Measurement and statistical evaluation of hot water tapping profiles in (non-)residential buildings

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Abstract. For a good design of water heaters, an exact knowledge of the hot water demand and its temporal distribution is required. According to DIN EN 12831-3, cumulative demand profiles must be determined that represent the daily tapping behavior in the building. In addition, knowledge of the simultaneity of tapping events and thus of the maximum tapping capacity is crucial for the use of central instantaneous water heaters (IWH), which offer advantages for the integration of regenerative heat generators. The following article presents the results of two measurement campaigns to record the domestic hot water demand in residential and non-residential buildings. In 19 water heaters of multi-family houses and 10 water heaters of non-residential buildings, data on temperature and volume of the domestic hot water and, if available, of the circulation are determined. The applied measurement technology for this purpose is presented. The recorded data is analyzed with the help of a Python tool. At first the focus is put on the necessary measuring period and the measuring interval. It is recommended to measure for at least four weeks and with a measurement interval of 5 s or less to be able to make reliable statements about load peaks for the design of IWH. Furthermore, cumulative demand profiles for multi-family houses and hotels are presented, showing that the profiles in the hotel depend on the change of guests checking in to checking out. In addition, the simultaneity of tapping events in non-residential buildings is considered and a good match with formulas for residential buildings from VDI 2072 is achieved.

Keywords. EN 12831-3, instantaneous water heater, measured tapping profiles, simultaneity.
DOI: https://doi.org/10.34641/clima.2022.73

1. Introduction

In Germany, heating of domestic hot water (DHW) requires about 91.6 TWh primary energy per year [1]. Obstacles to its decarbonization, especially in large-scale systems by using heat pumps and solar thermal collectors, are the current hygiene rules [2,3] for planning and operating DHW heaters. Based on these requirements instantaneous water heaters compared to conventional storage water heaters offer the following two advantages. First, because of their much smaller volume, water exchange is improved and the residence time of the water in the system is reduced. Any filters in the circulation system have to filter significantly less water. The extent to which the hot water temperature can be lowered directly is the subject of ongoing research [1,4,5]. The potential for a reduction of 5 K is 15.8 TWh per year for Germany [1]. Second, regenerative heat generators can be efficiently integrated in the buffer storage at lower temperature levels, e.g. for preheating [6]. The potential of this advantage amounts to up to 100 % of CO_2 emissions, as only CO_2 neutral energy sources can be used.

However, the design of heat supply systems with IWH is more complex due to their limited thermal transfer capacity. The capacity limit is defined by the heat exchanger and the maximum primary flow rate. If the tapping capacity exceeds this capacity limit for a short time, the outlet temperature drops and comfort problems may occur at the tapping point. The same applies in the event that the required storage temperature is undershot, which in turn can have a variety of reasons. Ideally, the design of the DHW heating system should be based on a dynamic system simulation with an object-specific, high temporal resolution tapping profile. Since this is not always possible, simple design recommendations are derived in the research projects FeBOp-MFH (FKZ: 03ET1573) and TA-DTE-XL (FKZ: 03EN1025) based on measurement campaigns in residential and non-residential buildings. On the one hand, these projects enable to measure the cumulative demand profiles and the total daily demand, which are required for a design of the storage tank and the heat generator according to DIN EN 12831-3 [7] or the solar thermal according to VDI 6002-1 [8]. On the other hand, these studies provide information about the simultaneity of use and thus the maximum required output of the IWH. By knowing the exact demand variables, it is possible to prevent oversizing of the systems and thus to install a system that is optimized both energetically and economically.

2. State of the art

Based on the above reasoning, a distinction between maximum capacity or simultaneity and cumulative demand profile and daily demands is made in the sections below.

2.1 Maximum capacity

In buildings with many taps, simultaneous tapping at all taps never occurs. For residential buildings, if the tapping capacity of the residential units $\dot{Q}_{RU}$ is the same, the total capacity can be determined using the simultaneity factor φ (shown in Fig. 1) and the number n of residential units according to equation (1) and equation (2) (e.g. VDI 2072 [9]).

$$\dot{Q} = \varphi \cdot n \cdot \dot{Q}_{RU} \quad (1)$$

$$\varphi = 0.03 + \frac{0.5}{\sqrt{n}} + 0.47 \cdot \frac{1}{n} \quad (2)$$

A comparison of this relationship with current measured values is given in chapter 4.2.

