Simulation-Based Monitoring Analysis of Air-Source Domestic Hot Water Heat Pumps

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Abstract

The following research takes particular merit from long-term monitoring data of eight identical built-in compact air-to-water heat pump systems. Occupant-related domestic hot water consumption data were therefore analyzed in different German households within the same building envelope and boundary conditions. Research progress is made based on realistic domestic hot water profiles. Measurement uncertainties as well as influencing system parameters are quantified and a reliable and validated simulation model is provided. The obtained results depict significant deviations from standardized and deterministic calculation methods. Efficient operation was found to be case-sensitive and limited by storage tank volumes and thermal storage behavior. This approach documents these findings with respect to analyzed and simulated occupant consumption data and thus aims to enhance further building performance predictions.

Introduction

The domestic hot water demand (DHW) claims a proportionally growing impact on buildings' energy performance regarding building standards towards net zero. Providing realistic and reliable consumption data is therefore crucial for the design and efficient operation of building systems. In consequence, former studies put emphasis on benchmarking the DHW demand since draw-off patterns of multiple appliances and individual consumption behavior lead to strongly fluctuating demands. Due to these deterministic and random DHW characteristics (Hendron and Burch, 2007) statistical methods are better suited to describe DHW demands and to avoid shortcomings of normative load profiles (Jordan and Vajen, 2001). Hence, dynamic simulation tools combined with statistic DHW profiles are widely approved to predict the DHW demand more accurately (Marini et al., 2015). The investigated DHW systems consist of air-to-water heat pumps. In general, heat pumps represent an energy efficient technology to increase the primary energy balance while using renewable energy (Hepbasli and Kalinci, 2009). Simulation studies of conventional DHW systems are found in literature (Kazmi et al., 2016) whereas recent studies of air-source DHW heat pump systems are rare or theoretical and lack the explicit correlation to monitored occupant's DHW consumption. The main focus of related research projects has been either on mechanical improvements regarding the compressor technology (Ibrahim et al., 2014), storage enhancements (Knudsen, 2002) or on measured data analyses of the systems' overall energy performance of Pollard (2010) and Hubacher (2015). Thus, this study aims to enhance the understanding of dependencies between individual consumption behavior and system efficiency. Influencing performance indicators are therefore defined based on the detailed analysis of consumption data and draw-off patterns. Subsequently, a validated simulation model is derived that considers consumption profiles from measured data. The model provides realistic performance results that differ significantly from energy performance predictions with standardized calculation methods DIN prEN 16147 (2015).

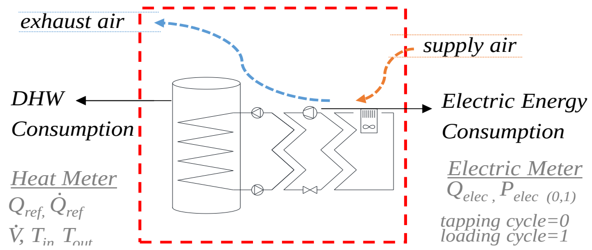

Figure 1: Heat Pump System - Measurement Setup

Preliminary Studies

System Description

The DHW heat pump system for the present research consists of the predefined DHW storage volume (Figure 1) in combination with the compressor and the ventilation unit. These so-called heat pump boilers are also known as compact heat pump systems (CHPS). The minimized measuring setup includes installed heat and energy meters (Table 1) that provide minute-wise measuring data from the bathrooms of eight apartments. Each apartment (household) was designed for three or four persons to achieve

Table 1: Measured Parameters

Electric Energy	*Units of Measurement*
$Q_{\text{elec (1),(0,1)}}$	kWh
$P_{\text{elec (1),(0,1)}}$	W
DHW Consumption	
Q_{ref}	kWh
$\dot{Q}_{\text{ref}}$	W
T_{in}, T_{out}	°C
$V_{(0,1)}$, $\dot{V}$	l, m^3/h
Climate	
T_{indoor}, T_{outdoor}	°C *(wet bulb temperature)*
RH_{indoor}, RH_{outdoor}	% *(relative humidity)*

