RESIDENTIAL DOMESTIC HOT WATER CONSUMPTION ANALYSIS FOR MULTIFAMILY BUILDINGS SUPPLIED BY DISTRICT HEATING

by

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The exact knowledge of domestic hot water (DHW) and heat consumption is necessary in the process of heat cost allocation and planning. In Hungary, heat cost allocation is based on summer months' heat demand. This method does not lead to an accurate result due to the fact that the DHW demand varies throughout the year. There are several studies dealing with consumption data analysis, but only some of them have exact estimations on DHW usage patterns the Central-Eastern European countries. In this paper the DHW consumption was analyzed in 115 "commi block" buildings, which are common in Central-Eastern Europe and Russia and are usually connected to the district heating network. The examined buildings are located in Budapest, Hungary. The installation of the monitoring system has started in December 2012. The consumption data is collected since March 2014. The DHW usage was calculated in different cases for every month: per heated area, per heated volume, and per flat. Average daily and annual data was also determined, the share of yearly DHW consumption over the months was calculated. The average daily and annual DHW consumption are 126 L per flat and 892 L per m^2, respectively. The average net heat consumption is 28.2 kWh/m^2 annually. Different DHW demand influencing factors were examined: the outdoor temperature and the residents' travelling habit is clearly influencing the DHW usage but no connection was found between the DHW consumption and economic indicators. The DHW consumption is approximately 30% higher in the winter than in the summer.

Key words: *DHW, district heating, water consumption, prefabricated building*

Introduction

The energy consumption of the buildings is significant: they consume 40% of primary energy in the EU [1]. In addition, buildings are responsible for 33% of greenhouse gas emission in the EU and 39% in the USA [1, 2].

The energy usage of heating is reducing due to different energy efficiency measures and therefore the exact knowledge of DHW consumption is getting more and more important. This trend is reflected by its large share in energy usage: DHW is responsible for 14% of the energy demand in the EU and 18% in the USA [3]. Residential buildings are the biggest DHW consumers: they account for 72% of DHW demand [4]. In these buildings the DHW consumption is approximately 30% of the energy demand but different rates are given in dif-

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ferent papers [5]. For example the energy demand of DHW in residential buildings is 20% of the total energy usage in Canada, 27.7% in Japan, 13% in Germany and 20% in UK [6-9].

District heating provides the opportunity to supply the DHW and space heating consumption in an environmental friendly and energy efficient way [10]. Applying this technology, the flue gas emission could be decreased and centralized out of the populated area, the energy consumption could be reduced and renewable energy sources could be integrated into the energy system [11].

Individual metering also provides a great opportunity to decrease the DHW and space heating energy consumption in residential buildings since after the installation 15-20% of energy could be saved [1]. Individual metering also gives the possibility for consumers to get details about their energy consumption [12].

The energy usage of the buildings is affected by different features. These are *the climate, the building-related characteristics, the user-related characteristics, the building service systems and operation, the building occupants' behavior and activities, the social and economic factors and the indoor environmental quality required* named by a Canadian-Japanese study [13].

Different opportunities are available to examine occupant behavior with different level of complexity using different methodologies. The behavior could be analyzed not only with the help of mathematical methods but simulations and caseworks could also be created [14]. The behavior of the occupants influences greatly the energy use in buildings. Changing the behavior, the energy consumption in residential and commercial buildings could be reduced by 10-25% and 5-30%, respectively [15].

The DHW consumption was analyzed in several studies. The quantity of DHW use is clearly affected by the weather conditions: the DHW consumption is higher in colder months than in warmer ones [16]. It was also established that more DHW is used for non-sanitary purpose in winter than in summer [14]. The number of occupants in a household significantly influences the average DHW consumption and difference could be recognised between the weekdays' and weekends' DHW profiles as well [4, 5]. The knowledge of daily DHW profiles are also important. Studies show that two peak consumption periods could be recognized in the daily profiles: one in the morning and one in the evening [17-19]. During these peak periods, the average DHW use is several times higher than in non-peak periods [17]. The share of DHW demand in the European residential buildings is: 36% dish/cloth wash, 40% shower, 10% bath, 14% sink [20]. In case of residential buildings in the USA, this share is: 19% cloths, 6% dish wash, 35% shower, 8.5% bath, 31.5% sink [20].

