EFFICIENCY OF SANITARY HOT WATER HEAT PUMPS BASED ON A FIELD TEST

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Abstract

Following a general European trend, sanitary hot water heat pumps (SHW) become more and more popular. In Switzerland in 2015 4919 sanitary hot water heat pumps have been sold at a 2014 to 2015 rate of growth of 14.9 % [1].

In order to gain knowledge about real field performance of SHWs, the Swiss Federal Office of Energy is funding a field trail of five heat pumps installed in single family houses. The assessed units are typical compact units having a condenser installed inside the 300 l storage tank, using inside room air as heat source.

The measurement system is designed for collecting precise and detailed information in a temporal high resolution.

The study aims at an evaluation of the overall efficiency of SHWs based on field trail data. The detailed analysis comprise the influences of the user behavior such as tapping and setting temperatures as well as of the manufactures concepts regarding the layout and the controller concept.

Keywords: heat pump boilers, efficiency, field test, sanitary hot water

1. Introduction and motivation

In Switzerland, especially during the 1970 and 1980 years electrical driven sanitary hot water boilers have been installed in single family dwellings. These boilers have now reached the end of their lifetime. For new single family dwellings it is prohibited by law to install a conventional electric driven water boiler. Therefore there is a need for a new technology substituting the boilers. One of those technologies is the sanitary hot water heat pump (SHW). The units comprise an air-sourced heat pump, an electric auxiliary heater and a storage tank. In the units available on the Swiss and German market the storage size ranges from 200 l to 300 l [2] at almost all of the products.

In Switzerland support programs for the replacement of a conventional electric water heater by a SHW have been implemented under the Swiss competitive tenders for electricity savings scheme called ProKilowatt. The program offers a fixed financial support per unit installed. A former field study [3] has shown that the performance of the SHW given in data sheets cannot be reached under real field operation conditions.

In order to gain a more detailed knowledge about the real field performance of SHWs and the influencing factors, the Swiss Federal Office of Energy is funding a new field trail of five SHWs installed in single family dwellings. The new field test applies more sensors with a higher accuracy and an automated data collection system to prove or disprove the findings of the first field test.

2. Description of the SHW units and the monitoring concept

2.1. The units

The selection of the types and manufacturers of the SHW to be measured in the field test has been done according to their presence within the Swiss support program. Only models which appear in the program more than ten times have been selected. A second demand for the selected SHW is that they have been installed since the year 2014.

The SHW are located in single family houses and provide hot water for a number of two up to four occupants. The units are installed in the basement of the buildings and use inside room air as a heat source.

The structure of these units is quite similar, see **Fout! Verwijzingsbron niet gevonden.**. There is an insulated water storage tank with a diameter of approx. 600 mm, a height of approx. 1400 mm and a storage capacity of approx. 300 l. The cold feed water inlet is connected at the lower level and the hot water outlet at the upper level of the storage tank. None of the installations has a circulation system. The SHWs are equipped with an electrical driven auxiliary heater which is installed in the middle part of the storage tank. On top of the storage tank, the heat pump unit is mounted. All five assessed units are direct condensing heat pumps. The condenser is located on the inner surface of the storage tank at the bottom third. As refrigerant R 134a is used in all units. In Table 1 the technical data of the units are given.

At the building, where unit 5 is installed, a photovoltaic system is available. The control strategy of the SHW aims to increase the self-consumption of PV energy. When the photovoltaic system provides a certain power level, the temperature set value of the SHW is increased by 10 K. This leads to longer compressor operating hours and a much higher share of auxiliary heater usage. The evaluation presented in this article focuses on the evaluation of SHWs, which are not influenced by PV-oriented control concepts. The study comprises the measuring period from 1st July 2016 until October 31st at the units 1 – 4.

2.2. The monitoring concept

The measurement system is designed for collecting precise and detailed information in a temporal high resolution (5sec). The sensor data is written in a daily file which is send to the analysation server via UMTS once a day. The electrical energy consumption of the SHW and its main components is measured by electricity meters. The electricity meters have a S0-interface with a resolution of 10 pulses per Wh; the accuracy is class B (2 % of reading). The thermal energy of the tapped water is measured by a heat meter equipped with an inductive flow meter and two Pt500 temperature sensors. The flow meter has a resolution of 200 impulses per 1 l and an accuracy of 0.5 % of reading. Below a volume flow of 0.04 l/s the accuracy increases. The temperature sensors are mounted within ball valves, so the sensors are penetrating the water inside the pipe. The temperature sensors are PT500, class B, paired with Δt_{max} 0.15 K.

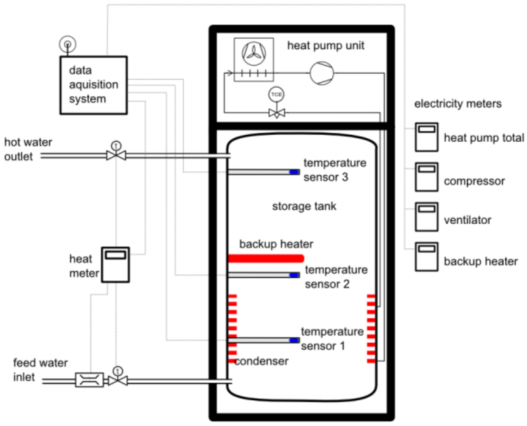

Fig. 1. Layout of a SHW and the monitoring concepts

Additionally temperature sensors (PT100) have been installed at the storage tank of the SHW. The position of these sensors is determined by the position of the sensor for the SHW controller. For this reason the sensor position varies from unit to unit. At unit 1, 2, and 3 there are two immersion pockets available; one in the bottom third and one in the middle or top third. The monitoring sensors are installed alongside the controller sensor or solo. At unit 4 the temperature sensors have been mounted at the surface of the storage tank, also at the same level as the ones the controller uses. At unit 2 and 3 an additional third temperature sensor has been mounted at the surface of the tank at the level of the auxiliary heater. In Table 1 the position of the sensors at the four units are given. The temperature and the humidity of the air inside the room where the SHW is located are measured with a combined temperature and humidity sensor.