the plus energy standard within the building envelope according to DIN V 18599-5 (2011) and to German funding guidelines during two years of monitoring. All apartments have been inhabited during the depicted monitoring period (06-Dec-2015 - 06-Nov-2016). The system boundaries and heat pump cycles were predefined in accordance to DIN EN 15450 (2007) for air-to-water heat pumps and DIN prEN 16147 (2015): Hereby the operating heat pump compressor ($Q_{\text{elec}(1)}$) marks the operating phase for DHW production which is defined as the loading cycle of the storage tank. Tapping cycles start with the end of the compressor phase including the subsequent loading cycle of the storage tank ($Q_{\text{elec}(0,1)}$). The dominant function of the ventilator during loading cycles is to provide thermal energy. Outside loading cycles the fan is used solely for space ventilation. In consequence, different performance factors are calculated which refer either to loading cycles (Equation 1) or combined loading and tapping cycles (Equation 2):

$$PF_{(1)} = \frac{Q_{ref(1)}}{Q_{elec(1)}} \tag{1}$$

$$PF_{(0,1)} = \frac{Q_{ref(0,1)}}{Q_{elec(0,1)}} \tag{2}$$

Table 2: Technical Specifications and Simulation Parameters

Ventilation		
$\dot{V}_{\text{air}}$ space ventilation	30	m^3/h
$\dot{V}_{\text{air}}$ DHW production	140	m^3/h
Storage Tank		
V_{nominal}	200	l
$Q_{\text{losses},(45\ °C/20°C)}$ per day	1.13	kWh
t_s set temperature for tapping	45	°C
Heat Pump		
P_{elec} heat pump	253	W
P_{elec} backup heating	1500	W

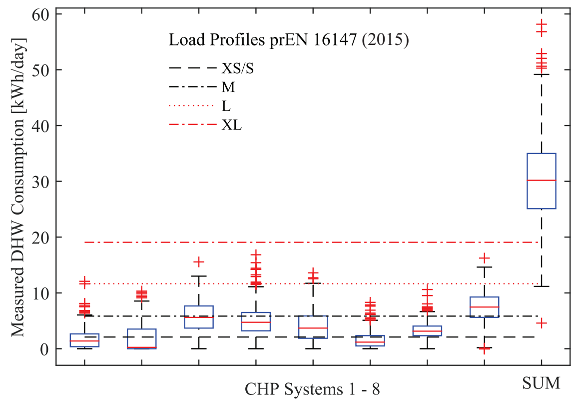

Figure 2: Measured DHW Energy Consumption [kWh/day] per CHPS compared to Standardized Load Profiles XS/S, M, L, XL.

Consumption Data Analysis

It is currently understood that performance gaps of buildings are also due to uncertainties and limited knowledge of consumption and operation data (Gaetani et al., 2016). Preceding findings for the CHPS already showed significant deviations between the measured and the actual energy demands of the systems which had been calculated according to DIN V 18599-5 (2011): For example, the observed mean DHW energy consumption per day and per household depicted in average significantly lower demands for all apartments than the applicated load profile 'L' per day (Figure 2). The latter is observed under standardized conditions of DIN prEN 16147 (2015) where different load profiles for CHPS are defined. In contradiction, comparative studies in the winter period verified that the net energy consumption for DHW exceeded the scheduled demand by 75% (Lorz et al., 2016). With regard to these preliminary studies, weekly statistics for single apartments showed rising consumptions in the winter and a decreasing demand for the DHW consumption in the summer season (Figure 3) with two significant reductions during holidays. Mean daily statistics indicated seasonal differences in consumption behavior and did reveal the fluctuating DHW demand in detail (Figure 4).

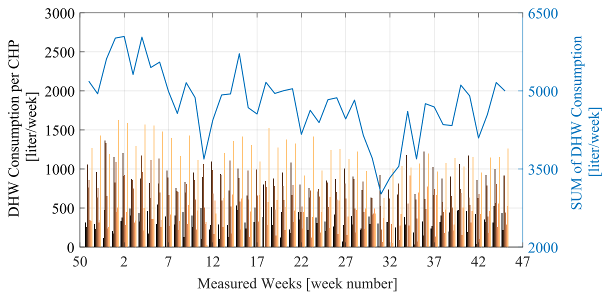

Figure 3: DHW Consumption [liter/week]