The DHW consumption, tab. 1, depends on the geographical location. The consumption is higher in Canada and in the USA than in European countries. The DHW consumption value also changes over the years. For example, the DHW demand in Denmark was 10 m^3 per person annually in 1989 and this value increased in 20 years to 15 m^3 per person annually (2009) [21]. Another example is Germany, where the ratio of DHW demand from total energy usage in non-residential buildings increased from 6% to 7% in 9 years (2005-2014) [22].

In this paper Hungarian prefabricated large panel system buildings were examined. All of them are connected to the district heating network and located in Budapest. The examination of these kind of buildings is important while they represent substantial part of the building stock in Hungary and in CentraL/Eastern Europe as well [25]. At the second half of the 20th century many of prefabricated large panel system buildings were built in this region due to the post war housing shortage [26]. These buildings are occupied in these days too and will be used for many more decades [26]. In Hungary (2011) 13.3% of the buildings are built

Table 1. Average DHW consumption in different countries

Average daily DHW consumption	Country	Reference
20 L daily per person	Denmark (2010)	[4]
33 L daily per person	Sweden (2012)	[4]
40 L daily per person	Norway (2010)	[4]
40.3 L daily per person	Estonia (2012)	[4]
43 L daily per person	Finland (2007, 2015)	[4]
45 L daily per person	Turkey (1996)	[21]
46 L daily per person	Finland (2012)	[4]
46 L daily per person	Hungary (2013)	[23]
47-86 L daily per person	Ontario, Canada (2003)	[4, 24]
56.8-75.8 L daily per person	USA (1988)	[21]
67 L daily per person	Canada (2011)	[4, 24]
79 L daily per person	Canada (1988)	[21]
119-283.5 L daily per person	USA (1994)	[21]
135 L daily per household	Finland (2007)	[4]
172 L daily per household	Halifax, Canada (2015)	[6]
194.4 L daily per household	Budapest, Hungary (2005)	[24]
208 L daily per household	Canada (2011)	[4, 24]
236 L daily per household	Ontario, Canada (2003)	[4, 24]
239 L daily per household	North America (1990)	[4, 24]
239 L daily per household	Toronto, Canada (1985)	[24]
256 L daily per household	Florida, USA (1988)	[24]

from large panels and 15.5% of buildings connected to different district heating networks. This ratio in Budapest (2011) is more significant: 24.0% of buildings are large panel system buildings and 28.1% of buildings are supplied by district heating [27].

The main objective of this research is to analyze the DHW consumption of residential multifamily buildings. The results show the most important DHW influencing factors and estimated DHW demands. These data could be used in both the process of heat cost allocation and planning of different renewable based energy sources *e.g.* solar collectors. The determined yearly DHW profile could be integrated into building energy simulation software and could provide design criteria for solar collector sizing as well [28].

Examined building stock

In this study the DHW consumption was examined in residential district heated buildings. All the examined buildings are served by the district heating company of Budapest (FOTAV Zrt.). The analyzed buildings are built with prefabricated large panel systems and connected to the online monitoring system. The FOTAV Zrt. provided access to their internal database and the collection of the data started in June 2017. At that time a total of 892 buildings were monitored and therefore these buildings consumption data was available in the database. The data sets could be saved in MS EXCEL format. The buildings were divided into two groups according to their district heating needs: in 125 buildings the heating system, in 767 building the heating and the DHW system were supplied by the district heating network. The 767 buildings where both heating and DHW consumption is present were sorted further based on their properties. In this paper only those buildings were examined in which the residential space rates amount to at least 95% of the total heated volume. The consumption data of these buildings was defective in many cases. Many buildings had for example incomplete time series. Other buildings consumption profile had unacceptable high peak probably due to the replacement of meters or measurement errors. Some buildings had much higher heat consumption in summer than in winter. The buildings with faulty data were removed from the examined database. In conclusion, 240 buildings' DHW consumption could be analyzed. In this paper the focus was on the large panel system buildings, which is a total of 117 buildings. In 2 cases the dataset were incomplete for the examined term too – from the middle of March 2014 to the middle of March 2020 – so finally 115 buildings' (including a total number of 15157 flats) DHW consumption was analyzed, fig. 1.

