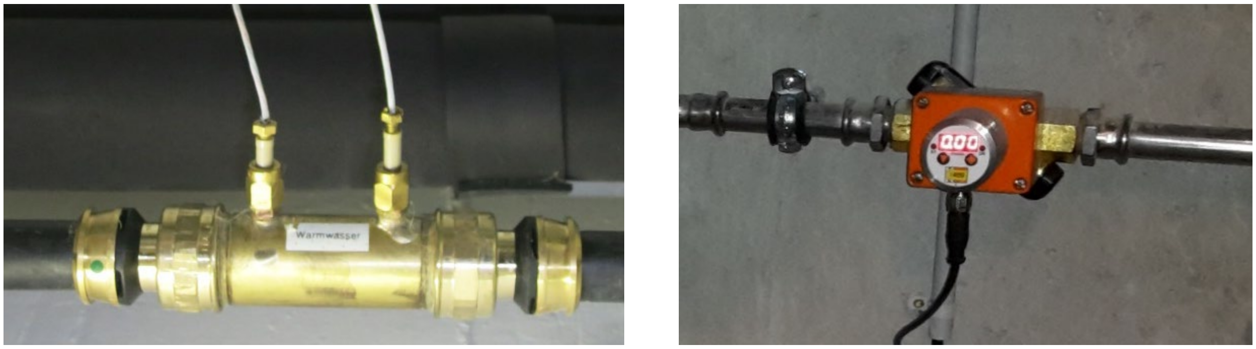

Figure 2: Double temperature measurement (left) immersed into the flow and a volume flow sensor (right).

The basic placement of the sensors in the system can be seen in Figure 2. It is understood that the real positioning can be slightly different for each case depending on the type of HP-system or building.

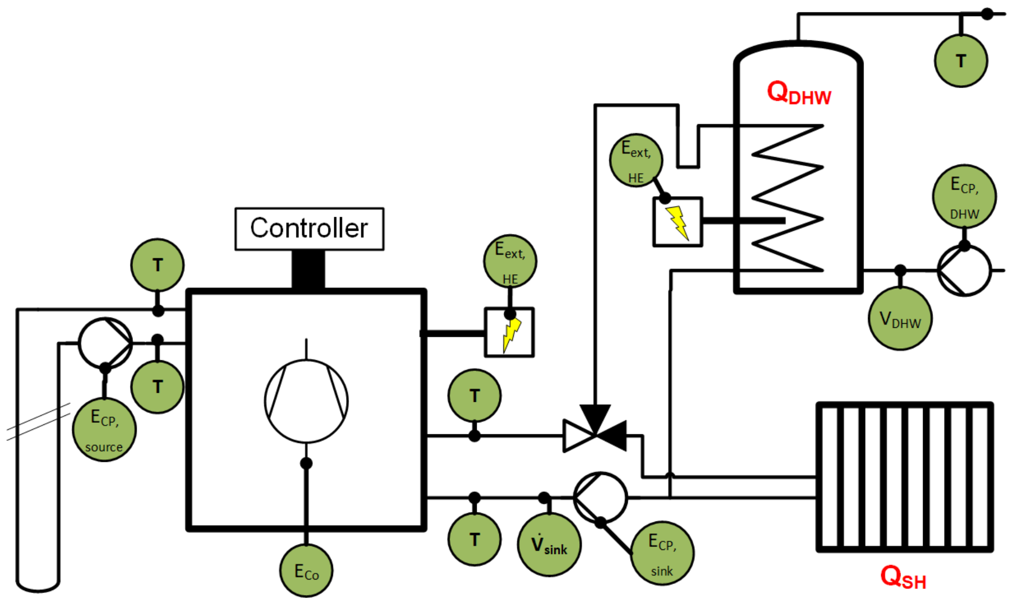

Figure 3: Basic placement of most important sensors in a typical heat pump system according to the WPZ (Arpagaus, Berthold, & Eschmann , 2018)

The data acquisition is carried out on site by a PLC, which also allows remote access via WLAN, LAN, or GSM. 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 (Miara, Günther, Kramer, Oltersdorf, & Wapler, 2011).

For data protection reasons, the link to the personal data is secured via specially generated ID's, whereby the personal data are stored in the other databases and are 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. (Arpagaus, Berthold, & Eschmann , 2018) 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 or manufacturer.

5. 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 systems were recorded than air/water heat pump 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 different sampling intervals.
As for the current field study carried out by the heat pump test center Buchs, Switzerland, all presented results that can be found in part II entitled "Results, Analysis and Optimization of current field studies" (Kuster, Prinzing, Berthold, Eschmann, & Bertsch, 2020) used the boundary and key figure definitions introduced by the EnergieSchweiz and presented in this paper.