Table 1. Technical data of the assessed SHW / number of occupants

	Unit 1	Unit 2	Unit 3	Unit 4
Number of occupants	4	3	2	2
Volume of the storage tank	285 l	308 l	270 l	295 l
Position of aux. heater (volume above)	~ 121 l (58 % of $V_{storage}$)	~ 184 l (60 % of $V_{storage}$)	~ 125 l (46 % of $V_{storage}$)	~ 186 l (63 % of $V_{storage}$)

power of auxilary heater	1.5 kW	1.5 kW	1.8 kW	1.5 kW
thermal power / COP of heat pump	1.66 kW / 3.2	1.7 kW / 3.11	1.7 kW / 2.94	3.1 kW / 2.9
applied tapping profile	EN 255, A15/W15-45	EN 16147, XL, A15/W10-55	na	EN 16147, XL, A15/W10-55
temperature sensors at the storage for monitoring (in percentage of high above bottom)	~ 15 %, 58 %	~ 10 %, 54 %, 93 %	~ 16 %, 41 %, 62 %	~ 29 %, 78 %

3. Demand of domestic hot water

Before focusing on the heat pump and the storage tank, this study takes a closer look on the demand side of the SHW. The following Fig 2 shows the daily tapping of hot water plotted as a histogram during the measurement period of 123 days. The binwidth has been chosen to 10 liters. When there hasn't been any tapping at all the respective day is included in the first bin (0 l/d to 10 l/d). The maximum daily tapping of hot water ranges between 110 l/d at unit 4 to 290 l/d at unit 1.

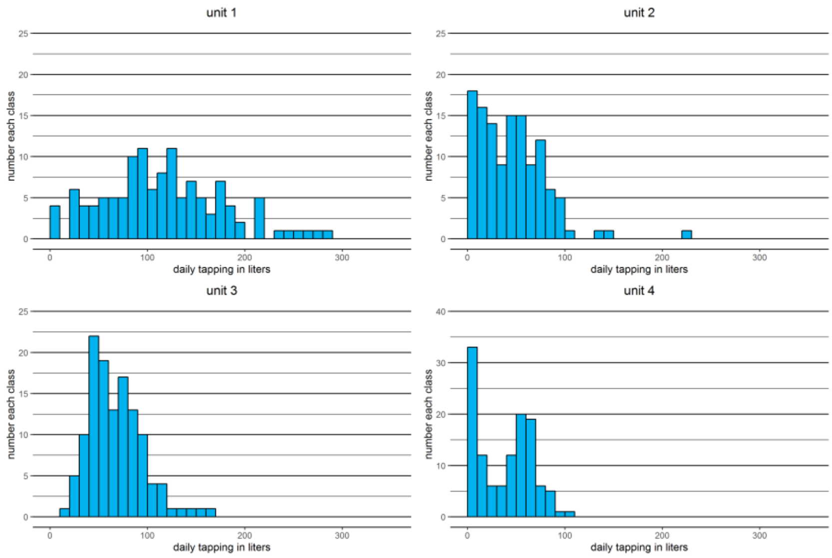

Fig 2. daily tapping of domestic hot water

At unit 1 there is a normal distribution with its mean at around 100 l/d, which occurred at 11 days. At unit 2 most of the daily tapping volume is smaller than 100 l, only 4 times daily tappings larger than 100 l/d occurred. Unit 3 again shows a normal distribution wit a mean value of about 50 l/d, which had been present at 22 days. At unit 4 all daily tappings have been less than 110 l/d. A [...] 10) tappings (0 l/d to 10 l/d). Hence, at all units besides unit 1 for most of the [...] ater accounts for one third of the storage volume at the most.

At test facilities the efficiency of sanitary hot water heat pumps is measured among the regulations of EN 16411 [4]. The standard provides several load profiles for the test procedure. The totalized amount of energy which has to be tapped during a load profile is given in the following table.

Table 2. Totalized energy according to DIN EN 16147 load profiles [4]

tapping profile	3XS	S	M	L	XL
totalized energy	0.345 kWh	2.1 kWh	5.845 kWh	11.655 kWh	19.7 kWh

For comparing the daily energy demand of the monitored SHWs to the load profiles according to EN 16147 the following classification has been done. The first class is from 0 to 0.7 kWh, the second one from 0.8 to 1.2 kWh, which represents an energy demand of the order of load profile 3XS. The third class is from 0.13 to 3.9 kWh (of the order of class S), 4.0 to 8.7 kWh (of the order of class M), and 8.8 to 15.4 kWh (of the order of class L). The following Fig 3 shows the number of days on which the energy demand has been in the respective class.