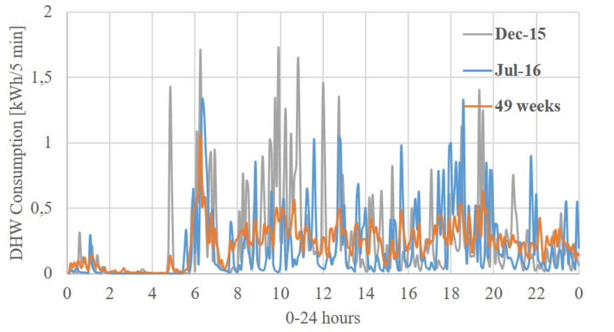

Figure 4: Seasonal Differences - Mean Daily Statistics of DHW Consumption for exemplary CHPS [kWh/5 min]

These variations are also reflected on the large scale by weekly aggregated consumption data throughout the monitored year (Figure 3). From the perspective of the building's energy balance design, it has been concluded that normative tapping profiles (DIN prEN 16147, 2015) or generalized DHW consumption patterns are insufficient to predict the energy demand of the CHPS accurately.

Performance Data Analysis

In the following, further data analysis was conducted to elaborate performance indicators for each CHPS system. Pearson's correlation coefficient formula (Hinkle et al., 2003) has been used in the first step to investigate dependencies between performance factors for loading cycles and tapping cycles ($PF_{(1)}$ and $PF_{(0,1)}$ in Equation 1 and 2) with regard to seasonal differences of the measured parameters and time durations (Figure 5 and Figure 6). According to Hinkle et al. (2003) correlation factors below 0.3 are of negligible influence. The measured data sets of December 2015 and July 2016 served to compare correlation factors of exemplary summer (orange color) and winter (blue color) seasons. So far, any temperature-related CHPS performance was not deducible (Figure 5a and 5b) as observed indoor air-source temperatures (T_{indoor} in Figure 5a) were constant and stable above 20 °C during most loading cycles ($PF_{(1)}$). In other words, the bypass-control for the supplied air flow (indoor-outdoor switch) delivered nearly constant temperature boundary conditions during the monitoring period (in the average range of 20 - 25 °C during loading cycles). The observed time ratios for tapping and loading cycles resulted in highly positive correlation factors (Figure 6a: $\rho = -0.760$ / -0.612) with regard to performance factors (Figure 6b: $\rho = 0.968$ / 0.952) during tapping cycles and tapping volumes $V_{(0,1)}$ (Figure 6c: $\rho = 0.807$ / 0.768).

Correlation factors for tapped DHW volumes in the summer period turned out slightly higher and the average duration time of loading cycles tended to