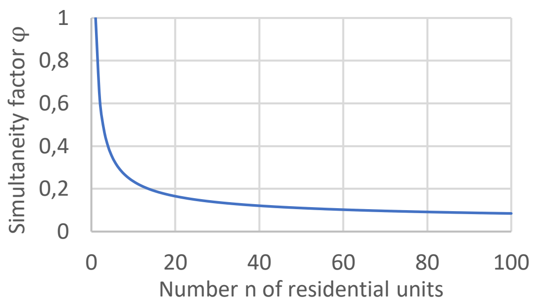

Fig. 1 - Simultaneity factors according to VDI 2072 [9]

An important focus of this work is set on the measurement interval used. In many measurement campaigns (listed in [10]) logging intervals of 1 minute and longer are used. Also the DIN EN 12831-3 requires logging at every minute if possible [7]. However, the authors [10] conclude based of their measurements, that a resolution of seconds is essential. In chapter 4.1 we investigate the influence of temporal resolution on different statistical indicators together with recorded secondary data.

2.2 Cumulative demand profiles and daily values

For the design of DHW heaters according to DIN EN 12831-3, a cumulative demand profile (CDP) must be used. According to DIN EN 12831-3 two way are applicable to determine this object-specific CDP:

1. Measurement of the DHW flow rate on a minute basis, considering the temperature of the hot and cold water – only for retrofit

2. Calculation by multiplying normalized CDP (e.g. Annex B of DIN EN 12831-3) with daily demands, based on statistical analyses – both for new and existing buildings

The determination based on measured values has the highest accuracy for an existing object. [7] For new buildings, there is still a lack of normalized CDP.

3. Measurement campaign

The measurement concept of the DHW profiles for this study is shown in Fig. 2. Independent of the building type and water heating system, both heat flows, tapping capacity and circulation load (if available), can be measured with high temporal resolution.

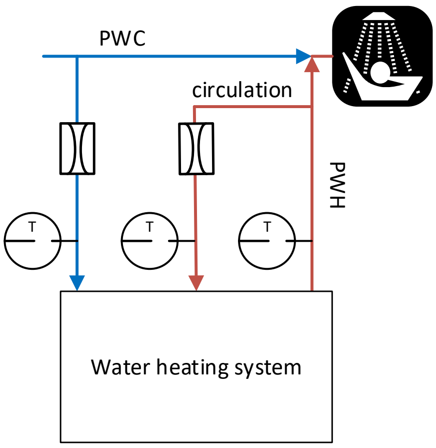

Fig. 2 - Scheme of measuring points used in this study.

In Germany, the building stock is dominated by one- and two-family houses (see Fig. 3). However, buildings that have three or more units, which account for 18 % of Germany's building stock (see Fig. 3), represent approximately 54 % of all residential units in Germany. [11]

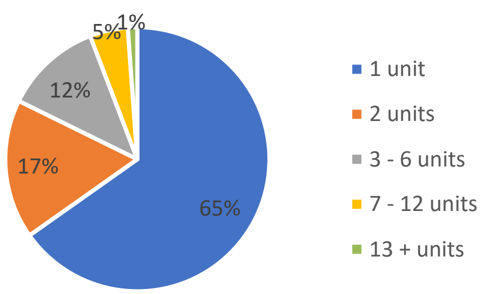

Fig. 3 - Units per building in Germany, data [11]

Therefore, multi-family houses are a relevant sector to make the production of DHW sustainable. The number of multi-family houses and the number of residential units in these houses considered in this study is shown in Fig. 4. The monitoring system is designed for the long term; a continuous period of six weeks outside the vacations is selected for the present analysis.