The energy demand at unit 1 mostly ranges in class S (41 %) and M (43%). It is the only unit, where - on 9 days (7%) - the energy demand reaches to class L. The energy demand at unit 2 is mostly within class S (56 %) with some

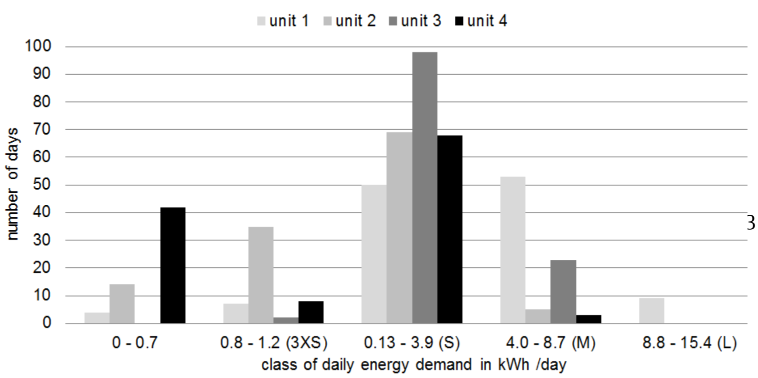

Fig 3 daily energy demand

exceptions in class 0 (11 %), 3XS (28 %) and M (4%). The energy demand at unit 3 is mostly in class S (80 %) as well; class M has a share of 18 %. At unit 4 there are two peaks. Most of the days, there is an energy demand according to class S (56 %). Class 0 has a share of 35 %. These are also those days where there was no energy demand according to the absence of the occupants.

The following shows the mean cold feed water temperatures and the hot water outlet temperature at the end of each tapping plotted as a histogram. For small tappings, the measured temperature is strongly influenced by the temperature of the water which is in the pipe when there is no tapping. For this reason tappings smaller than two liters have not been considered in this plot. The mean values for the cold feed water temperatures range from 17.4 °C to 18.8 °C at the four units. All units show a normal distribution. The feed water temperature is strongly influenced by the length of the tapping. The longer the tapping the colder the feed water temperature gets. The minimum value at the four units ranges from 11.7 to 13.7 °C. Due to the short measurement period of 123 days the seasonal impact on the feed water temperature could not be investigated yet.

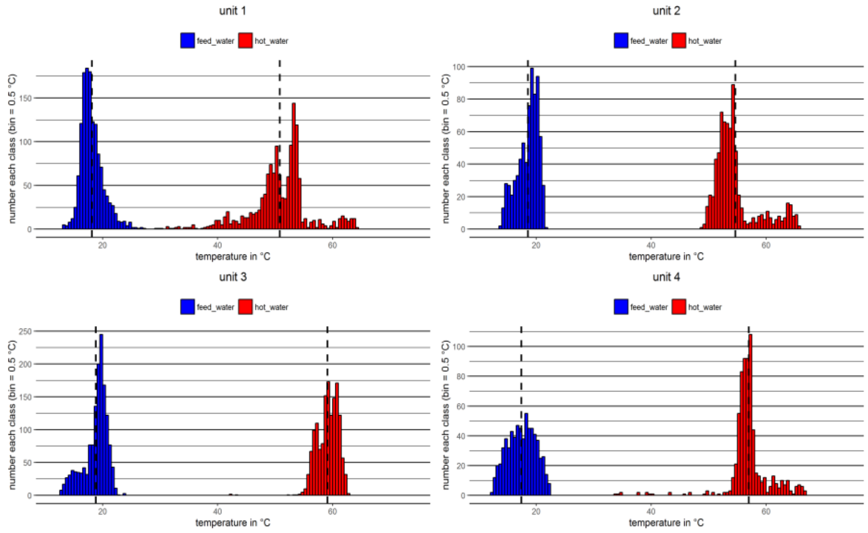

Fig. 4 temperature of feed and tapped water

The hot water temperatures at the end of each tapping show a much wider spread than the feed water temperatures at all of the units. At unit 1 the hot water temperatures reaches from 29.3 °C to 64.3 °C. The temperatures above 55 °C are caused by tappings which have been done after or while the storage tank was heated up due to legionella mode (see chapter 5.3). Temperatures below 48 °C are due to a higher amount of tapped water during times of the day, when the setback mode is active and therefor the HP disabled (see chapter 5.1). At 12 % of the tappings the end-temperature was below 45 °C, at 4 % it was below 40 °C.

At unit 2 the tapping-end temperature ranges between 48.5 °C and 65.7 °C. Once again, temperatures above 55 °C arise due to the weekly activated legionella mode. The units is providing DHW warmer than 45 °C all the time. At unit 3 the tapping-end temperature reaches from 42.1 °C to 66.2 °C and at unit 4 the temperature reaches from 33.9 °C to 67.0 °C. At unit 4 there have been twelve tappings (1.75 %) where the end-temperature was below 45 °C. All these tappings have been done during two days, where the HP was cut off due to a malfunction at the electricity mains.

4. Air conditions in installation room

The condition of the air in the installation room has been measured with a temperature and a humidity sensor. For the most part, the daily average temperatures range between 19 °C and 23 °C. Due to spatial conditions in the installation rooms, it has not been possible to place the sensors at all units in the same way. At unit 1 the sensor measures the condition of the intake air. At unit 2, 3 and 4 the sensor is located near the exhaust of the SHW. The installation rooms are of different size and structure and they all have a window to the outside of the building. The status of the window has not been monitored. At unit 1 an average reduction of the inside room temperature of 1.5 K could be detected. At unit 2, unit 3 and unit 4 the temperature drops by 8 K while the compressor is running. A significant reduction of the inside relative air humidity in general cannot be stated.