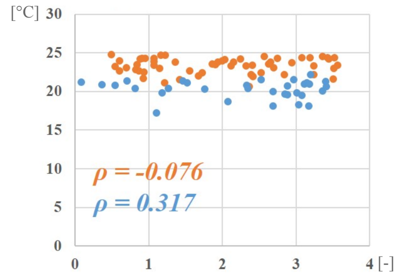

Figure 5a: f: $PF_{(1)} \rightarrow T_{indoor}$

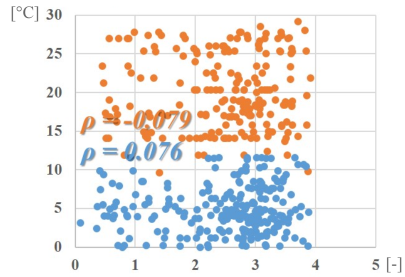

Figure 5b: f: $PF_{(1)} \rightarrow T_{outdoor}$

Figure 5: Source Temperature Correlation Analysis

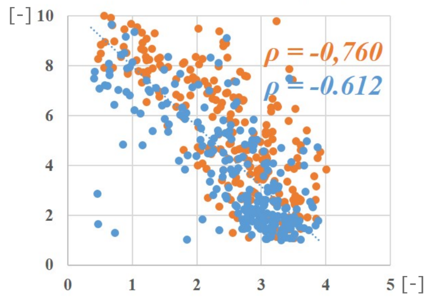

Figure 6a: f: $PF_{(0,1)} \rightarrow time_{\,ratio(0,1/1)}$

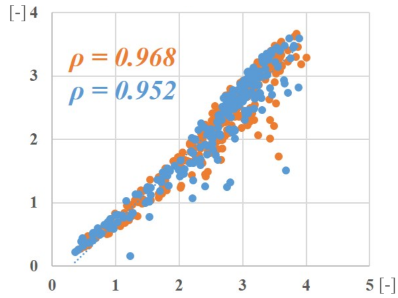

Figure 6b: f: $PF_{(1)} \rightarrow PF_{(0,1)}$

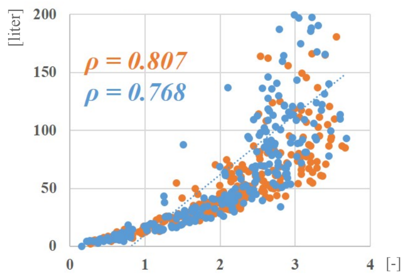

Figure 6c: f: $PF_{(0,1)} \rightarrow V_{(0,1)}$

Figure 6: Consumption Correlation Analysis

be shorter (decreasing time ratio in Figure 6a). In the second step detailed and individual DHW profiles were analyzed by statistical means with reference to mean values, variation coefficients and standard errors to quantify user-related performance dependencies (Table 6). Generally speaking, individual DHW profiles can be characterized by corresponding variation coefficients reflecting the degree of fluctuating DHW consumption during the reference period. Normalized variation coefficients which define dispersions of the mean values (Hinkle et al., 2003) are better suited to describe irregular DHW consumption since peak values of DHW consumption may be balanced out in favor of the average value (high fluctuations of DHW consumption do not necessarily yield higher standard errors). Especially CHPS with low average DHW consumption per day (< 50 liter/day) and moderate standard errors rely on higher normative variation coefficients (e.g. CHPS 2, 6 and 1 in Table 6). In summary, the results indicate that high and therefore efficient performance values are necessarily based on major and regular DHW tapping profiles (small variation and high DHW consumption): These CHPS were respectively identified by means of measured $PF_{(0,1)}$ greater than 2.0 and DHW consumptions per day exceeding 50 % of the maximum storage tank volume. The average performance factor for December ($PF_{(0,1)}$ of 2.41) turned out to be slightly higher than in July ($PF_{(0,1)}$ of 2.34) and confirms seasonal fluctuations in individual consumption behavior (Figure 4).

Simulation Modelling

Except from temperature boundary conditions (room temperatures and estimated cold water inlet temperatures for six CHPS), most DHW parameters were reconstructed for the simulation. For the purpose of simulation modelling, the Carnot Toolbox (CARNOT Blockset (2011) in Matlab Simulink (2016)) was used to implement the heat pump, the storage tank and the measured tapping profiles from heat meter data. The standard storage model in Matlab has been modified to include the additional heating device features. Discharging and direct charging ports are represented by thermal nodes (double ports) to calculate the energy balance. The exact position and detailed heat exchange features (heat exchange pipe diameter, position and length) were unknown. Therefore, the storage model was kept simple from pre-defined standard parameters and tested for functionality from empirical data since in-situ testing with detailed temperature measurements inside the tank was not possible.

Specifications (Table 2) and simulation parameters for the heat pump model were implemented while using a linear characteristic model (source, heating and electric power matrix). For this purpose, an initial operating matrix for thermal and electric power of the heat pump (DIN 14511-3, 2013) was defined. Since data for some essential parameters were missing (e.g. the refrigerant volume) the specifications of a similar compressor type have been used to modify the Carnot heat pump model. The heat pump model characteristics have been derived from operating temperature points of 35/45/55/60 °C and source temperatures of 10 °C and 15 °C for modeling energy balances and heat flows. The refrigerant mass flow terms $\dot{m}_r$ $(q \cdot \rho)$ and enthalpy changes ΔH $(c_p \cdot \Delta t)$ are calculated as isothermal simulation processes:

- Heating power of the evaporator

$$\dot{Q}_{\mathrm{h}} = (q \cdot \rho \cdot c_p \cdot \Delta t)_{\mathrm{evaporator}} \tag{3}$$

- Cooling power of the condenser

$$\dot{Q}_{\mathrm{c}} = (q \cdot \rho \cdot c_p \cdot \Delta t)_{\mathrm{condenser}} \tag{4}$$

- Compressor power

$$P_{\mathrm{elec}} = (q \cdot \rho \cdot c_p \cdot \Delta t)_{\mathrm{compressor}} \tag{5}$$