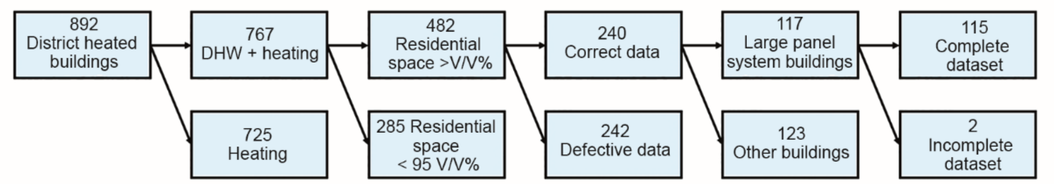

Figure 1. Examined buildings

The location of the analyzed buildings and the features of the city districts are in tab. 2. Half of the buildings are located in district XIII and several buildings are in district XV too. Despite the fact that there are only nine buildings in district III more than 2000 flats belong to them. The share of the employed people between all people are similar in every district but the gross income has wider deviation between the different districts. The difference between the maximum (district XI) and minimum (district XV.) average gross incomes in the examined districts is more than 4500 USD annually per person.

The database of FOTAV Zrt. contains residential space ratio, number of dwellings, heated volume and DHW consumption data. The number of floors, the structure material, the shape of the roof and the size of the buildings were determined through a geoinformatic software. The buildings were visualized virtually and their features were collected manually into a table format. The heated area was calculated from heated volume data using 2.63 m headroom value which is the standard height of panel blocks. Commi block buildings were selected and examined separately because this kind of buildings are more typical and in further researches they could be examined more specifically.

Only one of the examined buildings has pitched roof, all the rest have flat roof. Most of the buildings have several floors: 57% of them have 11 floors and 16% of them have 10 floors. Buildings with five floors are also characteristic, representing 17% of this building stock. The number of the dwellings is between 40 and 360, the heated area of the whole building is between 2300 m^2 and 20624 m^2. The buildings have in average 15 flats in every floor

Table 2. Features of the analyzed buildings and the city districts they are located [27, 29]

District	Examined buildings	Examined flats	Share of employed people	Gross income [thousands USD annually per person]
III	9	2136	44.8%	12.9
IV	1	192	47.9%	11.4
X	6	542	44.7%	10.4
XI	6	891	43.2%	14.5
XIII	57	7671	49.0%	13.3
XIV	8	994	45.1%	13.5
XV	18	1762	44.1%	10.0
XVII	6	400	44.2%	10.9
XIX	1	192	44.6%	10.9
XX	1	129	43.0%	10.2
XXI	2	248	43.7%	10.0

and the flats have average 52 m^2 heated area. The flat number in a floor was calculated as the ratio of number of flats and number of floors. The heated area in a flat was determined as the ratio of the heated are in a building and the number of flats.

The DHW consumption data were measured with different resolutions. The examination of the accuracy was based on the worst scenario when the resolution is 0.1 m^3. If the consumption increase, the relative error decrease. Figure 2 shows the daily average hot water consumption, the number of buildings and the accuracy. The accuracy was calculated based on the measurement accuracy of 0.1 m^3 and the daily average hot water consumption. The analyzed buildings' consumption data have less than 2% relative error.