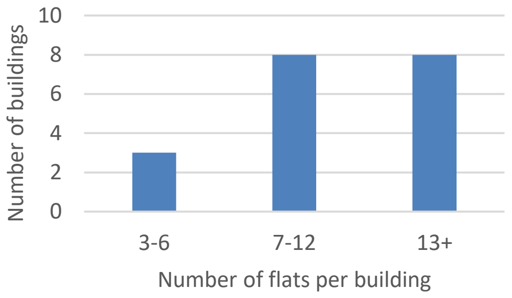

Fig. 4 – Number of units in the residential buildings considered in the study

The measurement results of the non-residential buildings taken as a base in this study are determined in 2 hotels with 5 water heaters as well as in 4 campsites with 5 water heaters. The minimum evaluated period is at least 4 full weeks, whereby at least a part of the measurement period for the campsites is measured during the vacation season.

Due to the specific focus, the two projects use different sensors that allow for different evaluations. These are described in the following chapters.

3.1 Measurement system for residential buildings

Over a period of two years, 19 residential buildings with central hot water supply are equipped with a monitoring system to optimize the system performance. During this time span, the monitoring system is further developed (lessons-learned), so that it varies between different buildings. The basic measurement principle is based on a data logger that reads the flow rate of a calibrated cold water flow sensor as well as the temperatures of drinking cold water, drinking hot water and circulation in minute intervals and transfers them to a server. In some installations, the flow rate of the circulation line is also measured. Flows are either read as instantaneous value or as cumulative volume since installation, the latter will be used in the following.

In the beginning, OneWire contact temperature sensors are coupled directly or via an additional arithmetic unit. Later, PT1000 contact temperature sensors (class A, 2L) are used. The flow rates are measured with commercially available ultrasonic water meters approved for heat meters according to MID 2014/32/EU.

3.2 Measurement system for non-residential buildings

The measuring system (see Fig. 5) consists of a router for data transmission, a data logger, a heat meter, 2 *Keyence FD-Q* clamp-on ultrasonic sensors and 3 contact temperature sensors P1000 (class A, 2L). The measurement period is at least 4 full weeks and the data is logged every second.

Fig. 5 - Measurement system for non-residential buildings

Different *FD-Q* series sensors are used depending on the pipe material and diameter. On a test facility at *ISFH* with a Coriolis reference sensor (accuracy 0.1 %), a calibration factor is determined to correct for systematic errors as shown in Fig. 6 for a specific pipe material, pipe diameter and fluid temperature. These factors can be found in [12]. By calibrating the sensors, a measurement accuracy of ± 2 % is achieved for flow velocity above 0.5 m/s.

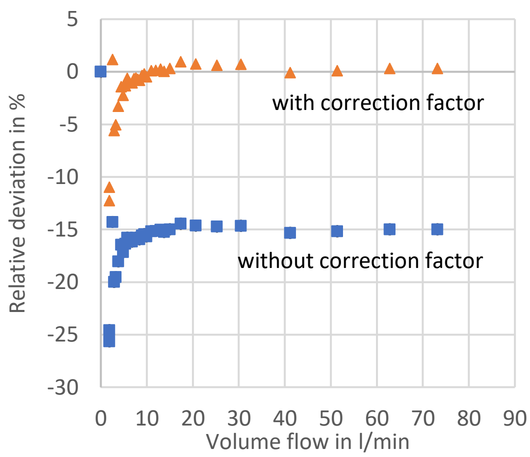

Fig. 6 - Influence of correction factors on the measurement accuracy of *Keyence FD-Q* sensors using the example of the *FD-Q 32C* with a 35mm CU pipe and 55°C water temperature [12]

4. Statistical evaluation

A *Python* tool was developed at *ISFH* for the statistical evaluation of the measured data, which is briefly described below. Subsequently, with the help of this tool, evaluations of the peak load, the necessary logging interval and determined CDP are presented.

The tool uses the *Pandas* package (version 1.3.3 [13]) for the calculation. With the help of the tool the measurement data of an object are read. Data gaps of one measuring point are closed by interpolation with the previous and next measured value. The *Pandas interpolate* function with the *time* method [13] is used for this purpose. In case of larger gaps, the measured values of this time step are not filled and the user is informed about the gap. Therefore, larger gaps in the non-residential measurement data may result in reduced cumulative values.

