High frequency flow and temperature measurements of domestic water in two office and education buildings

Frandsen, Martin; Vind Madsen, Jakob; Lund Jensen, Rasmus; Zbigniew Pomianowski, Michal

Published in:
Energy and Buildings

DOI (link to publication from Publisher):
10.1016/j.enbuild.2022.112424

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Energy & Buildings 274 (2022) 112424

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

High frequency flow and temperature measurements of domestic water in two office and education buildings

Martin Frandsen *, Jakob Vind Madsen [1], Rasmus Lund Jensen, Michal Zbigniew Pomianowski

Aalborg University, Department of the Built Environment, Thomas Manns Vej 23, 9220 Aalborg Øst, Denmark

ARTICLE INFO

Article history:
Received 2 July 2022
Revised 13 August 2022
Accepted 22 August 2022
Available online 25 August 2022

Keywords:
Domestic hot water, DHW
Domestic cold water, DCW
DHW energy efficiency
Domestic water flow rate
Water draw-off profile
DHW recirculation system
Measuring campaign

ABSTRACT

For a long period, the energy use for domestic hot water (DHW) in non-residential buildings has been neglected. As energy use for space heating, ventilation, and lightning has been reduced through the years, the energy share for DHW production has increased. With today's focus on energy efficient buildings, the DHW systems must not be left behind the other fields to obtain a holistic approach to energy efficient buildings. To develop more energy efficient DHW systems for non-residential buildings, more knowledge is needed regarding draw-off durations, flow rates, and water temperatures from different draw-off types.

This paper presents high frequency measurement results in two Danish office and educational buildings, which show that three DHW systems only utilize between 3.4 and 7.5 % of the total energy used for DHW production. Above 85 % of the total energy use is lost from the recirculation circuit to secure a high hot water temperature at the draw-off point. However, temperature measurements at the draw-off points show that a significant share of the heat is lost from pipes not covered by recirculation. One reason is draw-off durations are approximately 50 % of the time below 10 s at washbasins and kitchen sinks. Another reason is actual maximum flow rates are far from the calculated design flow.

The high frequency measurements at multiple draw-off points give essential knowledge of use patterns for washbasins, kitchen sinks, and service sinks in non-residential buildings. This knowledge can contribute to developing energy efficient DHW systems and new types of DHW production.

1. Introduction

European buildings are responsible for above one-third of the total energy use and of the total greenhouse gas emission inside the European Union (EU) [1,2]. According to Pomianowski et al. [3], the energy use in buildings is mainly used for space heating, especially in cold climates, like the northern European countries, where the heating need is more significant. However, increased focus on energy efficient buildings concerning heating, ventilation, and lighting has reduced the energy use per floor area. As a result of an energy reduction in those three areas, energy for domestic hot water (DHW) production is now responsible for a more significant share of the buildings' total energy use.

Pomianowski et al. [3] describe that approximately 15 to 40 % of the total energy needed in residential buildings is used for DHW. The energy share used for DHW is rising in new buildings. A study of nearly zero energy buildings around Europe [4] shows examples of residential buildings where the calculated DHW use is up to 57 % of the total energy use. A Danish case study [5] shows for non-residential buildings (schools and offices) that the energy share is only between 6 and 8 %, which might seem small. However, the same Danish case study shows that up to 90 % of the energy for DHW in non-residential buildings is lost from production, recirculation, and storage. In Denmark, the building regulation [5] has reduced the energy compliance for non-residential buildings from 95 to 41 kWh/m^2/year from 2006 to 2018. However, in Denmark, the assumed DHW use for non-residential buildings in standardized energy calculations is unchanged at 100 l/m^2/year in the same period, showing the missing focus in energy use for DHW compared to other fields.

Abbreviations: BMS, Building management system; DCW, Domestic cold water; DH, District heating; DHW, Domestic hot water; HEX, Heat exchanger.

* Corresponding author.
E-mail address: martinf@build.aau.dk (M. Frandsen).

[1] The author has moved after this work was done.

https://doi.org/10.1016/j.enbuild.2022.112424
0378-7788/

1.1. Challenges of today's domestic water systems

Today, non-residential buildings are often constructed with recirculation circuits that secure hot water close to the draw-off points. However, multiple sources clarify the significant losses from the recirculation of DHW. In 1982 Ovesen [6] described how hot water recirculation systems were invented to save hot water use by raising the hot water temperature closer to the draw-off points. Furthermore, the recirculation system increases the comfort related to the waiting time for hot water at the draw-off points. Ovesen mentions that the focus should change to reducing energy losses in a better balance with comfort and water use. This focus on heat losses due to DHW recirculation has increased through the years, and with good reason. The Danish case study [7] shows that the DHW recirculation results in significant heat losses of between 30 and 75 % of the total energy to DHW production in multi-family houses, 0–60 % in single-family houses, and 50–90 % in non-residential buildings. The magnitude of heat losses is based on the total pipe length of the recirculation system and DHW usage. Non-residential buildings often have lower DHW usage and longer pipe lengths than residential buildings, which results in recirculation losses having a more significant share of the total energy use.

Compared to residential buildings, the comprehensive review by Fuentes et al. [8] from 2017 states that, in general, limited literature exists about consumption profiles in non-residential buildings like educational institutes, hospitals, and offices.

Study from 2013 [9] shows measurements in Estonia for educational buildings, kindergartens, office buildings, and shopping centers. This study highlights that for 16 different office buildings, the standard EN 806–3 overestimates the DHW peak flow rate ten times on average and between 5 and 16 times. In 20 different educational buildings, the DHW peak flow rate is overestimated eight times on average and between 4 and 16 times with the same standard. Another study from 2018 [10] concludes that up to 30 % of the total energy use, including plug loads, in an Irish university building from 2012 is used for heating and pumping DHW, including losses from DHW production. The comprehensive study from 2019 [11] of DHW in non-residential buildings shows that DHW systems, with recirculation pipes, in four university buildings in Austria have a low energy efficiency of between 2 and 12 %. Moreover, the study indicates potential energy saving in one of the buildings from 13.0 kWh/m^2/year to 9.8 kWh/m^2/year (24.6 %) by shutting off the circulation pump on weekends (changing the control strategy). Lastly, the potential energy savings are calculated by changing from central DHW production with district heating (DH) to electrical point-of-use heaters, reducing energy use from 13.0 kWh/m^2/year to 1.4 kWh/m^2/year (89.2 %). That reduces CO_2 emissions from 37.2 t to 6.8 t with Austrian primary energy and CO_2 factors.

The abovementioned references [9–11] include measurements and calculations of energy and water flow at the DHW production and the recirculation circuit. However, measurements at the draw-off points are missing. The heat loss from distribution and connection pipes[1] can be estimated and added to the energy calculation with flow rate and water temperature measurement at the draw-off point. The authors of this paper have not found any studies of non-residential buildings where the energy loss from the recirculation circuit to the draw-off points is considered.

Moreover, flow rate measurement at all the draw-off points connected to the same DHW production allows comparing the actual and design flow rates throughout the pipes in the system. The flow rate to each draw-off point and pipe dimension influences the tapped hot water temperature. With water temperature measurements at the draw-off points, the temperature decay of the water in the distribution and connection pipes can be specified. Furthermore, a comparison of the actual and design temperature can be performed.

1.2. Potential of measurements at draw-off points

The lack of knowledge of the last part of the DHW system complicates designing energy efficient DHW systems able to deliver high comfort levels for the user. Fuentes et al. [8] state that the water use profiles are significantly different among building types and draw-off profiles need to be monitored for specific building types.

Different types of tools for designing DHW systems are available, which are summed up by [8]:

- Models from technical standards
- Stochastic models
- Time-series forecasting models
- Statistical, behavioral, and data learning models
- Databases of DHW tapping profiles

The most used tool is technical standards. However, some researchers find databases with actual measurements better for designing DHW systems because these draw-off profiles provide more realistic operating conditions than commonly used repeating daily profiles [12].

The background for all the abovementioned models are databases with recorded data. Fuentes et al. [8] state that more data, especially for non-residential buildings, is required in greater quantity and with a higher sampling rate to describe the building types' DHW demand and design efficient DHW systems.

Future water and energy use predictions are more accessible with high frequency measurements of flow rates and temperatures for entire DHW systems (production and draw-off points). With high frequency draw-off profiles, more precise knowledge about cold and hot water use, flow rates, temperatures, and simultaneity in draw-off actions, can help design reliable DHW systems and control strategies. The sampling rate of the collected data for a database's draw-off profiles is essential to capture rapid and often short draw-off peaks. Marszal-Pomianowska et al. [13] suggest 2 Hz or higher sampling rate. The study ascertains that 2 Hz is a good balance between the amount of data to store and collecting enough data points to capture fast flow rate changes.

1.3. High frequency measurements of the DHW production and the connected draw-off points in non-residential buildings

From the studied literature, the utilized energy from DHW systems in non-residential buildings appears to be remarkably low. On the other hand, limited information about energy use and losses from DHW systems in non-residential buildings was found. Moreover, there is a lack of information about water use patterns concerning draw-off durations, flow rates, and temperatures at the draw-off points in non-residential buildings.

The objective of this research is to help fill the knowledge gaps with on-site measurements in two modern Danish university buildings, where flow rates and temperatures are measured at the DHW production, in the recirculation circuit, and at the draw-off points, which contributes to the following three fields:

i) Energy use and losses from entire DHW systems, with novel information about the energy losses from distribution and connection pipes.

[1] Distribution and connection pipe is the pipe from the circulation circuit (hot water supply) to the draw-off point. Distribution pipe has more than one draw-off point connected whereas connection pipe only has one.

ii) Detailed use patterns of draw-off durations, flow rates, and temperatures of hot and cold water to washbasins, kitchen sinks, and service sinks in university/office buildings.

iii) Comparison of actual and design flow rates in DHW systems. Together with the analysis of the simultaneity factor between multiple draw-off points.