The following equations describe the thermodynamic heat balance for the heat exchanging medium with ∂Q_{hx} to be solved in Matlab (Hafner, B., 2003):

$$\frac{\partial Q_{hx}}{\partial t} = \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{losses} \tag{6}$$

The maximum of $\dot{Q}_{hx}$ depends on the maximum Δt between the hot and cold side of the heat exchanging mass flows (refrigerant) which define the outgoing temperatures (Number of Transfer Units Method, NTU, (Shah and Sekulić, 2003)):

$$\dot{Q}_{\mathrm{hx}} = \varepsilon \cdot (\dot{m} \cdot c_p)_{min} \cdot (T_{h,in} - T_{c,in}) \tag{7}$$

The function term for parameter ε describes the efficiency for the specific type of heat exchange:

$$\varepsilon = f\left(NTU, \frac{(\dot{m} \cdot c_p)_{min}}{(\dot{m} \cdot c_p)_{max}}\right) \tag{8}$$

The tapping events (Q_{ref}) have been indicated for all eight CHPS and served as input signals for the tapping station model. In two of eight apartments measured indoor-air temperatures were available and served as additional input parameters to simulate the storage tank losses and air-source temperatures. Measured operation power of the CHPS for compressor, ventilation and backup heating have been checked for accordance with technical specifications (Table 2). For model validation, the on/off signals for the heat pump compressor, the electric power consumption for the ventilator and the additional heater have been derived from measured data.

In addition, the specific built-in bypass was implemented which enables the system to optimize the air-control and to switch between outdoor and indoor-air-source during the operating modus. Based on measured data, simulations and simulation data analysis focused on the characteristic months for summer and winter in the south of Germany to reveal seasonal differences.

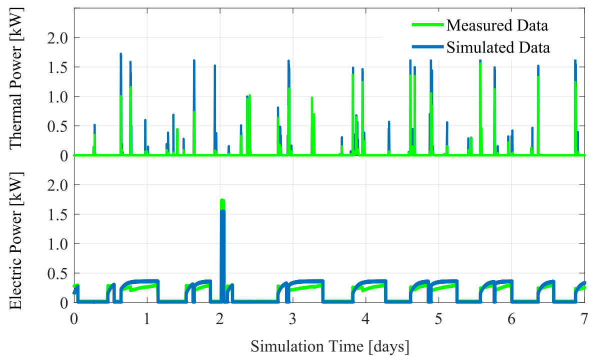

Figure 7: Simulated and Measured Thermal Power ($\dot{Q}_{ref}$) and Electric Power (P_{elec}) for sample CHPS.

Table 3: Simulation Results - Absolute Deviations

	Dec-15		Jul-16	
CHPS	Q_{ref}	Q_{elec}	Q_{ref}	Q_{elec}
1	—	10.86	2.78	7.19
2	14.58	8.68	7.02	1.36
3	4.76	-12.22	1.82	-3.12
4	17.03	0.56	14.36	6.07
5	34.76	3.35	19.69	6.41
6	11.00	2.65	5.35	3.01
7	19.96	5.36	12.51	2.92
8	-3.45	12.3	11.53	1.76
	Absolute Mean Deviation			
[kWh]	14.09	3.94	9.38	3.20

Results and Discussion

Simulation Results

As mentioned before, heat exchange features from testing conditions are imperative to model the stratification and recovery behavior of the storage tank properly; especially for adjusting the heat exchanger model in detail. Spur et al. (2006b) for example verified behavioral differences between storage types (one stratified, two non-stratified pipe systems, $V = 180$ l) with vast measurements. The storage performance or effectiveness of the two analyzed and non-stratified systems varied between 10 % and 32 % under identical testing conditions ($t_{\text{cw}} = 10\,°\text{C}$ and $t_{\text{dhw}} = 45\,°\text{C}$). Knudsen (2002) quantified performance losses from stratification up to 23 %. Any performance information was not accessible for this study and specific storage type. Apart from possible measurement errors this circumstance implies additional uncertainty when measured and simulated performance results are compared. In general, minute-wise monitoring data is recommended for DHW simulation purposes with regard to time scaling (Jordan and Vajen, 2001) and was realized for heat and energy metering. Hence, the simulation results for thermal and electric power illustrate similar curve characteristics (Figure 7) but especially peak demands for tapping events (Q_{ref}) are not reproduced correctly for given tapping signals. Simulated values for Q_{ref} showed positive deviations of 9-14 kWh from measured data of Q_{ref} for nearly all CHPS (Table 3) with gradual differences.