4.1 General analyses

Measuring period

The measured peak load is not only a function of the temporal resolution, but also of the duration and period of the measurement. Based on estimated information from the operator, the measurement period is chosen to cover the expected maximum utilization period.

According to DIN EN 12831-3 [7], minute-by-minute data is used for the design of water heating systems and the duration of the measurement period is not specified. With the tapping data measured in the non-residential buildings, it has to be checked whether the minute-by-minute recording of measured data is suitable for the design of various systems for domestic hot water heating. In Fig. 7 the peak load measured in the period up to the respective day is plotted over the measurement period of 28 days. It shows that in 9 out of 10 water heaters the maximum peak load occurred within the first 14 days, in the last case the measured peak load increased by another 2.5 % by extending the measurement period.

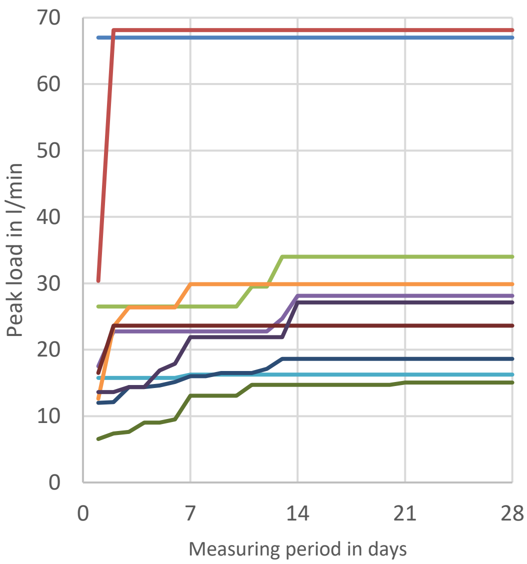

Fig. 7 - peak load measured up to the respective day over the measurement period for 10 examined non-residential water heaters

Logging interval

To investigate the influence of the logging interval, the data are calculated using the method *resample(f'{interval}s').mean()* from the *Pandas* package [13]. Here, we artificially decrease the temporal resolution of data, by calculating the mean value of the measured data in set intervals. This represents a standard cumulative water meter that is read according to the logging interval. The logging intervals chosen for the study are $t_m = 5$ s, $t_m = 10$ s, $t_m = 30$ s, $t_m = 60$ s, $t_m = 120$ s and $t_m = 300$ s. In the case of data gaps, the function fills in empty values. All further calculations are then performed with these averaged values.

For the calculation of the peak load, the time interval with the highest measured value was determined for the respective period under consideration. Fig. 8 shows the normalized peak loads determined for 4 water heaters in hotels relative to the peak load per second over the logging interval. The plot shows that the determined peak values decrease with increasing logging interval, in some cases significantly.

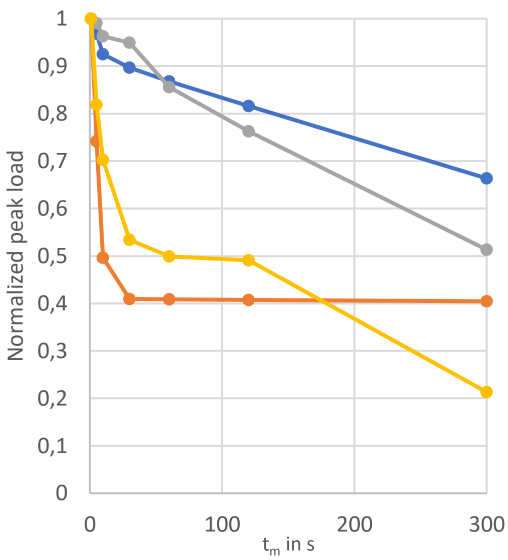

Fig. 8 - Dependence of the measured, normalized peak load over the logging interval for 4 water heaters in hotels

To examine this issue in more detail, the influence on the maximum tapping volume flow during the measurement period is considered for all 10 water heaters mentioned in section 3.2. For $t_m = 5$ s it is obvious that the peak load is underestimated by 6.6 % on average (0-26 %). For $t_m = 60$ s, the peak loads are underestimated by 27.7 % on average (15-59 %). In both cases, as already expected from Fig. 8 there is a wide spread deviation (compare Fig. 9), which is related to different durations of the maximum tapping. For the 10 non-residential water heaters the normalized 1-minute peak load is up to 60 % smaller than the 1-second peak, whereas the 5 s peak is practically as large as the second peak in half of the cases.