The paper starts presenting the methodology of the conducted measurements in section 2. Section 3 presents the results and analysis of the measurements, starting with the energy use and losses from the investigated DHW systems, followed by the recirculation control strategy of the systems. Next, the daily water usage, draw-off durations, flow rates, and temperatures of the investigated washbasins, kitchen sinks, and service sinks are shown. Last, in section 3, a comparison of actual and design flow rates in two distribution pipes is shown. The discussion is found in section 4 and the conclusion in section 5.

2. Methodology

The methodology section consists of five subsections describing the case buildings, the general use of the buildings, the used measurement equipment, the calibration procedure of the equipment, and a description of the sampling rate for the measurements.

2.1. Case buildings

The measurements were conducted at two university buildings in Aalborg, Denmark, in two different periods with two years between.

The first case building, CREATE, Fig. 1, is a 20,700 m^2 multi-story building consisting of lecture rooms, group rooms, offices, open study areas, and small student and staff kitchenettes. The top of Fig. 1 presents CREATE viewed from the outside, and below is a sketch of the investigated DHW system. CREATE is divided into six building sections with separate DHW productions, where section 5, marked with red, is investigated. The heat exchanger (HEX) is placed in the technical room on the 3rd floor, from where the DHW is distributed to the other floors in main (1), distribution (2), connection (3), and recirculation pipes (4), as marked in Fig. 1. When referring to the recirculation circuit, it is the main and recirculation pipes. Measurements of flow and temperature of hot and cold water are conducted at the highlighted draw-off points in the sketch in Fig. 1 (four washbasins, one kitchen sink, and one service sink), the pale color draw-off points exist but are not measured. DH flow and temperatures for DHW production are measured at the HEX. Additionally, at the HEX, the recirculation flow, recirculation return temperature, DHW supply temperature, and DCW flow are measured. The measurement period at CREATE is from 19 to 10-2018 to 03–01-2019.

The second case building is TMV 23, seen in Fig. 2. TMV 23 is a 9,280 m^2 multi-story building used for the same purpose as CREATE but with laboratories on the ground floor. Fig. 2 highlights the two investigated DHW systems in the east of the building; TMV 23 2nd floor and TMV 23 3rd floor. A sketch of the two DHW systems is shown in Fig. 2, where a HEX is located on each floor in a common technical shaft, supplying eight and three draw-off points with hot water. At TMV 23, flow and temperature are measured at all connected draw-off points except for the dishwashers (both connected to DHW). The same quantities are measured at the HEXs as described for CREATE. The measurement period for TMV 23 is from 12 to 04-2021 to 24–05-2021.

The DHW is produced instantaneously in both case buildings, with HEX utilizing DH from the public utility. The hot water is distributed in cross-linked polyethylene (PEX) and stainless steel pipes at CREATE and only stainless steel pipes at TMV 23, where

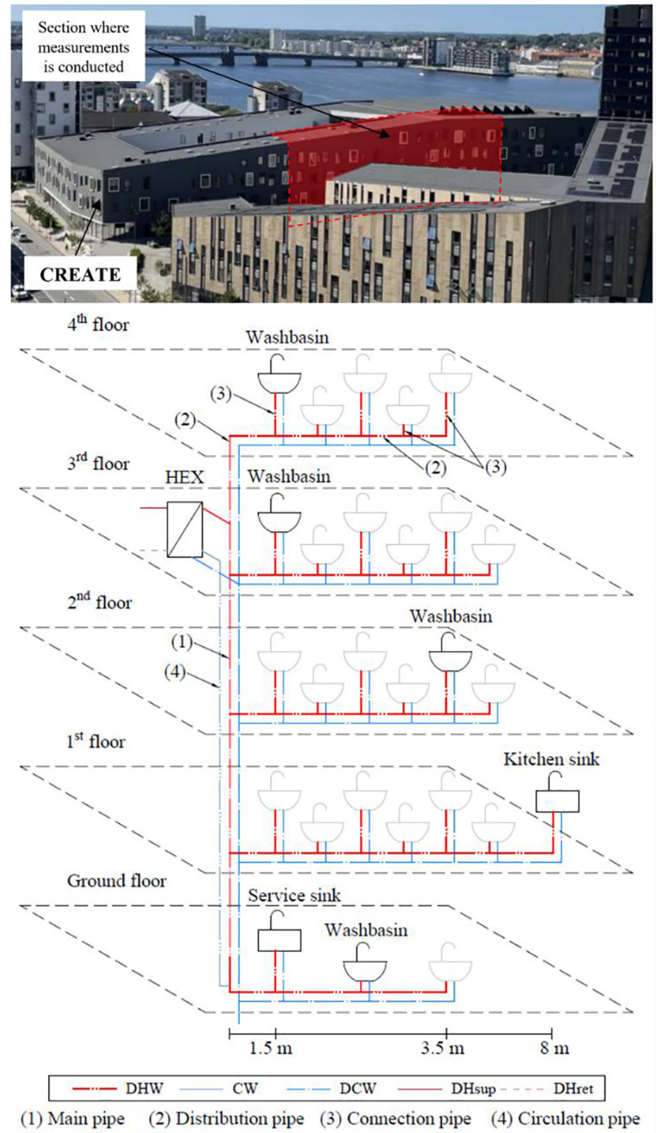

Fig. 1. The top shows CREATE, with highlighted section where measurements are conducted. The bottom shows a sketch (not to scale) of the DHW system. The measured draw-off points are marked with bold.

the pipes are located in the technical shaft, above the suspended ceiling, and in rooms of use. All pipes in the systems are insulated, except for the pipes in the rooms of use. The pipes are insulated with mineral wool like [14], with a minimum thickness of 20 mm, and thermal conductivity, λ_{10}, of 0.037 W/(m K). The three investigated DHW systems are constructed with a recirculation circuit.

2.2. Use of the building in measurement periods

The two case buildings are used by students and staff at Aalborg University, mainly for teaching, studying, and scientific work. The buildings are primarily used on weekdays during the period of lectures. Lectures usually start at 8:15 in the morning, and the last lectures end at 16:15.

The measurement period at TMV 23 was during the COVID-19 pandemic, where TMV 23 was partially opened to students and staff having a need of using facilities in the building. Two toilets at TMV 23 2nd floor have been locked during the measurement

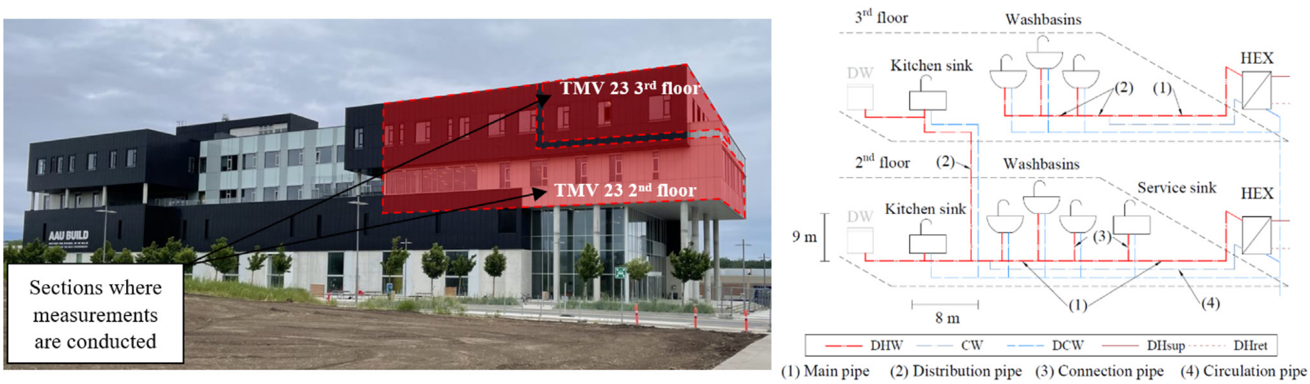

Fig. 2. To the left is TMV 23, with highlighted sections where measurements are conducted. To the right is a sketch (not to scale) of the DHW systems. The measured draw-off points are marked with bold.

period, and measurement from these has been excluded from the data treatment.

The draw-off points are used for different purposes. Washbasins for washing hands. Kitchen sinks for tapping drinking water, small cleaning tasks, and preparing foods. Service sinks are often used by cleaning staff for cleaning purposes.

2.3. Measurements and measurement setup

The measurements conducted are flow rate and temperature measurements in the investigated DHW systems. The measurements are split into two parts. The first part is the measurements conducted in technical rooms and shafts. The second part is the measurements at the draw-off points measuring flow rate and temperature for hot and cold water at washbasins, kitchen sinks, and service sinks.

The measurements are conducted with three types of measurement equipment:

i) In the technical rooms, the flow, supply temperature, and return temperature for DH to the DHW production are measured with the Building Management System (BMS). The BMS also measures the domestic cold water (DCW) flow to the HEX, the DHW supply temperature, and the recirculation return temperature.

ii) With KATflow 100 [15], an ultrasonic flow transmitter, the recirculation flow and DCW temperature are measured. KATflow 100 measures temperature with PT100 sensor and flow with ultrasonic clamp-on sensors. The KATflow 100 has a sample rate of 100 Hz and logs average values per second to a Raspberry Pi from where the data is accessible.

iii) The measurements at the draw-off points are conducted with Huba flow sensor type 236 [16], a vortex flow sensor. One sensor can measure one flow rate and one temperature, which gives two Huba flow sensors per draw-off point. The Huba flow sensors are mounted below the sinks right before the faucet. As Marszal-Pomianowska et al. [13] describe, it is essential to have a sufficient sampling rate to collect short and rapid changes in the water flow and temperature. To accommodate this valuable guideline, in this measuring campaign, industrial developed Porcupines by Seluxit [17] are used to collect data from the Huba flow sensors. Specially developed for these measurements, the Porcupine only logs data (flow rate and temperature) if a flow is detected. When flow occurs, the Porcupine logs data with a sampling rate up to 8 Hz. In periods with no flow, it logs a data point every five minutes to see the temperature decay/rise of the stagnated water in the pipes. This logging solution catches the rapid flow rate changes and minimizes the need for data storage. The data is uploaded to a cloud solution developed by Seluxit.