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 ± 0.1/0.02 K (absolute/relative) using PT-100 sensors and four-wire technology. Together with the prior calibration of the whole field measuring equipment in laboratory, an overall uncertainty of the target values (*COP, SPF*) of <10 % was achieved. These measurement accuracies require relatively complex and expensive measurement equipment.

Along with the extension of the ongoing field trials, preference is currently being given to including apartment buildings in the study in order to have more data available from heat pump systems in the medium and higher heat output range (20-100 kW).

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]
$E_{CP,Source}$	Electrical energy of the circulating pump at the heat source	[kWh]
E_{DHW}	Electrical energy of the HP in DHW operation	[kWh]
$E_{ext,HE}$	Electrical energy of the external heating elements	[kWh]
EnergieSchweiz	Federal authority on behalf of the Swiss Federal Office of Energy (SFOE)	
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	
GSM	Global System for Mobile communications	
GWHP	Groundwater/water heat pump	
$HGT_{20,12}$	Heating degree days for 20, 12 °C (heating limit)	[°C]
HP	Heat pump	
HUR	Heat utilization ratio according to definition of ENERGIESCHWEIZ (WNG)	
ISE	Frauenhofer Institute for Solar Energy Systems	
LAN/WLAN	Local Area Network/Wireless Local Area Network	
OST	Eastern Switzerland University of Applied Sciences	
PLC	Programmable Logic Controller	
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	
SPF	(JAZ) Seasonal performance factor according to definition of ENERGIESCHWEIZ	[-]
SPF1-2	(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 ENERGIESCHWEIZ (SNG_{TWW})	[-]
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), German: Wärmepumpen Test Zentrum	
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

Arpagaus, C., Berthold, M., & Eschmann , M. (2018). *Jahresbericht WP-Feldmessung 2017.* Bern: BFE, Bundesamt für Energie Schweiz.

Auer, F., & Schote, H. (2012). *Schlussbericht Zweijähriger Feldtest Elektro – Wärmepumpen am Oberrhein: Nicht jede Wärmepumpe trägt zum Klimaschutz bei zum Klimaschutz bei Erdreich-Wärmepumpen mit positiver Ökobilanz Kritis-che Bewertung von Luft-Wärmepumpen.* Lahr.

Dunbabin, P., & Wickins, C. (2012). *Detailed analysis from the first phase of the Energy Saving Trust's heat pump field trial.* London: DECC.

Erb, M., Hubacher, P., & Ehrbar, M. (2004). *FAWA Feldanalyse von Wärmepumenanlagen.* BFE, Bundesamt für Energie.

Fachvereinigung Wärmepumpen FWS. (2019). *Statistik 2018.* Bern: FWS.

Gleeson, C. P., & Lowe, R. (2013). *Meta-analysis of European heat pump field trial efficiencies.* London: Elsevier.

Kuster, R., Prinzing, M., Berthold, M., Eschmann, M., & Bertsch, S. S. (2020). *Field performance of domestic heat pumps for heating and hot water in switzerland, Part II- Results, analysis and optimization.* Purdue University: 18th International Refrigeration and Air Conditioning Confernece at Purdue.

Miara, M., Günther, D., Kramer, T., Oltersdorf, T., & Wapler, J. (2011). *Wärmepumpen Effizienz, Messtechnische Untersuchung von Wärmepumpenanlagen zur Analyse und Bewertung der Effizienz im realen Betrieb.* Freiburg: ISE, Fraunehofer Institut für Solare Energiesysteme.

Miara, M., Günther, D., Langner, R., Helmling, S., & Wapler, J. (2014). *WP Monitor, Feldmessung von Wärmepumpenanlagen* . Freiburg: ISE, Frauenhofer Institut für Solare Energiesysteme .

Nordman, R., Andersson, K., Axell, M., & Lindahl, M. (2010). *Calculation methods for SPF for heat pump systems for comparison, system choice and dimensioning.* Sweden: Technical Research Institute of Sweden.

Prinzing, M., Berthold, M., & Eschmann, M. (2019). *Jahresbericht WP-Feldmessung 2018.* Bern: BFE, Bundesamt für Energie Schweiz.

SEPEMO-Build. (2012, May 31). (SEPEMO) Retrieved September 30, 2019, from http://sepemo.ehpa.org/

ACKNOWLEDGEMENT

The results published in this report were obtained and funded in close cooperation with EnergieSchweiz. The content and conclusions of this report are sole responsibility of the authors.