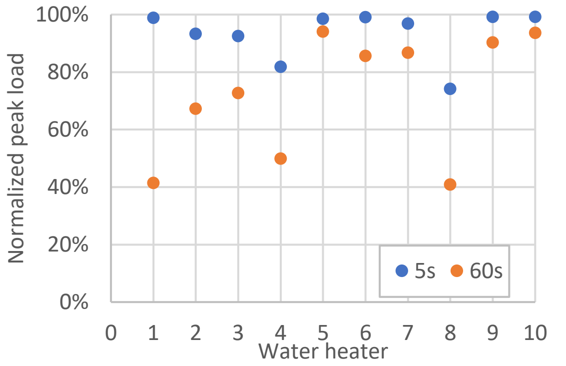

Fig. 9 - Deviations of the normalized peak load due to logging interval for 10 non-residential water heaters.

To increase the data base of the sample, the daily peak loads were also evaluated. A total of 310 measurement days are considered for the 10 non-residential water heaters and the results are listed in the Tab. 1.

Tab. 1 - Deviation of the normalized peak load due to the logging interval for 310 days

t_m in s	5	60
Mean	4.8 %	26.6 %
Min	0 %	3 %
Max	32 %	69 %

4.2 Object-specific analyses

Residential buildings

In the following, we investigated how the average daily tapping demand (temperature differences normalized to 10 °C cold water heated to 60 °C hot water) per residential unit behaves in different buildings. The results are shown in Fig. 10.

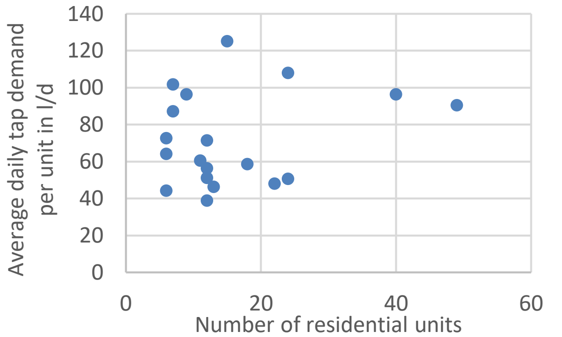

Fig. 10 – Average normalized daily tapping demand (@10/60 °C) per residential unit

The average daily amount of water tapped per residential unit fluctuates between 39 l/d and 125 l/d; this fluctuation is independent of the total number of residential units in the building. According to [14], the results are within a range that can be expected, but no information is available for the buildings on the number of persons or occupant structure of the buildings, so no further correlation between tapped water and residents can be investigated.

Furthermore, the CDP of the daily tappings are examined. The cumulative energy demands Q_{ti} and hot water demands V_{ti} are formed from the individual values by means of cumulative totals based on the *Pandas* function *cumsum* [13].

$$Q_{ti} = \sum_{t0}^{ti}(\dot{Q}_i \cdot \Delta t) \quad (3)$$

$$V_{ti} = \sum_{t0}^{ti}(\dot{V}_i \cdot \Delta t) \quad (4)$$

For each time t_i of the day, the cumulative energy demand Q_{ti} or the hot water demand V_{ti} is calculated from the sum of the individual quantities. The individual quantities result from the instantaneous flow $\dot{Q}_i$ rep. $\dot{V}_i$ and the duration Δt of a time step. These are then normalized to the daily total demand to provide for comparability.

Based on the days with the highest DHW demand, a CDP was calculated for each property, although one property with 3 - 6 and one property with 13 + residential units could not be included due to data gaps. Thus, for the three classes of residential buildings (compare Fig. 3), a mean CDP is formed for each class. These graphs are shown in Fig. 11. In addition, an average, a minimum and a maximum CDP is determined, averaged over all buildings.