The conducted measurements are used for the objectives described below:

i) To calculate the total energy use for the DHW production. It is calculated with the DH flow rate and temperature difference between DH supply and return, measured by BMS.

ii) To calculate the energy loss from the recirculation circuit and HEX. It is calculated with the recirculation flow rate and temperature difference between DHW supply and recirculation return, measured by KATflow 100 and BMS.

iii) To calculate the energy loss from distribution and connection pipes. Calculated with the DHW flow rate at draw-off points and the temperature difference between the average DHW temperature in the recirculation circuit and the DHW temperature at the draw-off point, measured with BMS and Huba flow sensors.

iv) To calculate the energy used for heating DCW. Calculated with the DCW flow rate to the HEX and the temperature difference between DHW supply and the DCW. Measured with BMS and KATflow 100.

v) To collect essential draw-off profiles for DHW and DCW flow rate and temperature measured with Huba flow sensors. These are used to calculate the tapped water flow rate and temperature according to Eq. (1) and Eq. (2).

$$q_{tapped} = q_{DCW} + q_{DHW} \tag{1}$$

$$t_{tapped} = \frac{q_{DCW} \cdot t_{DCW} + q_{DHW} \cdot t_{DHW}}{q_{DCW} + q_{DHW}} \tag{2}$$

where q is flow rate in [l/min], and t is temperature [°C].

2.4. Calibration of measurement equipment

Huba flow sensors and Katflow 100 s have been calibrated in the laboratory prior to the measurement periods. Measured flow rate and temperature are calibrated against true values, covering the measurement interval for each quantity. A water weight system determines the true flow rate, where a stable flow is established, and the water is weighted over a period. The true temperature is determined by a water loop holding a constant temperature. The water temperature is kept constant when calibrating the flow rate and vice versa.

After installing the Huba flow sensors in the DHW system, a second calibration of flow rates was needed. Even though the sensor manufacturer did not inform about that measured flow rate depends on the water's temperature. The second flow rate calibration ensured that the measured values were temperature dependent.

Finally, to secure credibility of the flow rate measurements in operational condition, the DHW volume over a week was measured by the Huba flow sensors and compared with the volume measured by the BMS system. At TMV 23 2nd and 3rd floor, the deviation was 2.7 % and 1.9 %, see Table 1.

3. Results

First, the two buildings' annual energy and DHW use are presented. Then, the energy and water use, energy losses, and energy utilization are presented for the three investigated DHW systems. After that, measurements at washbasins, kitchen sinks, and service sinks are analyzed. Finally, deviations between measured and design flow rates in pipes are shown.

3.1. Building heating and DHW use

From the two buildings' BMS, the total DH use for DHW production and DHW use on building level since construction has been accessed. The DH use is read from the main heat meter to the buildings' DHW production units, measuring the DH supply and return. The DHW use is read from the water meter to each DHW production. Table 2 shows that TMV 23 has a higher annual total DHW use than CREATE. Furthermore, Table 2 shows the DH use for DHW production in volume and energy. The energy and volume are used to calculate the yearly average temperature decay of the DH for DHW production to be 14.1 °C and 14.4 °C for CREATE and TMV 23, respectively. Keeping in mind that these buildings are not using low-temperature DH, such cooling of DH is below the accepted temperature decay from the DH public utility and is considered inefficient and cause financial penalties for building owners. The poor cooling results from the DH can not get below the temperature in the recirculation pipe.

3.2. Energy use and energy losses from the three DHW systems

This part presents the energy use for DHW production, the associated energy losses, and the utilized energy share for the three DHW systems in the measurement periods.

Fig. 3 shows the energy use and losses to utilize 1 kWh of energy as tapped hot water. All energy quantities are calculated according to the explanations in subsection 2.3. The first group of columns shows the total DH use for DHW production. The second group of columns shows the amount of energy lost from the recirculation circuit and the HEX. The third column shows the energy lost from the distribution and connection pipes before 1 kWh is utilized as tapped hot water in the end. The last column group shows that energy to the circulation pump is a minor part of the energy use for DHW production.

The relation between "Total energy use (DH)" and "Utilized energy" shows a utilization of 5.0 %, 7.5 %, and 3.4 % of the total energy use for DHW production at CREATE, TMV 23 2nd floor, and TMV 23 3rd floor, respectively. The recirculation circuit and HEX losses together represent the largest share of the total energy use, 87.1 %, 89.2 %, and 89.1 % for the three systems. For TMV 23 3rd floor: 29.1 kWh is used for DHW production, 25.9 kWh is lost from the recirculation circuit and HEX, and 2.2 kWh is lost from distribution and connection pipes before 1 kWh is utilized and tapped as hot water at the draw-off points. 0.4 kWh is used for the circulation pump.

TMV 2nd floor has the most significant share of kitchen and service sinks, which have higher hot water flow rates and longer draw-off actions in relation to washbasins, shown in subsection 3.5. As a result, energy utilization is increased. TMV 23 3rd floor only has washbasins connected with low water use, resulting in a lower utilized share of energy than CREATE and TMV 23 2nd floor.

Table 1
DHW use for a week measured by Huba flow sensor and BMS.

	TMV 23 2nd floor	TMV 23 3rd floor
Measured with Huba [l]	160.9	124.0
Measured with BMS [l]	156.6	126.4
Deviation [%]	2.7	1.9

Table 2
The buildings' annual DHW use, annual energy use for DHW production in volume, and energy in secondary energy.

	DHW use [l/m^2/year]	DH for DHW [l/m^2/year]	DH for DHW [kWh/m^2/year]
CREATE	13.6	146	2.4
TMV 23	16.2	228	3.8

3.3. Control strategy of recirculation

The control strategy of the circulation pump and the DHW recirculation are investigated to evaluate the influence on the significant loss from the recirculation circuit. Fig. 4 shows the recirculation flow rates and temperatures of the three systems on four representative days, showing the control strategy for weekdays and weekend days. The recirculation system in CREATE is operating 24/7, but with a 3 °C lower temperature at night. Both recirculation systems at TMV 23 run from 6:00 to 19:00 and shut down at night. The recirculation return temperatures, particularly at CREATE, are high according to the Danish requirement of 50 °C [18] in the DHW system. The flow rates in the three systems seem high according to the temperature decay between supply and return. With a lower flow rate, the recirculation return temperature is lowered, and higher utilization of the DH is possible.

Additionally, a lower flow is equivalent to a lower pressure loss, lowering the circulation pump's energy. Especially the recirculation on TMV 23 3rd floor has a high flow when looking at the temperature decay of 0.3 °C between supply and return. The measured draw-off profiles show that it would be advantageous to run the circulation pump Monday to Friday from 07:00–17:00, where 85.7 % of all draw-off actions from washbasins and kitchen sinks occur. With the service sinks, it is 75.5 %. A significant share of tapped water from service sinks is happening between 04:30–05:30. It makes no sense to run the circulation pump on weekends from an energy perspective.

3.4. Daily water usage per draw-off type

This part presents the daily usage of hot, cold, and tapped water at the three draw-off types. Fig. 5 depicts the daily usage for the measured draw-off points at CREATE, TMV 23, and "all combined" with green, orange, and black colors, respectively.

The first finding is the deviation in daily hot and cold water use within the draw-off types. No water is tapped in 21 %, 23 %, and 45 % of the measured days, respectively, for the washbasins, kitchen sinks, and cleaning sinks. Additionally, the hot water use is zero on 30 %, 35 %, and 49 % of the measured days. Days without any hot water usage and the recirculation circuit still running result in energy waste, which is the situation at TMV 23 and CREATE, especially on weekends. Looking at the days when water is tapped, there is no tendency in the used water volume. The range of tapped water use for all draw-off types is between 0 and 120 l/day. The hot water use at washbasins is most consistent, with most days between 0 and 20 l/day.

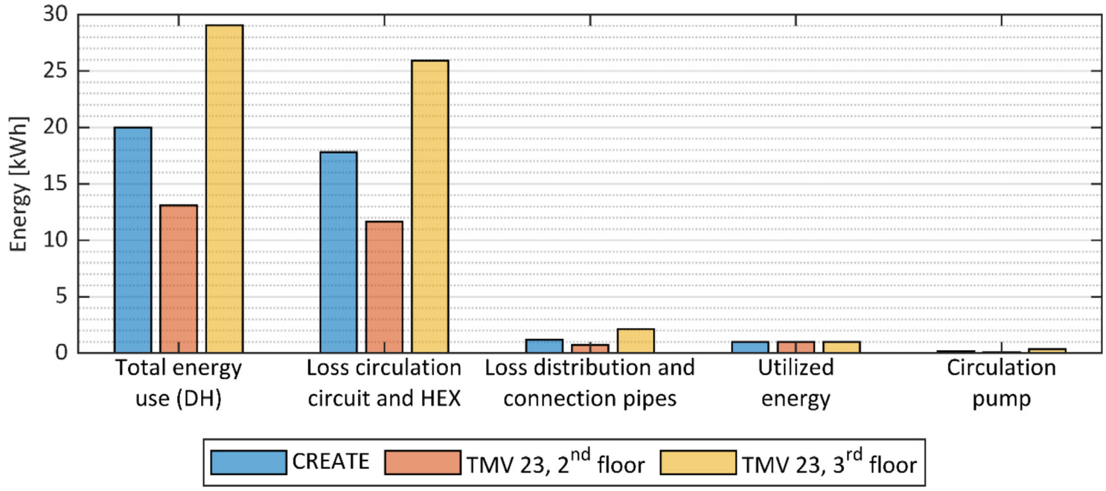

Fig. 3. Energy use and energy losses to utilize 1 kWh of energy in the measurement periods.