During the validation process measurement inaccuracies from heat meter data were identified prior to these thermal deviations: The heat meter resolution for Q_{ref} and $\dot{V}$ turned out to be significantly lower ($Q_{\text{ref, min}} = 1000$ Wh, $\dot{V}_{\text{min}} = 0.01\ \text{m}^3/\text{h}$) than the energy meter resolution. The former is leading to deviations between measured and simulated thermal energy since minor draw-off's (e.g. handwashing, etc. with $\dot{V} < 0.01\ \text{m}^3/\text{h}$ or $\dot{Q}_{\text{ref}} < 406$ W with $\Delta t = 35$ K) are out of logging range. Comparative integration for Q_{ref} of measured power data (P_{elec}) from the same counter module resulted in monthly deviations of +14-15 %. This percentage may approximately account for the share of unrecorded tapping volumes as the monitored thermal energy data from the heat meters shows positive deviations in the range of 14 % and 17 % per month compared to simulation results (Table 4, Figure 7).

Table 4: Simulation Results - Relative Deviations

	Dec-15		Jul-16	
CHPS	Q_{ref}	Q_{elec}	Q_{ref}	Q_{elec}
1	—	0.20	0.07	0.16
2	0.30	0.15	0.20	0.04
3	0.03	-0.13	0.02	-0.05
4	0.11	0.01	0.12	0.09
5	0.24	0.05	0.27	0.12
6	0.18	0.05	0.16	0.08
7	0.32	0.09	0.18	0.05
8	-0.01	0.11	0.08	0.02
	Relative Mean Deviation			
[-]	0.17	0.07	0.14	0.06

Study results of Marini et al. (2015) depicted similar efficiency deviations around + 14 % to + 22 % when comparing simulated and measured data even though these do not explicitly address measurement errors. It is assumed that measurement constraints are the distorting cause of thermal deviations. This hypothesis is supported by the fact that influences on remarkable low DHW consumption and on strongly fluctuating tapping seem particularly high (e.g. CHPS 2: relative deviation: 0.20 and 0.30; mean V (liter) per day: 41 l; normative variation coefficient: 7.41 %). As for electric metering, the average deviation results of 6-7 % or up to 4 kWh of electric energy consumption per month and CHPS seems of negligible importance for the overall building energy performance.

System Performance

Based on the analyzed monthly data, the targeted minimum coefficient of performance of 2.3 (DIN EN 15450, 2007) has been achieved by four out of eight

CHPS in summer and by five in winter months (Table 6). At first sight, the relationship between low DHW consumption and minor performance factors seems contradictory, although simulation results verify these case-sensitive findings. On a closer look, the calculated performance factors show distinct variations and linear dependencies between the DHW consumption of the duration of tapping and loading cycles (time-ratio in Figure 5). Similar correlations can be stated compared to Table 6: For the monitored period CHPS No. 2 marks the leading system with the highest normalized variation coefficients (7.41 %), but at the same time the one with the lowest average DHW consumption per day (< 50 liter) and with the poorest seasonal performance factors ($PF_{(1)}$ < 2.0). Proper dimensioning of the installed CHPS components for different DHW consumption profiles are therefore put in question.

Storage Sizing

CHPS storage tanks were thus subject of investigations since measured values for tapping volumes were frequently found to be considerably lower than the nominal storage content (< 200 liter) has to offer. For this reason, storage tanks are suspected to be partly over-dimensioned considering actual and seasonal fluctuating DHW consumptions (Table 6). Similar findings can be found in related research of (Knudsen, 2002) that assume common storage tanks of 200 - 300 liter to be oversized for typical DHW consumption.