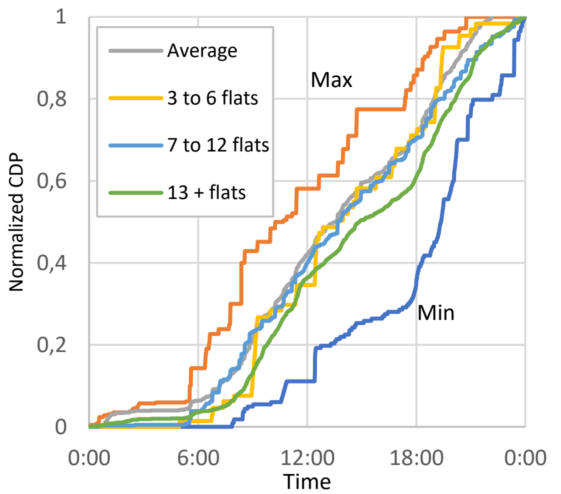

Fig. 11 - Cumulative demand profiles of the residential buildings

Non-residential buildings

The non-residential buildings surveyed are 5 central water heaters in hotels, where one is only supplying showers and washbasins for a swimming pool. Two other water heaters are supplying 1 and 3 kitchens in addition to their assigned guest rooms. Furthermore, 5 shower houses at campsites are measured. In the following, exemplary evaluations of these water heaters are discussed.

Fig. 12 shows the daily peak load over the number of guests for a hotel object. A distinction is made between the number of guests recorded after check-in on the previous day and the number recorded after check-in on the day of measurement. The plot shows that the peak load correlates significantly better with the number of guests on the previous day

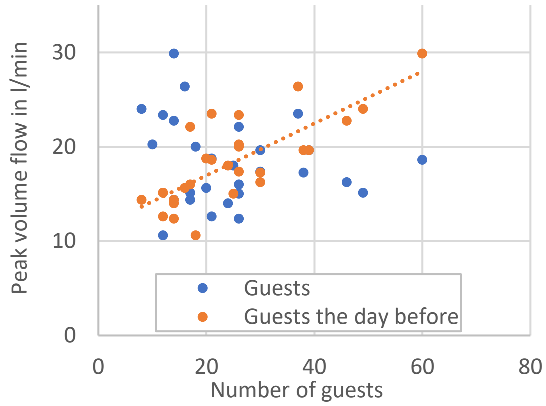

Fig. 12 - Maximum daily volume flow depending on the number of guests present

Furthermore, the results show that with a similar number of guests on the previous day, the maximum load can vary by more than 30 % (compare Fig. 12). This is related to user behavior and only with a measurement over a longer period of time, the possible simultaneity can be accurately represented even at constant load.

An explanation why the peak load correlates better with the guests of the previous day becomes obvious when looking at the cumulative demand profiles (compare Fig. 13). Here, there is a clear peak load in the morning. The guests recorded the day before the measurement have to be responsible for this peak, assuming no guest is checking in during the early morning hours from 00:00 h to 08:00 h.

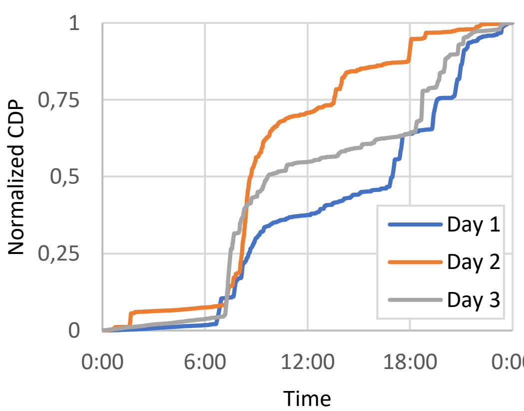

Fig. 13 - Daily cumulative demand profiles of a hotel

The guests present have an influence on the expression of the CDPs. To illustrate this, the guests for an exemplary period are listed in Tab. 2. The CDP of day 1 and day 2 show very clearly that more than half of the daily tapping is accounted for by the morning hours and thus the guests from the previous day have to be responsible for that tapping. However, if there are more guests in the evening than on the previous day, it is also possible that the main load will shift to the afternoon as on day 1.