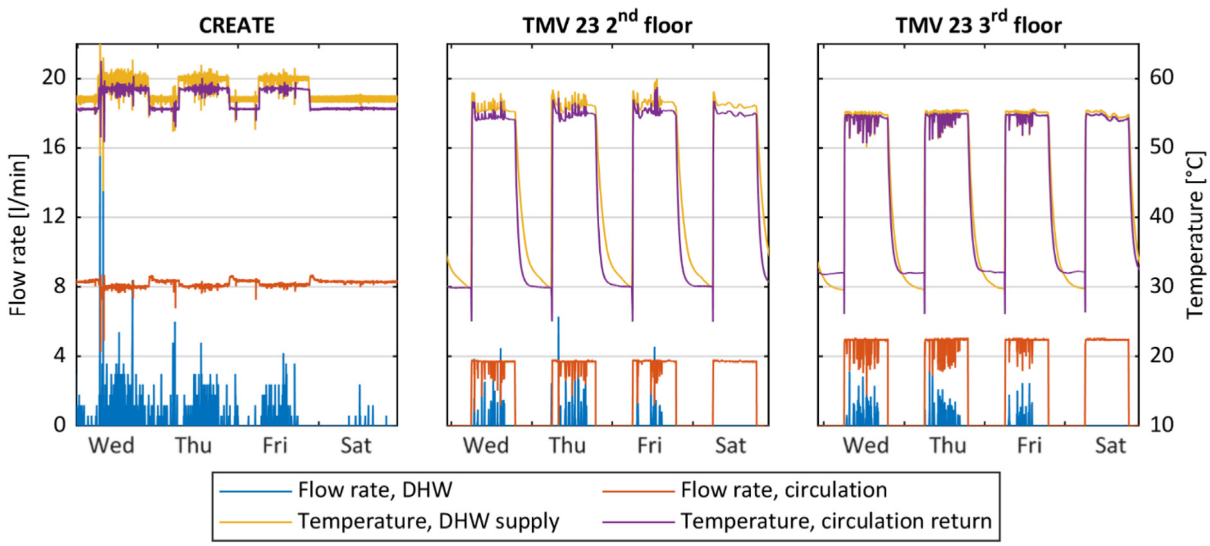

Fig. 4. DHW and recirculation flow rates and temperature for the three systems.

The DCW use at washbasins varies between the two buildings, and washbasins at CREATE significantly differ in cold water usage. The washbasin on the ground floor at CREATE has the highest DCW usage, and it is known to be used to tap drinking water.

The water use varies significantly for service sinks, from 45 % of the days with no usage to days with high usage compared to washbasins and kitchen sinks. This deviation is due to weekends with no cleaning and cleaning schedules where some buildings' areas are cleaned on specific days. The substantial variation in hot water use demands the DHW production to perform under various circumstances (use patterns). The DHW production unit is dimensioned according to a peak flow, but it only keeps the water warm in the recirculation circuit most of the time. This questioning the energy efficiency of DHW systems with recirculation and DH supply in office and educational buildings as TMV 23 and CREATE.

3.5. Draw-off actions. Duration, temperature, and flow rate

The following describes the underlying results for the poor energy utilization and new measured information regarding draw-off durations, flow rates, and temperatures for washbasins, kitchen sinks, and service sinks.

3.5.1. Washbasin

Washbasins are the most common draw-off point in CREATE and TMV 23. Generally, washbasins have the shortest draw-off actions and the lowest flow rate. Washbasins are mainly used to wash hands at lavatories, but some washbasins at CREATE are used to tap drinking water, known from visits to the building. Fig. 6 shows the duration of draw-off actions and the duration of breaks between two draw-off actions for all washbasins. If the break between two draw-off actions is below 20 s, the duration of the draw-off action before and after the break are added together, assuming that the same user is tapping the water. It is especially influential for the draw-off durations for washbasins, where many short breaks below 20 s occur when the user is soaping hands, and a sensor faucet is installed.

The duration of draw-off actions for the washbasins follows the same tendency, and on average, 85 % are below 20 s and 56 % below 10 s. The duration of the breaks is longer in TMV 23 than in CREATE due to a higher number of draw-off actions in CREATE. The breaks are shown no longer than 60 min in Fig. 6 because of the hot water temperature decay in the connection pipes between 0 and 60 min. Fig. 7 shows the temperature decay of stagnated water in a connection pipe, which has decreased to below 30 °C

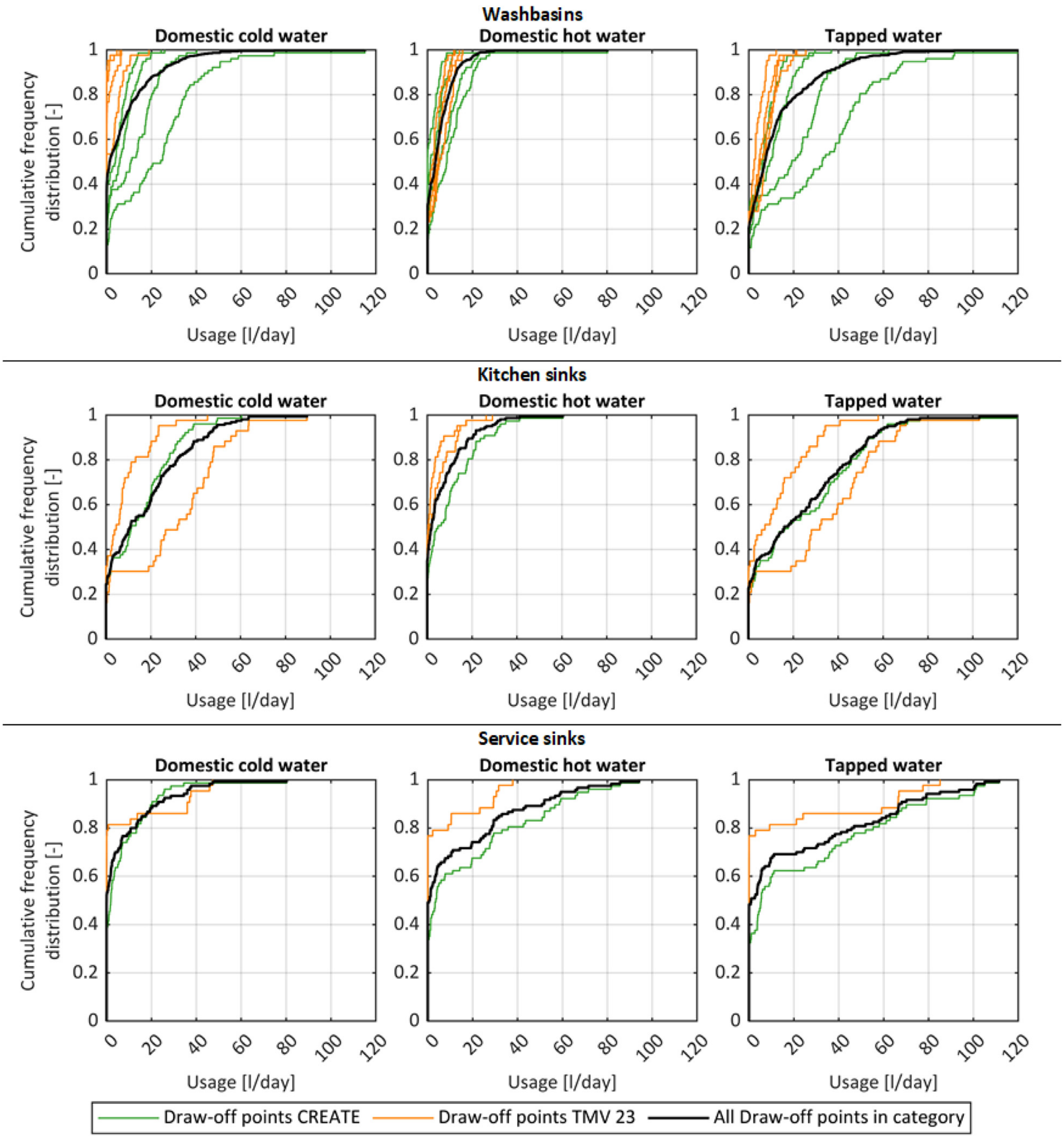

Fig. 5. Daily usage of hot, cold, and tapped water from washbasins, kitchen sinks and cleaning sinks in CREATE and TMV 23.

after 60 min, even with 40 mm of insulation. Consequently, the water temperature in connection pipes is around room temperature if the breaks between two draw-off actions are above 60 min. If the pipes are non-insulated, as they are in the rooms in CREATE and TMV 23, it only takes 33 min for the hot water temperature to drop from 55 to 30 °C. The temperature decays in Fig. 7 are calculated as a 1D heat balance between heat transfer through solid materials (conduction), surface heat transfer (convection and radiation), and thermal heat storage. From this calculation, a temperature change per second is calculated.

Fig. 8 demonstrates measured temperatures and flow rates for cold, hot, and tapped water for all measured washbasins. According to the low flow rates and the short draw-off actions, most of the tapped water is the stagnated water in pipes not covered by the recirculation. Consequently, most tapped hot water per washbasin is below 30 °C.