With reference to DIN EN 15450 (2007), the nominal storage tank volume V_{ref} is estimated respectively (Equation 9) with $c_w = 0.001163\ kWh/(kgK)$ and $t_s - t_{cw}$ =35°C for the temperature difference between cold water inlet temperature and the set value of the storage tank.

$$V_{ref} = \frac{Q_{Ref}}{c_w(t_s - t_{cw})}. \tag{9}$$

According to Equation 9, the values $V_{(0,1,\max)}$ for maximum Q_{Ref} are calculated and weighed with an additional weighing factor of $f = 1.15$ to consider stratification inside the tank. From the monitored CHPS and tapping cycles it can be concluded that actual storage tank volumes (CHPS 1, 3, 4, 5, 7) are oversized due to the maximum of measured DHW consumption and calculated sizes $V_{\text{ref, max}}$ (Table 5). Specifications for daily transmission losses are listed by value with 1.13 kWh/day (Table 2) that account approximately for 10 % of the maximally usable thermal energy of the fully loaded storage tank. The energy share of thermal losses affects therefore notably the system performance of minor consumption profiles.

Summary

- Preliminary data analyses carried out that the assigned and standardized load profile 'L' of DIN prEN 16147 (2015) overestimates the daily DHW energy consumption of the eight CHPS (Figure 2).

Table 5: Maximum DHW Consumption per day

	Dec-15	Jul-16
CHPS	$V_{ref,max}$	$V_{ref,max}$
1	—	**147**
2	359	150
3	165	**75**
4	187	**88**
5	**115**	**19**
6	175	271
7	**68**	**118**
8	173	327

- Analyzed mean performance factors $PF_{(0,1)}$ varied in the range of 1.90 - 2.84 for different CHPS (Table 6). Seasonal differences in DHW consumption were observed and showed in average a higher mean DHW demand in winter ($V_{(0,1)}$ = +27 %) and an equally higher system performance ($PF_{(0,1)}$ = +3%) than in summer. Climate-specific dependencies between outdoor-air or indoor-air on the system performance could not be confirmed by measured data for this specific CHPS (Figure 5).
- Fluctuating DHW consumption characteristics between the CHPS were described with normalized variation coefficients. Higher CHPS performance factors hinted to lower normalized variation coefficients and higher DHW consumption (Table 6).
- The outlined simulation model was validated by measured data. Results show higher deviations for thermal energy (Table 4: +17 % and +14 %) than for electric energy output (+7 % and +6 %).
- Deviations between simulation and measurement data had to be accepted due to missing parameters for stratification characteristics of the storage tank and due to measurement deficiencies of heat meter (flow meter) resolution. Spur et al. (2006a) outlined a specific influence on the storage performance from event-time and number of draw-off's, from duration of draw-off's and flowrates; these effects could not be further investigated for the study at hand but should be considered for general measurement setup in future research.
- The investigated storage tank volume of 200 liter was found to be partly oversized compared to measured peak demands of thermal energy Q_{ref} and calculated normative demands $V_{\text{ref,max}}$. For the measured mean DHW consumption of 30 - 160 liter per day it seems advisable to reconsider smaller storage sizes to enhance the thermal performance of the system.

Conclusion

This study presents a comprehensive approach, providing a thorough understanding of the CHPS where the obtained results are highlighting the case-sensitive energy performance and the limitations for the system's efficiency. The data-mining results presented in this paper are considered to be of sufficient reliability. Stratification data and sufficient measurement calibration and resolution are assumed to be crucial to enhance validation of CHPS simulation models. Evidence is provided that proper dimensioning (storage tank) and timing is essential to run the coupled system of heat pump and storage tank efficiently: Data evaluation revealed a causal relationship between minor DHW consumption, over-sizing of storage tanks and the monitored low system efficiency. Standardized load profiles overestimated the measured DHW demands. The obtained research results verified user-dependent consumption data as the restricting parameter in terms of energy efficiency and operational boundaries for the CHPS. The targeted minimum coefficient of performance of 2.3 (DIN EN 15450, 2007) for air-source DHW heat pumps was found to be mainly dependent on measured DHW tapping volumes and on storage tank losses because of minor consumption. With regard to storage tank volumes and daily consumption profiles, it can be concluded that an efficient system operation is limited due to proper pre-dimensioning and strongly depends on daily and fluctuating tapping volumes in the use-case (Figure 2).

In the latter case, this requires knowledge of realistic consumption profiles which vary on account of seasonal and behavioral patterns. Reviewing the fluctuating nature of DHW consumption and actual standardization, a probabilistic modelling approach of occupant's DHW consumption behavior should be considered to improve building energy calculations as already proposed in past research (Jordan and Vajen, 2001). The obtained simulation model can hereby support future estimations of DHW energy demand when coupled with propabilistic DHW consumption models.