Tab. 2 - Example data of a hotel

Day	Number of guests	Peak load in l/min	Sum in l
0	30	19.6	918
1	46	16.3	1074
2	14	22.8	896
3	24	14	574

This also becomes clear when looking at all measured daily CDP of the object, which are shown in Fig. 14. The green lines show the days when the number of guests is increased by more than 10, and the red lines show when the number of guests is decreased by more than 10 compared to the previous day. All other days are marked in blue. It is noticeable that on days with an increase of more than 10 people, the proportion of tappings up to 12:00 h at noon is mostly below average. In other cases, well over 75 % of the daily total is tapped until 12:00 h at noon on days with a decrease in number of guests more than 10.

Therefore, it should be considered whether the measurement period for the evaluation of lodging establishments should be daily from 0:00 h to 23:59 h or whether it would be appropriate to start the evaluation between the check-out and check-in time of a hotel (e.g. 13:00 h to 12:59 h). In this case, the housekeeping should be counted for the previous day.

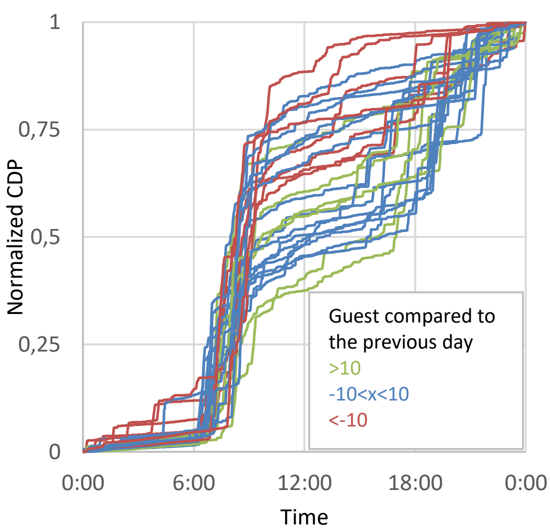

Fig. 14 – Normalized CDP of a hotel depending on the difference of guests checking in to out

The back-calculation of measured data to simultaneity factors is not possible without further ado. This requires precise knowledge of all the taps used, the pressure losses in the system and other variables. In order to be able to give an estimate of the simultaneity of tappings, the approach shown in Fig. 15 was chosen. Here, the measured maximum tapping capacity $\dot{Q}_{max,n}$ per installed shower is plotted on the first y-axis over the number n of installed showers. The heat demand $\dot{Q}$ was determined for this purpose according to equation (5).

$$\dot{Q} = \dot{m} \cdot c_{p,m} \cdot (\vartheta_{out} - \vartheta_{in}) \quad (5)$$

Here, for simplicity, a fixed mean specific heat capacity $c_{p,m}$ = 4,179 kJ/(kg·K) is assumed.

The trend line is calculated from the measured values with *Excel*. It shows a theoretical performance of a shower $\dot{Q}_{max,1}$ of about 27 kW. Since $\dot{Q}_{max,1}$ corresponds to the power of a shower, the second Y-axis, which gives the simultaneity factor over the number of showers installed, is normalized so that $\dot{Q}_{max,1}$ corresponds to 1. According to equation (2), the simultaneity factor for residential units from VDI 2072 [9] is plotted in blue. The number of showers installed is used for n. By this approach it is possible to give an estimation for the simultaneity without exact knowledge of other boundary conditions like for example the installed taps. The determined trend line of the non-residential buildings agrees well with the simultaneity factors for residential buildings. However, deviations of more than 100 % are found for individual objects.