An interesting finding for the washbasins is the different temperatures and flow rates for hot and cold water between the two buildings. Higher hot water flow rates with lower temperatures are tapped at TMV 23, whereas CREATE has higher flow rates and lower temperatures on the cold water. Still, the tapped temperatures and flow rates follow the same tendency. Presumably, the flow rate is changed depending on the hot and cold water temperature, so the tapped temperature is comfortable or acceptable for the user. This is seen from the washbasin on the ground floor in CREATE, where the hot water supply temperature is above 40 °C 66 % of the time. However, the tapped temperature still follows the other washbasins with significantly lower hot water tempera-

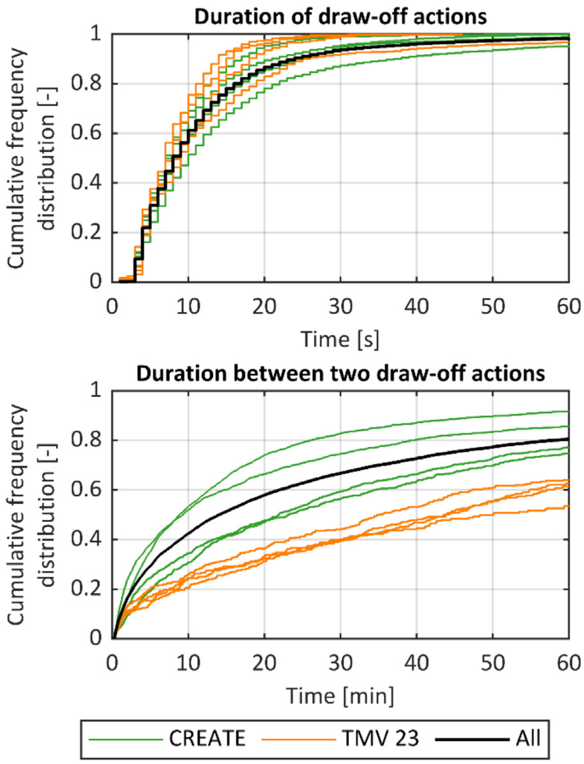

Fig. 6. Draw-off durations and durations between two draw-off actions at washbasins. Note different x-axis.

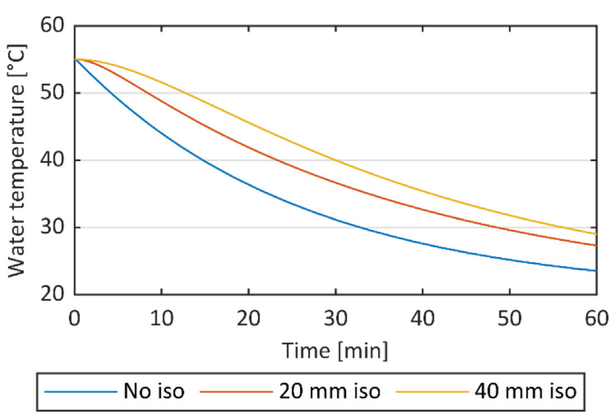

Fig. 7. Flow rate and temperature of hot, cold, and tapped water at washbasins.

tures available. The tapped temperatures for washbasins are 79 % of the time below 30 °C, which is the recommended design temperature from DS 439 [18].

Additionally, an initial investigation in TMV 23 showed a clear tendency for users to adjust the temperature setting when the tapped temperature is below 23–25 °C. From 8:00 to around 10:30, a few adjustments of the temperature settings were observed, as the cold water is around room temperature caused by the stagnation time during the night. As the cold water use rise during the morning, the cold water temperature usually drops from room temperature to 10–15 °C, and temperature adjustments at the washbasins start to happen.

The velocity (flow rate) in the distribution and connection pipes is essential to secure a fast water transition from the supply to the draw-off points. Therefore, the flow rates according to the pipe dimensions of the distribution and connection pipes have been investigated. It is clear for all washbasins that the hot water flow rate rarely reaches the design flow rate of 6 l/min from [18]. As a result, the water stagnates in the connection pipes, losing most of the energy before it is tapped, as seen in Fig. 3, where the magnitude of loss from distribution and connection pipes is close to or higher than the magnitude of utilized energy.

The length of the connection pipes influences the hot water temperature at the washbasins. The length of the connection pipes at CREATE is generally lower than at TMV 23. The length of connection pipes to washbasins at CREATE is around 3–6 m compared to 5–9 m at TMV 23, and the hot water temperatures are thus generally lower at washbasins at TMV 23. The tapped hot water is usually the stagnated water in the connection pipe.

3.5.2. Kitchen sinks

The investigated kitchen sinks are located in small student and staff kitchenettes and are primarily used to tap drinking water and small cleaning purposes. The kitchenettes have no oven or cooking plate, and whole meals are not prepared.

The three kitchen sinks have similar usage, see Fig. 9. The duration of draw-off actions is very similar and is average 72 % of the time below 20 s and 47 % of the time below 10 s, generally longer than the draw-off actions for washbasins shown in Fig. 6. Most of the breaks are below 30 min, where the water temperature in the connection pipes with 20 mm of insulation still are above 35 °C, according to Fig. 7.

Fig. 10 shows the measured temperatures and flow rates for hot and cold water at the three investigated kitchen sinks. Again, similar distributions are seen, indicating that kitchen sinks in kitchenettes have more similar use patterns in different buildings than washbasins.

For the kitchen sinks, an interesting finding is the cold water temperature, which is above 20 °C 60 % of the time. The kitchen sinks seem to be used most for tapping drinking water or other purposes, where no hot water is needed as the tapped temperature is below 25 °C 64 % of the time.

The hot water flow rate is below 6 l/min 88 % of the time for the three kitchen sinks, where the connection pipes are designed for 12 l/min according to [18]. These lower flow rates raise the question of a mismatch between actual and design flow rates or if the design flow rate from [18] is the maximum allowed flow in the connection pipes. If the design flow rate could be lowered and then accept a percentage of time with exceeded flow rates, the velocity in the connection pipes would increase and optimize the water temperatures at the kitchen sinks. The same applies to the other draw-off types.

3.5.3. Service sinks

The investigated service sinks are mainly used by the cleaning staff to tap water for cleaning purposes. Fig. 11 shows that the 50th percentile of measured draw-off durations for the service sinks is 17 s. The draw-off actions for service sinks are longer than for washbasins and kitchen sinks. Furthermore, the service sinks also have higher flow rates, as shown in Fig. 12. The service sinks are used differently between TMV 23 and CREATE. At CREATE, hot water is tapped with higher flow rates than TMV 23. Vice versa is, the cold water flow rate higher at TMV 23. Consequently, the tapped flow rate is very similar between the two buildings, but the tapped temperatures differ. The most important factor for the service personnel seems to be the high flow rate, to quickly fill the floor washing machines or a bucket of water.

3.6. Flow rate comparison between measured and design

As described, the flow rates in the connection and distribution pipes to washbasins and kitchen sinks are mainly below the design

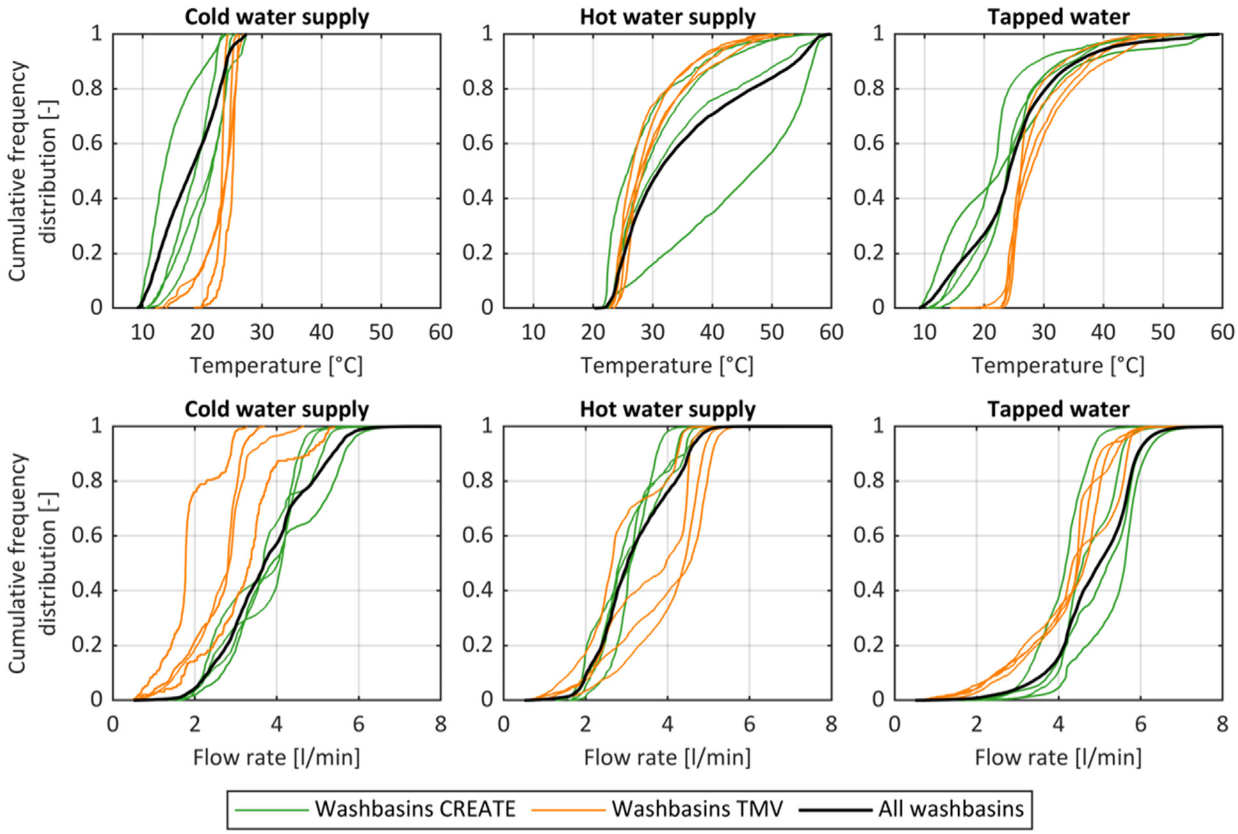

Fig. 8. Temperature decay of stagnated water in 12 mm stainless steel pipe (10 mm inner diameter) with varying insulation thickness.

flow rates from [18]. This subsection investigates the flow rates in two distribution pipes at TMV 23, supplying water for multiple draw-off points. The measured flow rates in these distribution pipes show the actual simultaneity factor between draw-off points compared to the design case.