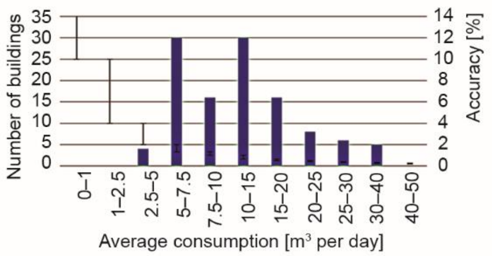

Figure 2. Daily average consumption and accuracy

The DHW consumption analysis

The monthly and daily DHW consumption data were calculated in every building and examined in different cases: per heated floor area, per heated volume and per flat. The monthly and daily values were determined as the average of the same month and day data of examined time period. Figure 3 presents the boxplot diagram of the daily DHW consumption of the buildings. The DHW consumption data have large deviation and their value changes over the year: when the outdoor temperature decreases the DHW consumption increases. Despite the large deviation of the consumption value, 50% of the data is within 20% wide range from the average value.

Annual and daily average DHW consumption data were also calculated. These values could be important in the planning process during the determination of the occupants' future consumption. The average daily consumption is 126 L per flat, 0.93 L per m^3, and 2.45 L per m^2. The annual consumption is 45888 L per flat, 339 L per m^3, and 892 L per m^2.

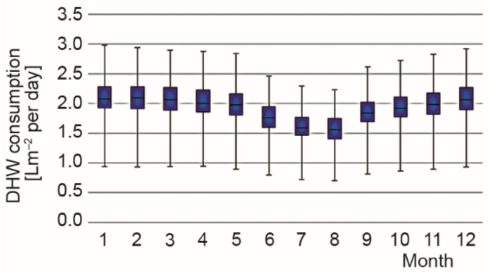

Figure 3. Daily DHW consumption in large panel system buildings

Calculating the average DHW consumption, it was taken consideration that the buildings have different geometry. The value of the heated area, the heated volume and the number of flats have big deviation. The consumption data of each building was examined in the proportion of their physical parameters during the calculation process using the same methodology. Equation (1) shows the calculation method for the determination of per heated area value:

$$V_{\mathrm{DHW,a}} = \frac{\sum V_{\mathrm{DHW},i} A_i}{\sum A_i} \tag{1}$$

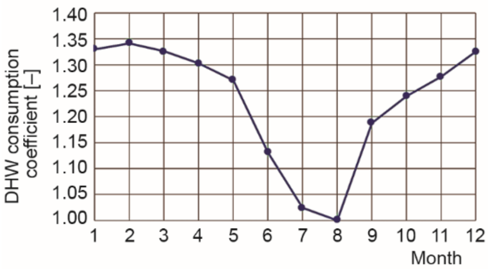

Figure 4. Daily DHW consumption coefficient

The minimal consumption was determined and used as a baseline for the evaluation. The dimensionless data of different cases are very similar: the maximum deviation is only three parts per thousands. Figure 4 shows the daily dimensionless DHW consumption coefficient data when it is normalized with the heated area. When monthly values are applied the difference between the numbers of the days distorts the results. The minimal daily consumption is in August and the maximal consumption is in February. The DHW consumption is approximately 30% higher in winter than in summer months. The effect of the summer holidays is also clearly visible. The big difference between the consumption data in August and in September could also be justified by the difference in flat usage behavior during at the end of summer holiday period and at the beginning of school.