5. Operating characteristics

The four different units come along with different approaches in respect to the operating concept for the heat pump and the auxiliary heater. In particular concerning the following aspects the units partly differ one from the other:

- position of temperature sensor used for control
- set value for HP, potentially varying during the time of the day
- hysteresis for HP
- position of auxiliary heater
- concept of anti-legionella mode
- concept of auxiliary heater control (besides anti-legionella mode)

All aspects are influencing the efficiency of the system as well as the user comfort. Firstly the share of thermal energy provided by the auxiliary heater has a strong impact on the efficiency of the system. Secondly the temperature at the condenser is affected and consequently the COP of the heat pump. In addition the temperature in the storage tank is crucial for the amount of storage losses.
Table 3 lists up key parameters of the four units and in the following sections the characteristics of the units' operation condition and efficiency will be elaborated.

Table 3. Control key parameters of the units

	Unit 1	Unit 2	Unit 3	Unit 4
Sensor for HP control (in percentage of high above bottom)	~ 15%	~ 63%	~ 10%	~ 29%
Standard mode (time frame set value & hysteresis)	8:40 – 15:40 (1) 53 °C – 5 K	22:00 – 7:00 55 °C – 4 K	21:15 – ~ 4:00 (2) 54 °C (3) – x K (4)	throughout 54 °C (3) – ~5 K (6)
Setback mode	HP off (5)	48°C – 4K	HP off (5)	-
Position of aux. heater (volume above)	~ 121 L (58 % of $V_{storage}$)	~ 184 L (60 % of $V_{storage}$)	~ 125 L (46 % of $V_{storage}$)	~ 186 L (63 % of $V_{storage}$)
Anti-legionella mode	65 °C; once a week	65 °C; once a week	off	66.6 °C (3); once a week
Auxiliary heater (besides anti-legionella mode)	disabled	enabled	enabled	na

(Notes: (1): settings changed during monitoring period but always midmorning until early afternoon, see figure Fig 5; (2): exact time setting not know, seems to be in the very early morning, somehow between 3:00 and 5:00; (3): setting not known, value/info according to monitoring; (4):settings not know and could not be derived from the measurement data; (5) setting not known; according to the monitoring data HP disabled or very low set value <20°C; (5) setting not known; assumption according to measurements)

5.1. Operating characteristics of the HP

At three of the four units, the temperature set value for operating the heat pump is not fixed all day long. There is a daily time frame enabling the standard operating mode of the system (see Table 3). In the remaining time of the day, the setback mode is enabled. During setback mode the temperature set value is either reduced or the heat pump is even deactivated. By the way of contrast, at unit 4 the standard mode is applied all day long.

In figure **Fout! Verwijzingsbron niet gevonden.**Fig 5 the daily course of the operation time of the four heat pumps is shown resulting from the different approaches. At unit 1 the standard mode is activated during daytime, in particular from midmorning until early afternoon, the remaining time of the day the setback mode deactivates the HP. At unit 2 and unit 3, the standard mode is activated during night time, e.g. in order to benefit from the lower electricity prices within night tariff.

Fig 5. Operation of the heat pump and the auxiliary heater during the evaluation period July – November 2016

The setback mode reduces the temperature set value by 7 K at unit 2 and deactivates the heat pump at unit 3. Mostly, the three units operate once a day for 1.5 h to 5 h (in few exceptional cases longer or shorter) depending on the amount of tapped water (see details further below). At unit 1 (standard mode during daytime) at one fourth of the days the HP runs a second time during the standard operation mode, when the temperature at the control sensor TS1_15 % falls below the hysteresis (5 K). In these cases, the duration of the operation lasts from a couple of minutes (in cases, when the end of the standard mode time frame limits the operation) up to 2 h. Both of the units, at which the standard mode is enabled during night time, does not (unit 3) or only very seldom (unit 2) a second time during the standard mode time frame. At unit 3 this time frame ends before tapping in the morning occurs. At unit 2, where the time frame ends at 7:00, the position of the control sensor (above the middle of the storage) brings about, that the HP does normally not start due to the tapping in the morning.

At unit 4, there is a different operation characteristic of the HP in comparison to the above mentioned three units. The heat pump operates two or three times a day for about 1 h, except for days with low tapping volume or with increased storage temperature due to anti-legionella mode. This is for the following two reasons. For one thing, there is no setback mode applied; the standard temperature value is applied all day long. For another thing, the control sensor is located at the bottom third (TS1_29 %). The HP starts at least after 30 l has been tapped.

Fig 6 gives a deeper inside on the single HP cycles. Separately for each unit, the duration of each HP operation phase (right y-axis) is given in relation to the amount of water, which has been tapped since the end of the last HP operation and is possibly partly tapped still while the current HP operation. For example, if there has been a tapping of 100 l since the end of the last HP operation, the operation time of the HPs amounts to 3.5 h … 4 h.