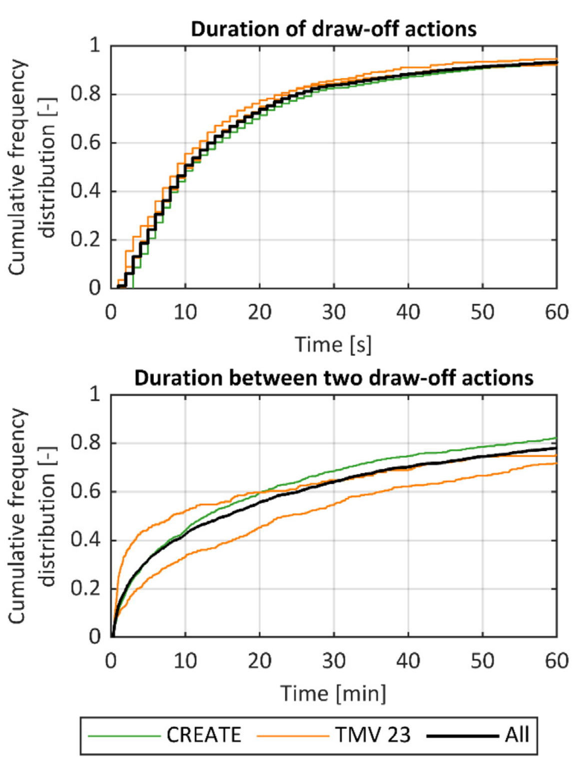

Fig. 9. Draw-off durations and durations between two draw-off actions at kitchen sinks.

Fig. 13 shows the measured flow rates and the design flow rate from [18] in two distribution pipes. The most significant variations are seen for the water flow rates in the distribution pipes on the 3rd floor, supplying three washbasins. The hot water pipe is designed for 15 l/min, but the maximum flow rate in the measurement period of 42 days is 8.6 l/min, and 99 % of the time, the hot water flow rate is below 5.3 l/min. The cold water flow rate on the 3rd floor is also significantly lower than the design flow rate. However, the increase of the cold water temperature due to stagnation in the distribution pipes is not as critical as the hot water temperature decrease when looking at the energy utilization and comfort at washbasins. During the total time with hot water flow to the three washbasins, only 0.3 % of the time, two washbasins are used simultaneously. For cold water, it is 0 %.

The measured and design flow rates for the distribution pipes on the 2nd floor supplying water to two kitchen sinks, shown in the upper graphs in Fig. 13, have smaller deviations from the design value than the distribution pipe on the 3rd floor. Still, the hot water distribution pipe has significantly lower measured flow rates than prescribed by [18]. Again, only 0.4 % of the total time with hot water flow, the two kitchen sinks are used simultaneously. For cold water, it is 0.2 %. For all nine investigated draw-off points at TMV 23, it is 0.8 % of the time with hot water flow that two draw-off points are used simultaneously, and 0.7 % for cold water. Consequently, the simultaneity factor for draw-off points is very low in university/office buildings.

4. Discussion

The measurement campaigns are conducted from October 2018 to January 2019 and April 2021 to May 2021, with high occupancy

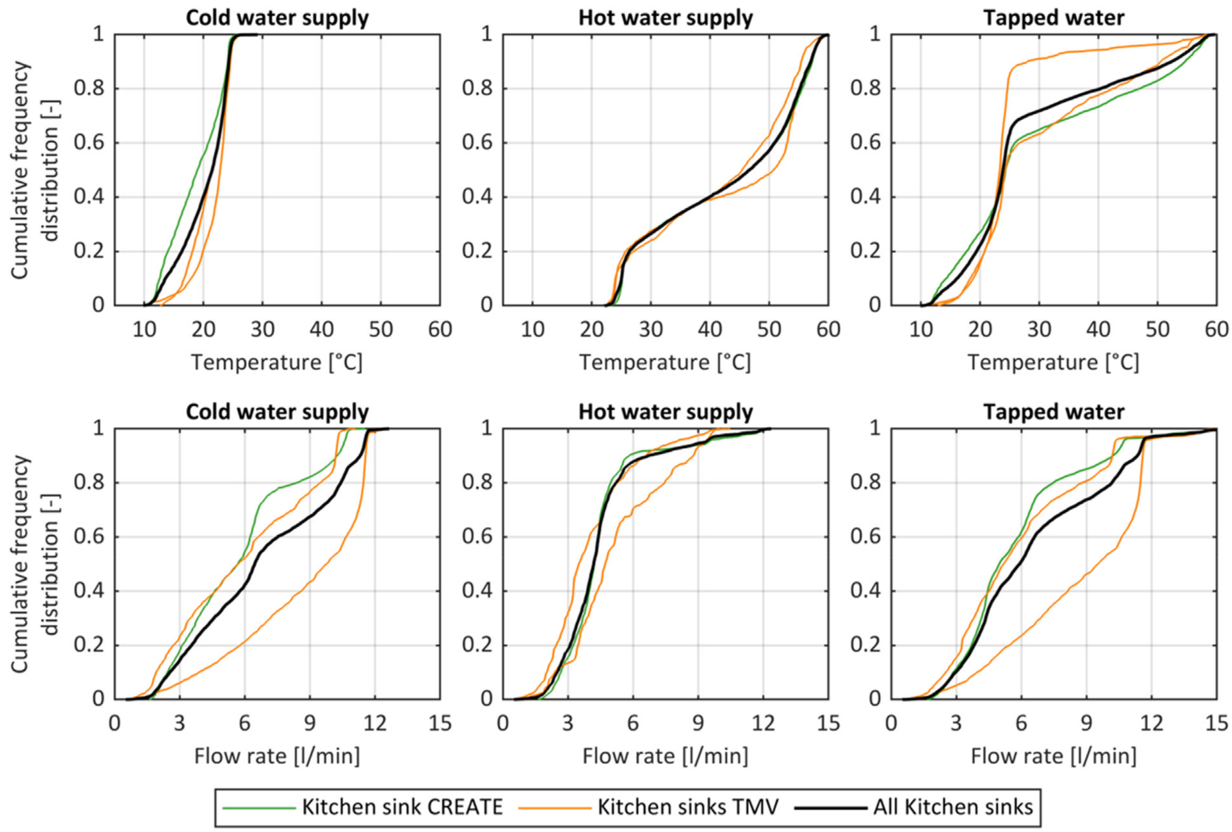

Fig. 10. Flow rate and temperature of hot, cold, and tapped water at kitchen sinks.

rates. In these university buildings, the occupancy rate is highest from February to May and September to December due to the students' presence. In January and June, the presence is lower since most students are preparing for exams at home. There are no students in the buildings in July and August, and staff presence is low due to the summer holidays. Suppose the measurement campaigns were conducted in other periods of the year. In that case, the authors believe that the results presented in this paper would not have been significantly different, especially not energy-wise better when recirculation and HEX losses have a significant loss, as shown in Fig. 3. The water use is lower during the summer holidays and the utilized energy will be even lower.

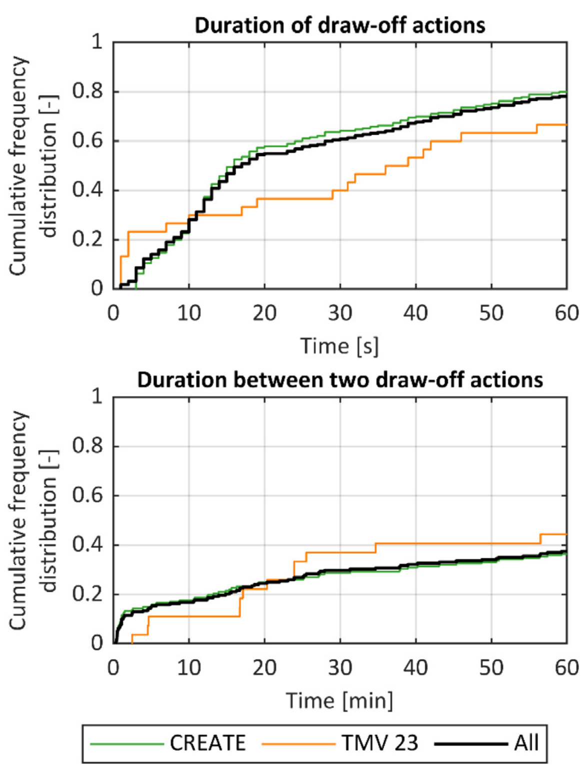

Fig. 11. Draw-off durations and durations between two draw-off actions at service sinks.

The results of this measurement campaign can be generalized to other non-residential buildings with similarly DHW setup, e.g. recirculation and no showers. With this measurement campaign, a data collection of measured domestic water use is started. For the authors, nothing indicates that these results can not be used in other parts of the world. However, more measurement campaigns in Denmark and other countries can help extend the knowledge of geographical impact.

By comparing the total measured DHW use for CREATE and TMV 23 (13.6 l/m^2/year and 16.2 l/m^2/year) with the design value from Danish building regulation (100 l/m^2/year) [5], it is evident that the building regulation overshoot the use. The main reason for this overshoot is that only two design values for DHW use are selectable, residential and non-residential. Non-residential covers a large building variety, with significantly different DHW demands. From low consumers as, offices, and education institutes to high consumers as hospitals and sports centers. A Danish measurement campaign [19] shows that showering is the crucial DHW draw-off point, with 76–86 % of the total DHW use. The authors suggest the design value for DHW use can be divided into more than two categories or a lower design value with an option to add an extra use if a shower is available in the building.