Advanced strategies that are able to cope with the consumption sensitiveness of CHPS could also apply heuristic or machine learning approaches that are based on consolidated consumption scenarios.

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Nomenclature

	Parameters Electric Meter
Q_{elec}	Electric energy, kWh
P_{elec}	Electric power, W
	Parameters Heat Meter
Q_{ref}	Reference (thermal) energy, kWh
$\dot{Q}_{\mathrm{ref}}$	Reference (thermal) power, W
$T_{\mathrm{in\ /\ out}}$	Tapping temperatures, °C
$V_{(0,1)}$, $\dot{V}$	Tapping volume (flow), l
	Weather Parameters
$T_{\mathrm{in\text{-}/outdoor}}$	Measured wet bulb temperatures, °C
$RH_{\mathrm{in\text{-}/outdoor}}$	Measured relative humidity, %
$\dot{Q}_{\mathrm{in}}$	Thermal energy flow cold side, W
$\dot{Q}_{\mathrm{out}}$	Thermal energy flow hot side, W
Q_{hx}	Exchanged thermal energy, W
Q_{losses}	Thermal loss flow, W
q	Heat flow, J/s
ε	Heat exchange efficiency
$\dot{V}_{\mathrm{air}}$	Air flow, m^3/h
$T_{hot,in}$	Heat exchange temperature hot side, °C
$T_{cold,in}$	Heat exchange temperature cold side, °C
t_s	Set temperature storage tank, °C
t_{cw}	Set temperature cold water inlet, °C
Δt	Temperature difference, K
ΔH	Enthalpie difference, J/(kg K)
c_p	Specific heat capacity, J/(kg K)
c_w	Specific heat capacity (water), kW h/(kg K)
ρ	Density, kg/m^3
$\dot{m}_r$	Mass flow, kg/s

Tables

Table 6: DHW Consumption - Statistics

CHPS	1	2	3	4	5	6	7	8	**1-8**
49 weeks monitoring									
Mean V (liter) per day	47.44	40.58	125.91	111.12	86.58	33.27	69.02	163.57	677.49
Variation Coefficient	0.88	1.36	0.53	0.57	0.71	0.96	0.51	0.41	0.26
norm. Variation Coefficient	4.80 %	7.41 %	2.89 %	3.08 %	3.88 %	5.24 %	2.78 %	2.26 %	1.40 %
Standard Error	2.27	3.00	3.63	3.42	3.35	1.74	1.92	3.69	9.44
Dec-15									
Mean $PF_{(1)}$	–*	2.03	2.82	2.43	2.44	1.99	2.28	2.84	2.41
Mean $PF_{(0,1)}$	–*	1.68	2.41	2.10	2.15	1.75	1.70	2.59	2.05
Mean $V_{(0,1)}$	18.66	62.85	91.24	74.37	60.63	47.77	34.58	102.05	61.52
Variation Coefficient $V_{(0,1)}$	0.71	0.99	1.30	0.97	1.16	0.93	1.54	1.30	—
Variation Coefficient $PF_{(1)}$	–*	1.69	3.92	2.62	2.90	2.11	2.49	3.85	—
Standard Error $PF_{(1)}$	–*	0.29	0.11	0.14	0.12	0.18	0.15	0.11	—
Jul-16									
Mean $PF_{(1)}$	1.99	1.95	2.94	2.62	2.21	1.90	2.38	2.73	2.34
Mean $PF_{(0,1)}$	1.49	1.52	2.67	2.24	1.79	1.61	1.87	2.37	1.95
Mean $V_{(0,1)}$	29.53	33.01	77.75	63.35	43.47	29.76	37.77	71.80	48.30
Variation Coefficient $V_{(0,1)}$	1.27	1.26	0.86	1.64	1.42	0.90	1.79	1.33	—
Variation Coefficient $PF_{(1)}$	2.04	2.03	4.27	3.30	2.35	2.09	2.67	3.43	—
Standard Error $PF_{(1)}$	0.16	0.22	0.11	0.13	0.17	0.17	0.15	0.13	—

* missing data due to measurement failures