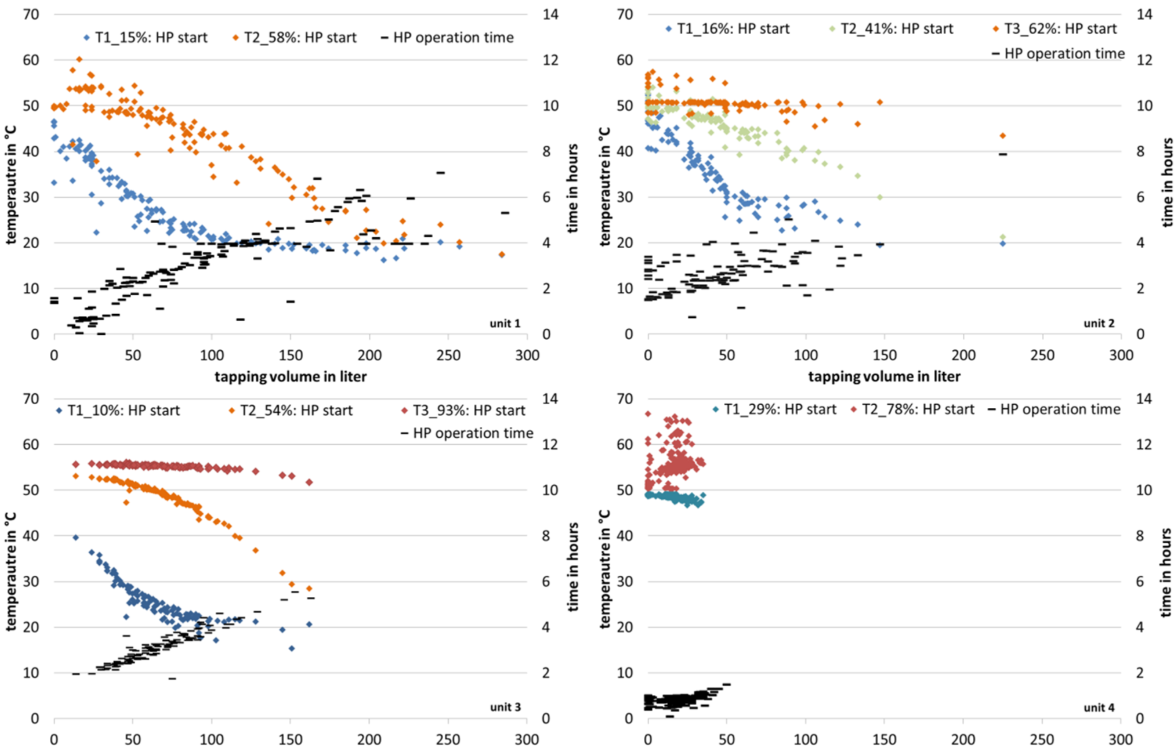

Fig 6. Storage temperature at different levels at the beginning of the heat pump operation (left axis), operation time of the heat pump (right axis) related to the amount of water tapped since the end of the previous heat pump operation until current HP start

In addition this figure displays the temperature at different levels of the storage tank at the beginning of each HP operation (left y-axis). The temperature is related to the amount of water, which has been tapped since the end of the last HP operation and before the beginning of the current one. The time period with setback mode implies that the temperature in the bottom and the middle part of the storage tank can drops quite far; depending on the amount of water has been tapped in this period. As a consequence, the HP operates at least for the first part of the operation time at favourable low temperatures. For example: At unit 1 the temperature ranges between 20 °C at the bottom (TS1_15 %) and 45 °C in the middle (TS2_58 %), if 100 l has been tapped since the last HP operation. Naturally, if even larger amounts have been tapped the temperatures in the middle and top drops further. Consequently, at the end of the setback period the temperature of the tapped water might be below 40°C (see chapter 3). This arises at some tappings in the morning. The risk of losing comfort could be avoided by starting the standard mode one or two hours earlier. A second reason for low tapping water temperatures at the end of setback mode periods with a large amount of tapped water was the shortening of the standard mode time frame from 7 h to 4 h at the beginning of October. The time span in which the HP is enabled has not been long enough to increase the storage temperature up to the applied set value. Consequently the useful storage capacity has been reduced.
At unit 2 and unit 3 the characteristic of the measured storage temperature is similar. However, the temperature in the top part never falls below a comfort level, because the amount of tapped water during the setback periods (and in general the daily amount of tapped water) is not as high as it is at unit 1 at some instances.
As consequence of the deviating control concept, the characteristic at unit 4 differs significantly from the other. As explained above, the HP starts each time the temperature at the bottom of the storage (TS1_29 %) falls by about 5 Kelvin below the standard set value. Therefore the temperature at TS1_29 % is always about 47.5 °C to 49.0 °C, at the beginning of the HP operation. Consequently the HP does not have the opportunity to start with low temperatures at the condenser, when heating up the water.

5.2. Efficiency and storage losses

In this section, the efficiency of the unit is evaluated in respect of the influence of the storages losses. The evaluation method is described and exemplarily the analysis of unit 1 is presented.

When evaluating the efficiency of a system which comprises a storage tank in the balance boundary, the temperature in the storage (state of charge, SOC) at the beginning and the end of the evaluation period has to be taken into account. For long evaluation periods, the difference of the SOC might be insignificant compared to the used energy. Here, the dependency of the efficiency on the amount of tapped water is in the focus of consideration. Therefore, short term periods have been evaluated using the following approach. The chosen evaluation periods fulfill the following criterion:

- Duration: 23 …25 h. This criterion is chosen in order to avoid a significant influence of varying heat losses due to varying time periods.
- Beginning and end: The period lasts from the end of a heat pump operation period until next end of heat pump operation period. This criterion is chosen in order to have a similar stratification in the storage and less uncertainty in the estimation of the storage temperature based on the two (three) temperature sensors mounted in the storage.
- SOC: The temperature at the beginning and the end of the evaluation period should not differ by more than 0.5 K.

In Fig 7, the efficiency $COP_{unit,cycle}$ (filled mark) of the chosen evaluation cycles (see criterion above) is given in relation to the amount of water tapped during this cycle. The expected correlation of efficiency and amount of tapped water is obvious. For unit 1 as for example, $COP_{unit,cycle}$ is about 2.5 when the tapping in the respective period amounts to 5.0 kWh/cycle. If only 2.0 kWh/cycle water has been tapped, the $COP_{unit,cycle}$ is significantly lower und amounts only to 1.5.