The connection between DHW consumption and travelling habits was examined and presented in fig. 5 [30]. The horizontal axis of the diagram shows the share of the days in a month when people travel and therefore they are not at home and do not consume DHW there. These values were calculated based on a report from the Hungarian Tourism Agency. This report contains the number of trips inland and abroad, the average length of the trips [nights/trips], and their share for months [%] during a year. In the research, 1000 people were asked about their travelling habits. These people were above 18 and were selected to get a representative sample. For this paper only the trips which took several days were examined. In case of one day travelling, people consume DHW at home almost the same way. First, the number of all trips were calculated for every month, then their summed long were determined. After that these values were divided by the number of people to get how many days an average people travel in a month. Then the inland and abroad data were summed and divided by the number of days in a month. Therefore the deviation of the number of days does not distort the results. On the vertical axis is the average daily DHW consumption. A linear trend line was fitted into the data in MS EXCEL, using the method of least squares. On the basis of the figure and the coefficient of determination it could be established that the consumers travelling habits clearly influence the DHW consumption.

Figure 6 shows the daily average DHW consumption compared to the daily average outdoor temperature. For this analysis, the average DHW consumption was calculated in every building using the data of the days with the same daily outdoor temperature. For every daily average outdoor temperature value, the average of the DHW consumption of the buildings was ordered. Different trend lines were framed into the consumption data and the coefficients of determination were calculated. According to the coefficients, tab. 3, and the physical explanation behind the trend of the consumption data, third degree polynomial trend line was fitted in MS EXCEL using the method of least squares. The connection shows that the change of the outdoor temperature influence the change of DHW consumption. At higher outdoor temperature, there is bigger consumption reduction. It occurs not only due to the lower demand of DHW but also because of the summer holidays. Correcting the consumption data according to the travelling habit the data does not change significantly: there is still bigger reduction in higher temperature. It means that there are other influencing factors in DHW consumption, such as the amount of DHW used for showering (length, frequency, *etc.*). However, to analyze such phenomena a much deeper analysis should be done, which requires more detailed measurements and also questionnaires are required, which can help to identify usage patterns and user habits.

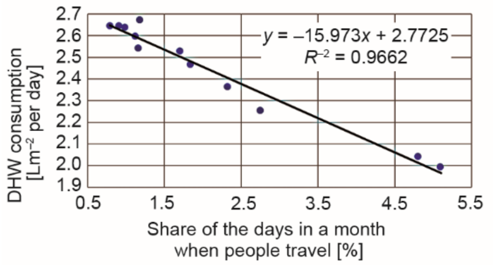

Figure 5. Daily average DHW consumption according to the travelling habit

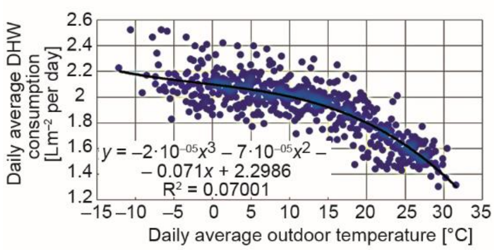

Figure 6. Daily average DHW consumption according to the daily average outdoor temperature

Table 3. Coefficients of determination using different trend lines

Polynomial degree	1	2	3	4	5
R^2	0.6304	0.695	0.7001	0.7106	0.7115

The average annual DHW consumption was calculated in the examined districts as the average of the yearly consumption of the buildings in the districts. These values were compared with the average gross income per capita (2014) and the share of employed people (2011) given to the same districts, fig. 7 [27, 29]. On the basis of the figure there is no significant relationship between these economic indicators and DHW consumption.

The annual net DHW heat consumption per heated area values were determined for every building in accordance with eq. (2). In the process of calculating the specific heat and density of water were determined. The DHW temperature is 50 °C and the cold water temperature is 15 °C. [18]

$$Q = \frac{c\rho V_{\mathrm{DHW},i}(t_{\mathrm{HW}} - t_{\mathrm{CW}})}{A_i 3600} \tag{2}$$