Furthermore, the measurements show an insufficient cooling of the DH over the HEX, as it is not possible to get the DH return tem-

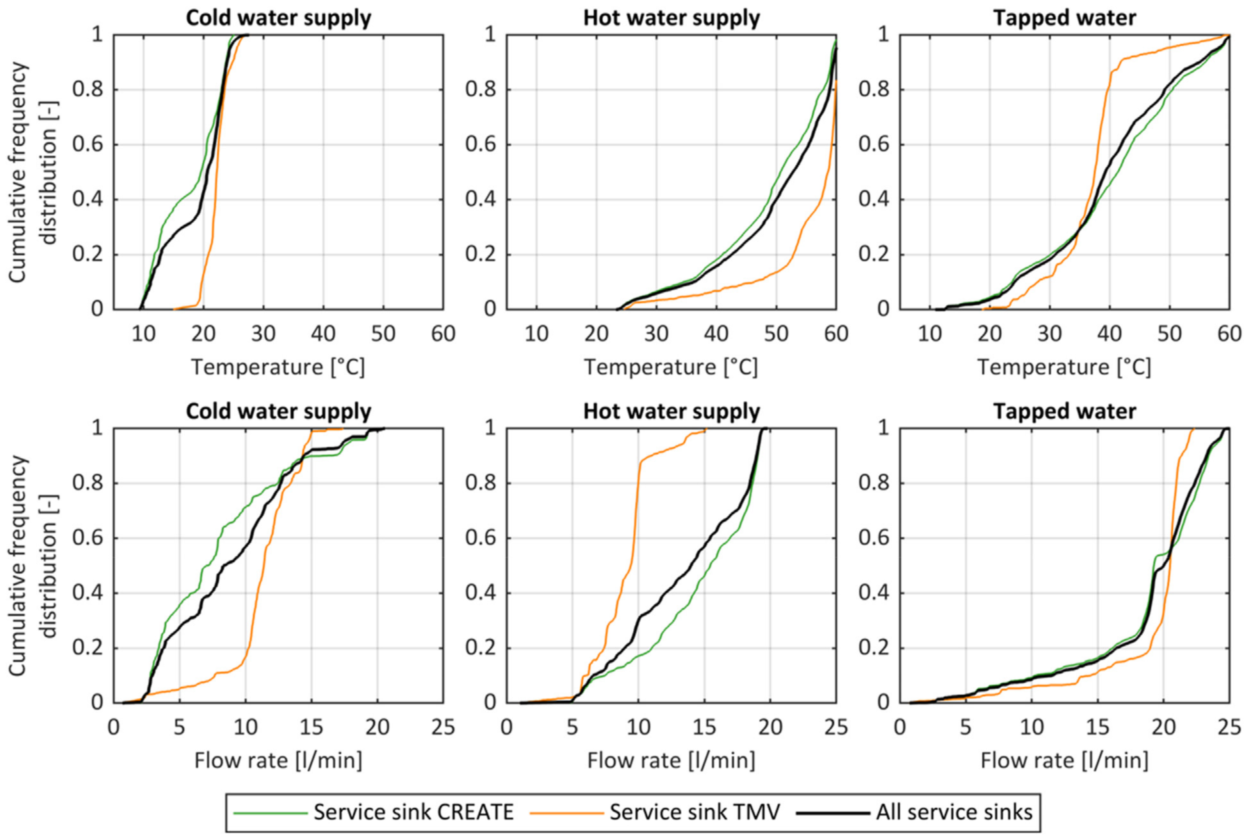

Fig. 12. Flow rate and temperature of hot, cold, and tapped water at service sinks.

perature below the recirculation return temperature. In the entire lifetime of the two buildings, the average coolings of the DH used for all DHW productions are 14.1 °C and 14.4 °C for CREATE and TMV 23, respectively. Looking at the three investigated DHW systems individually, the average cooling is 17.6 °C, 12.1 °C, and 9.8 °C at CREATE, TMV 23 2nd floor, and TMV 23 3rd floor, respectively. The higher cooling at CREATE is due to a higher DH supply temperature to the HEX. The poor utilization of DH for DHW systems with recirculation is not considered in Danish energy compliance calculations [20]. In Denmark, such poor utilization is punished by additional expenses to the public utility, and more work in addressing this operation cost should be performed.

The utilization of DH for DHW production in systems with recirculation and relatively low DHW use (like the investigated buildings) does not seem to be the optimal solution. The high return temperature of DH is problematic. The DH return from DHW production can be utilized for space heating in cold seasons. However, in warm periods with no need for space heating, the DH either has a high return temperature to the public utility or the heat is lost from the DH pipes in the building, which is disadvantageous according to overheating/cooling needs. If DH is not used for DHW production, it could be possible to shut off the DH in warmer periods.

There is a clear correlation in use patterns between the draw-off types across CREATE and TMV 23 when looking at the measured duration of draw-off actions, flow rates, and temperatures. With more measurements from different non-residential buildings, it could be advantageous to use measured draw-off profiles to design DHW systems instead of presupposed values from technical standards. Using measured draw-off profiles would better estimate the simultaneity factor between different draw-off points, as described in section 3.6. New design methods taking these simultaneity factors into account would be advantageous to develop. It could be a design tool for selecting pipe diameter using actual measured flow rates from a database instead of presupposed values.

The DCW systems also show room for improvement. Preferably, the cold water temperature is around 10 °C, and the Danish Ministry of Environment and Food recommends keeping the cold water temperature below 12 °C [21]. The cold water at kitchen sinks, where drinking water is tapped, is 97 % and 60 % of the time above 12 °C and 20 °C. When the cold water temperature is above 20 °C, most of the time (time with no draw-off actions), it is in the temperature range where Legionella grows (20–48 °C) [22]. Legionella also has good conditions in most distribution and connection pipes for hot water. In some periods, the connection pipes to kitchen sinks and service sinks have sufficient temperature to limit or kill the Legionella growth. The water in the connection pipes to the washbasins, to a rare degree, gets above 50 °C, which is where the Legionella growth stops and has a decimal reduction time[2] of 80–120 min [22]. Therefore, Legionella seems to have excellent conditions in connection and distribution pipes to draw-off points with short draw-off actions and relatively low flow rates. This issue must be examined, as it is a health risk for the users, which can occur in many buildings.

For future work, more measurements in various non-residential buildings are needed to specify the use pattern to a degree where enough data is available to design water systems. Furthermore, investigations of the users' comfort preferences for flow rate and temperature at washbasins could be valuable information for designing DHW systems. The measurements show that the tapped water temperature at washbasins is below the recommended 30 °C

[2] Decimal reduction time is the required time to kill 90 % of a colony of microorganism under specified condition and constant temperature [22].

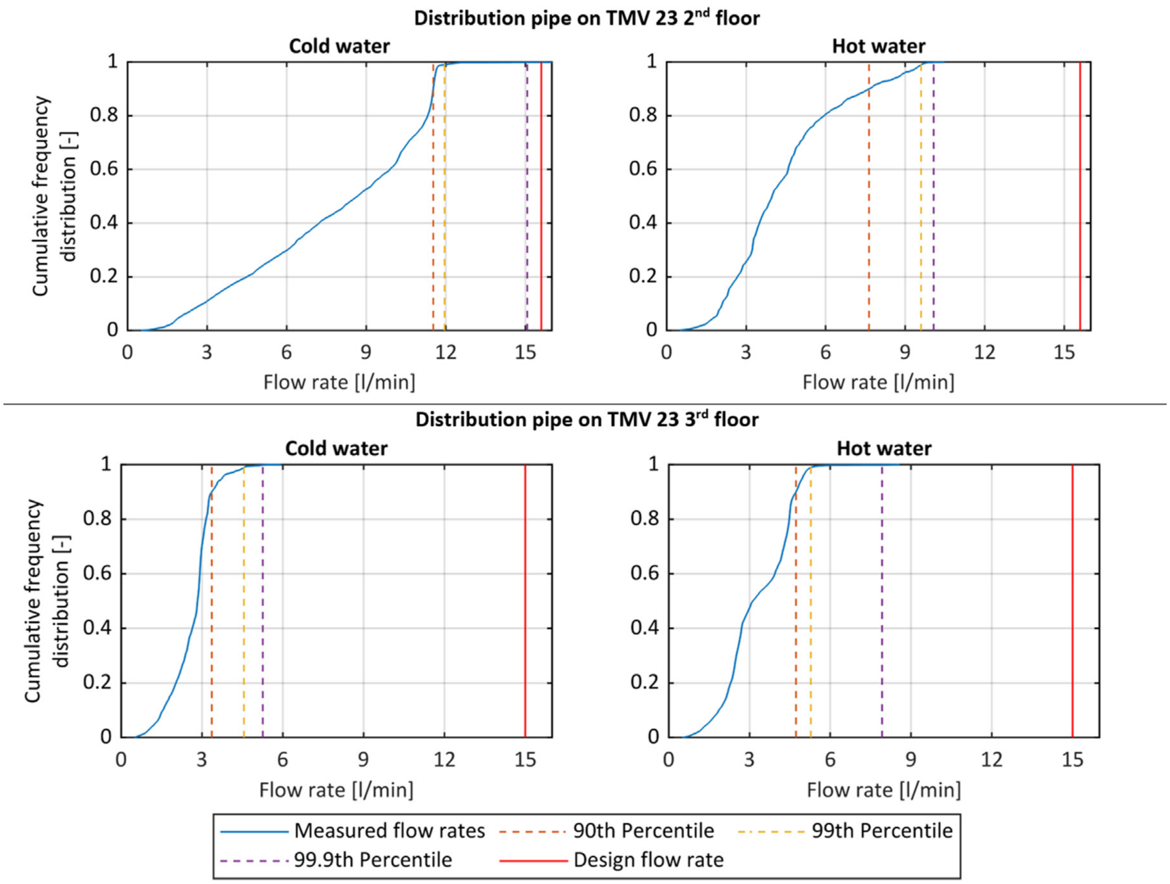

Fig. 13. Comparison of the measured and design flow rates in the hot and cold distribution pipes in TMV 23 2nd and 3rd floor. The distribution pipes on the 2nd floor are supplying two kitchen sinks. The pipes on the 3rd floor are supplying three washbasins. The design flow rates are calculated with use of DS 439′s presupposed values [18].

from [18], 79 % of the time. The measured temperatures raise the question if the tapped temperature below 30 °C is acceptable or if the systems are poorly designed. Furthermore, an initial investigation in TMV 23 shows that the users change the temperature setting when the tapped water temperature gets below 23–25 °C.