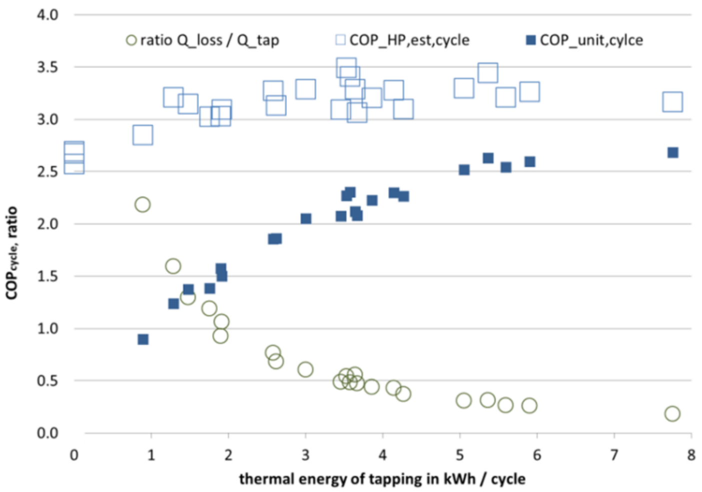

Fig 7. $COP_{unit,cycle}$ and $COP_{HP,est,cycle}$ determined for a heat pump cycle (end of heat pump operation until next end of heat pump operation) for cycles of 23h … 25h without operation of the auxiliary heater

In order to analyse the storage losses of the units, heat pump cycles without any tapping have been evaluated. Two different parameters, the electric stand-by power consumption and the heat loss rate, have been derived.

The electric stand-by power gives the average power consumption of the unit during periods without water being tapped. It comprises both the energy consumption of the heat pump (compressor and fan) to compensate the storage losses and the energy consumption of the controller during this period. For the evaluation period the criterion for the beginning and the end as well as for the SOC are the same as mentioned above.

$$P_{standy-by} = \frac{(E_{compressor}+E_{fan}+E_{controller})}{time_{evaluation}} \tag{1}$$

The heat loss rate is calculated by the decrease of the storage temperature for a period without tapping. The evaluation period starts with the end of a heat pump operation and ends with the beginning of the next one. The chosen evaluation cycle should be the third one after a stand-by period at the earliest. This is for the following reason: In usual operation (tapping, heating up, …) the very bottom of the storage below the condenser is quite cold. In stand-by periods the temperature above this “cold water area”, where the sensor TS1 is positioned, is reduced not only by storage losses but also by an internal heat transfer from the hot water above to the cold water below. Therefore, the calculated heat losses would have been overestimating the real heat losses. After two days in stand-by the temperature gradient in the bottom part is lower.

For calculating the energy content in the storage each temperature sensor a defined share of the storage volume has been assigned to:

$$\dot{q}_{loss} = \frac{[(TS1_{start}-TS1_{end})\times V1+(TS2_{start}-TS2_{end})\times V2]\times c_p\times \rho}{(TS1{,}2_{avg,surf*}-TR_{avg})} \tag{2}$$

With:
$TS1,2_{avg,surf*}$: The average values (average over the evaluation period) of TS1 and TS2 have been weighted by an assigned surface area.
TR_{avg}: The average values (average over the evaluation period) of the room temperature

The storage losses at other operation conditions are calculated by the following formula:

$$\dot{Q}_{loss} = \dot{q}_{loss} \times (TS1{,}2_{surf**} - TR) \quad (3)$$

$TS1,2_{surf**}$: TS1 and TS2 have been weighted by an assigned surface area; using a slightly different allocation method

The values calculated on behalf of the described method just give an estimation for the storage losses. Mainly the following aspects influence the uncertainty of the results. Since only two or three sensors are installed, the knowledge about the temperature is limited. The differences in the insulation at different parts of the storage envelope are not known and could therefore not been taken into account. Furthermore, various influences of microcirculation in the connection pipes could also not been taken into account in detail. If there have been any losses due to these microcirculations during the evaluation period used for calculating the heat loss rate, these losses are comprised in the calculated value for the heat loss rate ($\dot{q}_{loss}$).

Exemplarily, for unit 1 the results of the evaluation of the storage losses are presented. During the evaluation periods (3 cycles in a row, each lasting for 23.9 h) the surface weighted storage temperature ($TS12_{avg,surf*}$) averages to 50.7°C while the room temperature averages to 24.5°C. Under these conditions the electric stand-by losses amounts to 31 W. By the temperature decrease in the storage a heat loss rate of 3.2 W/K is derived. Based on the heat loss rate and the current storage and ambient temperatures, the storage losses throughout the measuring period have been estimated. Therefore the average amount of energy lost due to storage losses might be as high as energy used for DHW at days, when only about 50 l/day have been tapped. For days, when 150l have been tapped the losses might not be more than one fourth compared the used energy.

In addition a notional $COP_{HP,est,cycle}$ has been calculated according to the following formula

$$COP_{HP,est,cycle} = \frac{(Q_{tap} + Q_{loss,est})}{E_{compressor} + E_{fan} + E_{controller}} \quad (4)$$

The $COP_{HP,est,cycle}$ estimates the efficiency of the HP only, in other words using a fictional balance boundary at the heat transfer from condenser to the storage. As mentioned above, the used method for estimating the storage losses comes along with considerable uncertainties. This should be beared in mind when assessing the results shown in Fig 7. The difference between $COP_{unit,cycle}$ (filled rectangular marks) and $COP_{HP,est,cycle}$ (unfilled rectangular marks) illustrates once again the influence of storage losses. $COP_{HP,est,cycle}$ ranges from 3.0 to 3.5; apart from teeny tap capacities. The temperature in the bottom part of the condenser has not dropped very much, when only a small amount of water has been tapped since the last HP operation. Therefore, the efficiency of the HP is lower than in cases, where a larger amount of water has been tapped before starting the HP again.