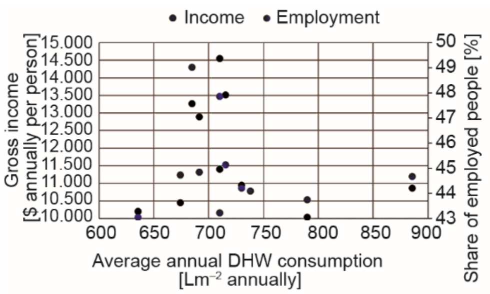

Figure 7. Average annual DHW consumption in different districts

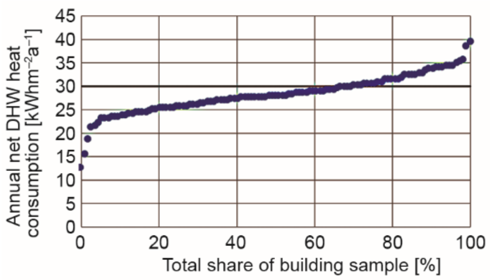

Figure 8. Annual net DHW heat consumption

The controlled value of DHW temperature was also included in the internal database of FOTAV Zrt. The DHW temperature is 50 °C in case of 57 buildings and it is 50 ±2 °C in 80% of the buildings. The 50 °C was not only used as hot water temperature value in eq. (2) because it is the most common value in these buildings but because the average of hot water temperature data is also 49.8 ≈ 50 °C.

The calculated net DHW heat consumption data are in fig. 8. The net DHW heat consumption according to the 7/2006. (V. 24) Decree about Determination of Energy Efficiency of Buildings is 30 kWh/m^2 annually if the heated area is under 80 m^2 [31]. The average flat area – ratio of the total heated area and the number of flats – is between 28-65 m^2 in the examined building stock. Therefore the results were compared with the 30 kWh/m^2 annually reference value. A Chi-squared test was performed for the presented data, which proved that the dataset shows normal distribution. The minimum net heat consumption is 12.7 kWh/m^2 annually, the maximum net heat consumption is 39.6 kWh/m^2 annually, the average net consumption is 28.2 kWh/m^2 annually. On the basis of this examination, the 30 kWh/m^2 annually value determined by the decree is an accurate net DHW consumption value for the examined multifamily buildings.

Conclusions

The DHW consumption data of six years (March 2014-March 2020) was analyzed in 115 Hungarian residential buildings. These buildings are prefabricated large panel system buildings. They are located in Budapest and connected to the district heating system. The DHW consumption was examined in different cases: per heated area, per heated volume, and per flat. The deviation of the measured data is large, the yearly DHW consumption profile was approximated with average values. The DHW consumption increases when the outdoor temperature decreases, due to this fact the DHW consumption is approximately 30% higher in winter than in the summer months. The minimal and maximal consumption occurs in August and in February, respectively. The impact of economic indicators, travelling habits and outdoor temperature was examined. On the basis of the available data, the economic indicators (gross income, share of employed people) do not have significant effect on the DHW consumption. The travelling habits clearly influence the hot water usage, the effect of the summer holidays could be observed. The outdoor temperature also has a great effect on the DHW demand. On the outdoor temperature – DHW consumption data third degree polynomial trend line was fitted. The net DHW consumption per heated area values were calculated for every building. The results were compared with the value determined by the 7/2006. (V. 24) Decree about Determination of Energy Efficiency of Buildings. The distribution of the heat consumption data is normal and the average value is 28.2 kWh/m^2 annually. This value approximates the 30 kWh/m^2 annually data determined by the Decree accurately. Daily average and annual consumption was determined in every case. The daily average DHW consumption is 126 L daily per flat, the annual hot water consumption is 892 L per m^2.

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Nomenclature

A_i – building's heated area, [m^2]
c – specific heat of water (= 4.178), [kJkg^{-1}K^{-1}]
Q – net hot water heat consumption [kWhm^{-2}]
t_{CW} – cold water temperature (= 15), [°C]
t_{HW} – hot water temperature (= 50), [°C]
$V_{\mathrm{DHW,a}}$ – average DHW consumption, [m^3]
$V_{\mathrm{DHW},i}$ – building's DHW consumption, [m^3]

Greek symbol

ρ – density of water (= 988.1), [kgm^{-3}]

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