The location and heat source for DHW production needs to be further investigated. From the low DHW usage in an office and educational building, the heat source and location of the DHW production must be assessed. Electrical heaters placed close to the draw-off points could be advantageous, removing a significant share of the DHW and DH distribution pipes and associated heat losses.

5. Conclusion

This paper has presented high frequency measurements of domestic water systems in two Danish office and educational buildings. The measurements show very low energy efficiencies; 3.4 %, 5.9 %, and 7.5 % from three investigated DHW systems due to substantial heat losses from especially the recirculation circuit and the HEX; 87.1 %, 89.2 %, and 89.1 %. Furthermore, heat losses from connection and distribution pipes cause a significant temperature decay of the hot water due to stagnation in the pipes.

The measurements of DHW usage show that the design value from the Danish building regulation overestimates the DHW usage in the investigated building significantly. However, the measurements show similarities in use patterns between the two buildings, both on building level and for three investigated draw-off types: washbasin, kitchen sink, and service sink. Each draw-off type has the same characteristics in draw-off duration, tapped flow rate, and tapped temperature. On the other hand, the daily usage per draw-off point varies due to changing number of draw-off actions per day. This variation in daily usage puts great demands on the DHW systems to manage various situations.

Furthermore, the measured tapped hot water temperatures at washbasins and kitchen sinks are often below the recommended temperature from [18]. The flow rates in distribution pipes are also significantly below the design flow rates. Two pipes for hot and cold water supplying three washbasins with water are designed for 15 l/min, but the measurement shows that the flow rate 99 % of the time is below 5.3 l/min.

From this measuring campaign, advice to other measurement projects can be given:

- First, perform initial test measurements with combined measurement equipment and data logging system before installing in systems. Initial tests can indicate faulty operation and data points.
- Second, be aware that in water systems, pressure changes in the system can indicate a false flow in a flow sensor.
- Third, measuring range from the manufacturer is not necessarily a rigid boundary. A test can prove the utilization of a wider measuring range. However, there can be a lower accuracy outside the range announced by the manufacturer.
- Fourth, to reduce the data storage of logging domestic water systems, only log data when there is a change in flow rate. Nevertheless, get a single data point regularly (this measurement setup uses every-five minutes) to indicate that the equipment is functioning. Then the logging frequency can be as high as the equipment allows.

The measurements presented in this paper contribute to filling the knowledge gaps in water use patterns in office and educational buildings. Knowledge can be used to design water systems with higher energy efficiencies and user comfort than in the two investigated buildings.

6. Data availability

The data set as supplementary material for this work is available in [23] and the DCE Technical Report describing the measurement location, equipment, and data structure is available in [24].

By using the data set in published work, this paper should be cited.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

The data set and data description is published in two publication. Availability is stated in the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] European Commission, "Energy performance of buildings directive," 2022. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed May 13, 2022).

[2] International Energy Agency, "Buildings - A source of enormous untapped efficiency potential," 2022. https://www.iea.org/topics/buildings (accessed May 13, 2022).

[3] M.Z. Pomianowski, H. Johra, A. Marszal-Pomianowska, C. Zhang, Sustainable and energy-efficient domestic hot water systems: A review, Renew. Sustain. Energy Rev. 128 (Aug. 2020), https://doi.org/10.1016/J.RSER.2020.109900 109900.

[4] H. Erhorn and H. Erhorn-Kluttig, "Selected examples of Nearly Zero Energy Buildings," Sep. 2014. Accessed: May 13, 2022. [Online]. Available: https://www.systemevergreen.ch/wp-content/uploads/2018/04/CT5_Report_Selected_examples_of_NZEBs-final.pdf.

[5] Bolig- og Planstyrelsen, "Bygningsreglementet," 2022. www.bygningsreglementet.dk (accessed May 13, 2022).

[6] K. Ovesen, Cirkulationssystemer for varmt brugsvand, Hørsholm, unknown, Statens Byggeforskningsinstitut, 1982.

[7] B. Bøhm, F. Schrøder, N.C. Bergsøe, Varmt brugsvand: Måling af forbrug og varmetab fra cirkulationsledninger, 1th ed., SBI forlag, Hørsholm, 2009.

[8] E. Fuentes, L. Arce, J. Salom, A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis, Renew. Sustain. Energy Rev. 81 (Jan. 2018) 1530–1547, https://doi.org/10.1016/J.RSER.2017.05.229.

[9] T.-A. Koiv, A. Mikola, A. Toode, DHW design flow rates and consumption profiles in educational, office buildings and shopping centres, Smart Grid and Renewable Energy 04 (03) (2013) 287–296, https://doi.org/10.4236/sgre.2013.43035.

[10] S. Nair, H. Hashim, L. Hannon, E. Clifford, End use level water and energy interactions: A large non-residential building case study, Water (Basel) 10 (6) (Jun. 2018) 810, https://doi.org/10.3390/w10060810.

[11] T. Kitzberger, D. Kilian, J. Kotik, T. Pröll, Comprehensive analysis of the performance and intrinsic energy losses of centralized Domestic Hot Water (DHW) systems in commercial (educational) buildings, Energy Build. 195 (Jul. 2019) 126–138, https://doi.org/10.1016/J.ENBUILD.2019.05.016.

[12] S. Edwards, I. Beausoleil-Morrison, A. Laperrière, Representative hot water draw profiles at high temporal resolution for simulating the performance of solar thermal systems, Sol. Energy 111 (Jan. 2015) 43–52, https://doi.org/10.1016/j.solener.2014.10.026.

[13] A. Marszal-Pomianowska, B. Valeva, V. Georgieva, O.K. Larsen, R.L. Jensen, C. Zhang, High resolution measuring system for domestic hot water consumption. Development and field test, Energy Procedia 158 (Feb. 2019) 2859–2864, https://doi.org/10.1016/J.EGYPRO.2019.01.1022.

[14] saint Gobain Denmark A/S - ISOVER, "Declaration of performance (DoP)-TEK0001-005," Vamdrup, Mar. 2018. Accessed: Aug. 02, 2022. [Online]. Available: https://www.saint-gobain.dk/sites/mac3.saint-gobain.dk/files/assets/MAM/assets/1/5FCEE7EEC7B5434E9A85A976BAA13A44/doc/083E0EE9F6BD42A194AB50CAA393A7CF/DoP-ISOVER_BoaFlex_Pipe_Section-ENG-03.18.pdf.

[15] Katronic Technologies Ltd., "KATflow 100 Standard Clamp-On Ultrasonic Flow Transmitter," 2015. [Online]. Available: www.katronic.co.uk.

[16] Huba Control, "Flow sensor 236," 2022. https://www.hubacontrol.com/en/products/vortex-flow-sensor/vortex-flow-sensor-236 (accessed May 13, 2022).

[17] Seluxit A/S, "Product Overview SLX Porcupine." Accessed: May 13, 2022. [Online]. Available: www.seluxit.com/wp-content/uploads/2020/01/porcupine_product_overview.pdf.

[18] Dansk Standard, "Norm for vandinstallationer Code of Practice for domestic water supply installations," Jul. 2009.

[19] A. Marszal-Pomianowska, R.L. Jensen, M. Pomianowski, O.K. Larsen, J.S. Jørgensen, S.S. Knudsen, Comfort of domestic water in residential buildings: flow, temperature and energy in draw-off points: field study in two danish detached houses, Energies (Basel) 14 (11) (Jun. 2021) 3314, https://doi.org/10.3390/en14113314.

[20] S. Aggerholm, K. Grau, *Bygningers energibehov : beregningsvejledning.*, 5. udg, Statens Byggeforskningsinstitut. Aalborg Universitet, Hørsholm, 2018.

[21] Miljøministeriet, "Bekendtgørelse om vandkvalitet og tilsyn med vandforsyningsanlæg," Oct. 2019. Accessed: May 13, 2022. [Online]. Available: https://www.retsinformation.dk/eli/lta/2019/1070.

[22] Jamie. Bartram, Y. Chartier, J. v. Lee, K. Pond, and S. Surman-Lee, *Legionella and the prevention of legionellosis*. World Health Organization, 2007. Accessed: May 13, 2022. [Online]. Available: https://apps.who.int/iris/handle/10665/43233.

[23] M. Frandsen, J. V. Madsen, M. Z. Pomianowski, and R. L. Jensen, "Data set - Domestic water at CREATE and TMV23," *VBN*. Aalborg University, Aalborg, Aug. 2022. 10.5278/hjq4-9673.

[24] M. Frandsen, J. Vind Madsen, R. Lund Jensen, M. Zbigniew Pomianowski, Domestic water measurement in two Danish office and educational buildings - Data set description, Aalborg (Aug. 2022).