5.3. Anti-legionella mode

At three of the four units an anti-legionella mode is enabled and the storage is heated up to 65 °C once a week (unit 1 and unit 2) and up to 67.7 °C (unit 4) respectively. The operation concepts differ significantly from one unit to the other. There are three main factors, which are influencing the electric energy consumption in the anti-legionella mode. Firstly there are differences in the temperatures of storage tank when starting up the anti-legionella mode. Secondly the actual volume, which has to be heated up, differs. Furthermore the heating-up might be done (partly) by the heat pump or by the auxiliary heater, solely or in addition.

Unit 1

The anti-legionella mode is activated each Monday at 11:40. At this time, the auxiliary heater starts and heats up the storage to 65 °C. Often (14 times out of 17) the auxiliary heater starts, while the HP is still in operation. This is due to the fact that the HP starts at 8:40 or 9:40 (the beginning of the standard mode time frame) and operates for 2.5 to 5.5 h (see Fig 5). Consequently, the auxiliary heater takes over a share of the HPs operation which results in a reduction of the overall efficiency of the unit. If the HP operation is finished right before the start of the auxiliary heater, the auxiliary heater operates for about 65 min and uses about 1.6 kWh_{el} while heating up the upper part of the storage by approx. 12 K (54 °C to 66 °C). At days when the HP has not finished heating up the storage, the operation time could be many times higher. Considering all 17 days in the evaluation period, the energy consumption of the auxiliary heater amounts twice as high as it would be when an optimized control concept would be applied starting the auxiliary heater instantly and only after the HP has stopped. Assuming that the $COP_{compressor,fan}$ (at the operation conditions while the auxiliary heater partly substituted the HP) averages to 2.7, the $SPF_{evaluation\_period}$ could have been increased by aprox. 6 %. (Note: The assumption of the $COP_{compressor,fan}$ at these conditions is made based on the assessment of the $COP_{compressor,fan}$ during the stand-by period).

Unit 2

At unit 2 the anti-legionella mode is activated once a week at different times of the day. It is activated 7 days and 2 h – 5 h after the last start (in particular cases the period is somehow longer or shorter). At the beginning of the mode, the heat pump as well as the auxiliary heater are in operation; the heat pump starts 2 minutes later than the auxiliary heater. While the auxiliary heater stops at 61 °C (T3_62 %), the heat pump heats up the storage to 65 °C. Due to the HP operation the storage is not heated up in the upper part only - like in the other units - but down below to the position of the condenser. There seems to be no obvious reason that both the auxiliary heater and the heat pump are used in anti-legionella mode in the way they are. The electric heater operates in a temperature range which is served by the heat pump as well, and there is no need for heating up the storage quickly. Once again a possible impact on the energy consumption by using an optimized control is estimated. If the auxiliary heater would not be used in anti-legionella mode the efficiency could have been increased by aprox. 6 %. Here a $COP_{compressor,fan}$ of 2.0 (at the operation conditions while the auxiliary heater partly substituted the HP) is assumed.

Unit 4

At unit 4 the anti-legionella mode is activated each 160 h (6 d and 16 h). The auxiliary heater heats up the storage by 12 K in average to 66.7 °C (TS2_54 %). The HP does not operate at the same time (excepted for two occasions out of the evaluated 17 cases). The energy consumptions ranges from 2.1 kWh to 3.3 kWh, depending on the temperature at the start. Since the same set value for the HP is applied all day long and the bottom sensor is used for the control, the temperature at the beginning of the anti-legionella mode varies only between 51°C and 56 °C. When comparing the anti-legionella mode at unit 4 to the one at unit 1 in cases where there has not been any overlap of anti-legionella mode with the standard HP operation, the electric energy consumption of unit 4 is about 60 % higher than the one of unit 1. This is caused by a different amount of water the auxiliary heater has to heat up (see Table 3). The temperature increase is similar.

5.4. Operation of Auxiliary Heater besides anti-legionella mode

At two of the units (unit 2 and unit 3) the auxiliary heater is in use also beyond the anti-legionella mode.

Unit 2

The auxiliary heater has been activated very seldom beyond the anti-legionella mode: only within four days during the four month lasting evaluation period. It starts in situations when the temperature at TS3_62 % sank (due to heat losses or tapping) by 11 K to 12 K below the HP's set value, while the HP had been already in operation. The auxiliary heater stops when the temperature has been increased to 3 K below the HP's set value. The electric energy consumption amounts to less than 1 % of the unit's total consumption during the evaluation period.

Unit 3

At this unit the auxiliary heater is in operation for a short period of 12 min to 18 min every day. This is for the following reason. The HP operation starts daily at the beginning of the standard mode time frame (21:15). The HP operates for 1.5 h to 5.5 h until the storage is heated up to 54 °C at the bottom (TS1_10 %) and 60 °C at the top (TS3_93 %). The auxiliary heater is activated daily 5 h after the beginning of the standard mode time frame. It heats up the storage tank by 1.7 K in average up to 59.9 °C in the middle (TS2_54 %) and 61.6 °C at the top (TS3_93 %). There is no obvious reason for this control concept. Assuming the operation of the auxiliary heater would have been replaced by the operation of the HP with a $COP_{compressor,fan}$ of 2.0, the $SPF_{evaluation\_period}$ could have been better by 10 %.