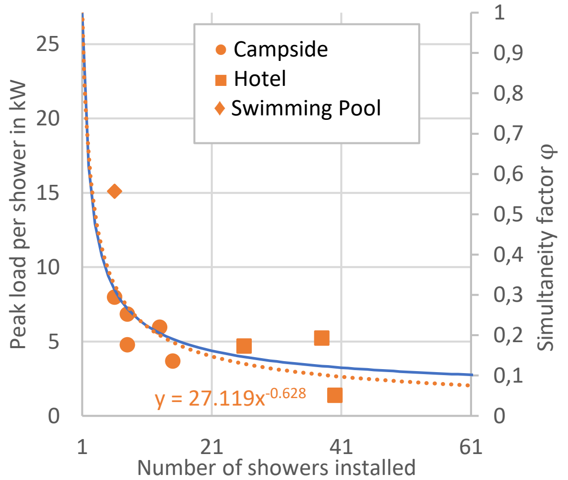

Fig. 15 – Comparison of determined simultaneity factors in non-residential buildings with the curve from VDI 2072 (blue)

5. Conclusion

In this paper, two measurement campaigns in residential and non-residential buildings with different methods for recording DHW consumption are presented. In the residential buildings, commercial heat and water meters are used to measure temperatures and total volumes in minute-by-minute resolution. In the non-residential buildings, clamp-on ultrasonic sensors and temperature sensors are used to measure the instantaneous volume flows in second-by-second resolution.

In the following, the evaluation is presented by means of a *Python* tool. First, the required measurement period and the measurement interval are examined for load peaks and daily CDPs. We have shown that the length of the selected measurement period of 4 weeks is sufficient for the evaluation. Since the peak loads depend on the user behavior even at the same utilization and can differ significantly, it is advisable to measure over a period of several days even at full utilization.

Furthermore, it can be noted that a minute-by-minute recording of measured values, as required in DIN 12831-3, is suitable for the determination of cumulative demand profiles and daily demands. However, for a statement about a short-term peak load, e.g. for the design of an IWH, these data are not suitable. For this purpose, tapping profiles should be measured with a logging interval of at least 5 seconds. A reliable extrapolation based on minute data is not possible. In this case, a prudent planner should apply at least a 60 % increase in the minute peak for the selection of an appropriate IWH.

Additionally, measured data from 19 residential buildings are considered. They show that information on the facilities and occupancy of residential units are necessary for a good design.

In the case of non-residential buildings, 10 water heaters are investigated, these are 5 in hotels and 5 at camping sites in total. An example of a hotel shows how the daily peak load correlates with the number of guests the previous day. The CDPs show that in most cases more than 50 % of the daily energy is used before 12:00 h at noon. Here, a shift in the CDP can be seen depending on the ratio of guests checking in to guests checking out. If significantly more guests check in, the load tends to be distributed more evenly throughout the day. If, on the other hand, significantly more guests check out, the load is strongly focused on the morning.

If we look at the load peak per shower installed, the trend line determined is a good approximation to the simultaneity factors according to VDI 2072, even if this standard is actually only established for residential buildings.

6. Outlook

In the course of the current research project TA-DTE-XL, many more non-residential buildings are going to be measured. With the help of these data, the authors want to confirm the findings on the dependence of the simultaneity factors on the installed showers in hotels, at campsites and to an extent in indoor sports facilities. This way, more precise design recommendations for instantaneous water heaters should be made. For this purpose, it should also be investigated to what extent a short-term exceeding of the design capacity of the IWH can be tolerated. In this way, it may be possible to reduce the proposed safety buffer during design.

7. Acknowledgement

The presented work is part of the research projects "TA-DTE-XL" (grand no. 03EN1025A) and "FeBOp-MFH" (grand no. 03ET1573).
TA-DTE-XL is a joint project with Viega GmbH & Co. KG, while in FeBOp ISFH is collaborating with Klimaschutz- und Energieagentur Niedersachsen (KEAN), proKlima – der enercity Fonds and Corona Solar GmbH.
The authors are grateful for the support of the State of Lower Saxony and the Federal Ministry for Economic Affairs and Climate Action (BMWK). The authors are responsible for the content and would also like to thank PAW GmbH & Co. KG, Oventrop GmbH & Co. KG, Solvis GmbH, Malotech GmbH, cbb software GmbH, Taconova GmbH, Reich + Hölscher, Varmeco GmbH & Co.KG, Bosch Solarthermie GmbH, Vaillant GmbH for their support.

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The data sets generated and analyzed during the current study are not available because more data will be collected and then published, but the authors will make every reasonable effort to publish them in the near future.