5.1. Seasonal performance

In this section the SPF calculated based on the evaluation period of four month is presented and set in the context of the above elaborated influencing factors.

Unit 1

The SPF of unit 1 amounts to 2.0 and thereby performing best among the evaluated systems. The DHW demand of the occupants is with an average value of 116 l/d significantly higher than in the other buildings consequently, the efficiency reducing influence of the storage losses is less than at the other units. However the storage losses are estimated to be about one third in comparison to the tapped DHW energy. A further influencing aspect, which is more favorable at this unit, is the storage temperature. The large amount of tapped hot water in combination with the daily time frame of the setback mode allows the temperature in the bottom and middle part of the storage to decrease significantly. This is on the one hand advantageous for the efficiency of the HP itself and on the other hand for reducing storage losses. The energy demand of the auxiliary heater has a share of 20 % of the overall consumption. The auxiliary heater is partly used for the legionella mode but partly unnecessarily (see section 5.3)

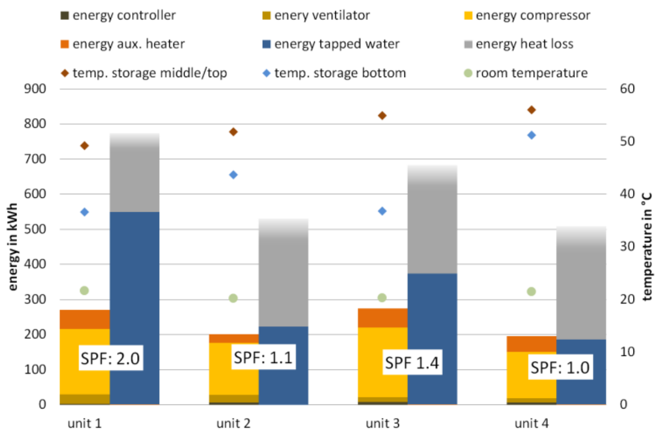

Fig 8. Seasonal performance of the four units, thermal energy and electric energy consumption and average temperatures during the evaluation period of four month

Unit 2

The SPF of unit 2 amounts to 1.1. The lower efficiency compared to unit 1 is due to the much lower DHW demand. The average amount of tapped hot water is 40 % of unit 1 (69 l/day). This results in a high share of storage losses. Assuming the heat loss rate being similar to the one of unit 1 more than half of the thermal energy generated by the heat pump and the auxiliary heater is lost due to storage losses. In addition the smaller amount of water being tapped results in higher overall temperatures in the storage tank, even though the maximum temperature is similar to the one at unit 1. At this unit the share of energy consumed by the auxiliary heater (12% of total energy consumption) is the lowest compared to the other units.

Unit 3

The SPF of unit 3 amounts to 1.4. Here the amount of tapped hot water ranges in between unit 1 and unit 2. The influences on storage losses and storage temperature are accordingly. Besides the different user behavior unit 3 differs from unit 1and 2 in two aspects. Firstly, the storage is heated up about 5 K higher than the others, but secondly no legionella mode is implemented. The first aspect is adverse, the second one is positive for the overall efficiency of the unit. The share of energy consumed by the auxiliary heater equals the one at unit 1 but it is used for no obvious reason.

Unit 4

The SPF of unit 4 amounts to 1.0. The average amount of tapped hot water is slightly smaller than the one at unit 2. This results in the abovementioned detrimental effects on the efficiency of the unit. In addition the deviating concept for the operation of the heat pump (no setback mode period during the course of the day; controller sensor at the bottom of the storage) results in continuously higher temperatures at the bottom part of the storage. The share of energy demand for the auxiliary heater amounts to 23 %.

6. Conclusion

The detailed evaluation of four sanitary hot water heat pumps provides an inside to the operation conditions resulting from the specific layout of the SHW and the SHW controller concept as well as from the respective user behavior.

While the size of the storage tank is similar at all units, the DHW demand differs significantly. The household with the highest DHW consumption (unit 1) uses three times as much as the household with the lowest average DHW consumption. But even at unit 1, the average daily energy consumption ranges between the load profiles M and L of EN 16147. However SHW with a 300 l storages tank are usually tested according to load profile XL, which comprises a tapped amount energy of almost double than L or even four times M. The following fact applies for all water heating technologies including storage tank: Low amounts of tapped water result in a high share of storage losses. In the analyzed systems these losses range from one third to more than the double in comparison to the tapped DHW energy.

Besides by choosing a system with a size of the storage tank meeting the actual demand of DHW of the inhabitants, the installer or inhabitant could influence the efficiency in a positive way by defining appropriate set values. These set values can be reduced for a period of time during the day. This ensures that the desired domestic hot water temperatures can be provided, but it also allows lower temperatures in the bottom part of the storage which affects the efficiency of the heat pump in a positive way. Exceptional high DHW demands could be served by increasing the heating power of the unit by using the auxiliary heater or the extension of the capacity by increasing the storage set value.

The controller concept of some fabricates could be improved by the manufactures by applying simple measures. At three of the units the auxiliary heater partly operates unnecessarily. The starting of the legionella mode could for example be aligned in respect the operation of the heat pump in better way.

In the following process of the project the following aspects will be evaluated:

- Changing the settings of the controller to more promising values, where possible
- Further evaluating the storage losses of the different units
- investigating the storage losses further based on the enlarging measuring period
- Evaluating the impact of the legionella mode

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