Domestic hot water consumption in multi-apartment buildings

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Abstract. The article presents the analysis of the hot water consumption in apartment buildings. This study was conducted basing on the data gathered from 626 apartments during two following years. By statistical analysis of the collected data, the correlation between the DHW consumption and both the size of the apartments and the number of occupants in the dwellings was evaluated. The dependencies between the hot water consumption and these two parameters were calculated. The results were compared to the data available in the literature. The article lists the areas of the greatest inaccuracies in the calculations basing on the available indicators and proposes an alternative method that corrects them. The results were used to develop a calculation model for daily hot water usage in multi-apartment buildings.

1 Introduction

Climate changes, rising energy costs and concerns about the energy security require careful analysis of the energy consumption. Residential building sector has consumed 11–35% of total energy at the national levels in most of the countries [1], which is also responsible for higher emission of greenhouse gas. A large part of the final energy supply in residential building is used for the DHW purposes. In 2012 in Poland, the energy consumption in this sector constituted at 18% [2]. However, in new buildings the energy for domestic hot water preparation is an important component, so important is also a description of the hot water consumption. The size of the hot water consumption has a significant impact on the energy consumption.

Consumption of hot water in residential buildings depends on many factors, sociological and technical, that are often impossible to determine. A typical variable used to describe water consumption is the average consumption of water per capita. It is debatable, because it is difficult to determine the number of people living in a building. The main parameters, which are known and can be used as a basis for estimating the consumption of hot water is the number of flats in a multi-apartment building, size of the housing and the sanitary equipment of dwellings. Researchers use different approaches to this problem, as shown in the next section of the article.

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2 Modeling the consumption of hot water

The number of occupants as a parameter of the hot water utilization is the most often analyzed factor in many countries. Parker [3] noticed that the occupants' count is the key determinant of the DHW consumption and used the occupancy pattern in modeling of the national energy consumption. Evarts and Swan [4] found higher DHW consumption in households of three people or less. The authors of the publication also noted higher unit consumption of hot water in homes with fewer residents, which is confirmed by the analysis Ahmed, Pylsy and Kurnitski [5], Merrigan [6], Georg, Pearre and Swan [7] and Hendron & Burch [8]. The authors found a linear relationship between the water consumption and the number of occupants. In the first publication, the authors presented that the consumption increases by 45 l/day for each additional person where the occupant number was above 2, and in the second publication by 39 l/day for each additional person. According to the Canadian Mortgage and Housing Corporation [9], Canadian seniors' buildings consume less than 44% of the DHW comparing to the standard family apartment buildings. In another study the author noted that the presence of children caused a higher consumption rate of DHW [5]. Foekema and Engelsma [10] found that there is also a relationship between the frequency of use and duration of a shower and the age and size of households in Dutch residential building. Unfortunately, despite of many studies, the calculation method used in Poland [11] or Germany [12] is very simplified. Polish regulations [11] concerning calculation of the average daily consumption of hot water uses the total space of a building as a parameter. In case of the German regulation, we have a reference to the number of occupants. However, the authors also added the factor that allows the conversion of the total building area to the estimated number of inhabitants. A very interesting approach can be found in SAP 2012 [13], relating to the dwelling with an area of 450m^2. The authors proposed a function that allows calculation of the number of users using the daily consumption of hot water, and then applied the correction factors to reduce the expected level of water consumption during the summer and to increase it during the winter. When creating simulations of energy use, it is important to utilize the profiles based on data from the actual country and the current economic situation. For this reason, in the further part of the study the authors analyzed the statistical data from the area of Dolny Śląsk and on this basis proposed a different computational model of the hot water consumption in residential buildings.

3 Analysis of the measured data

3.1. The measured data

The article presents the analyzes of the DHW consumption. The analyzes were performed basing on the measurement data from 16 multi-apartment buildings (626 apartments) located in Wroclaw, Poland. Each of the units (the apartments) has been equipped with a residential water meter for measuring the cold and hot water consumption. The data were being gathered every six months. In addition, the analyzes were supported by the data obtained from the estate manager and on the data from the survey regarding the number of people staying in the apartments. Comprehensive data about the apartments' floor area and the annual consumption of hot water came from 626 apartments. The data about the number of installation users was achieved from 78 apartments. The study covered the period from January 2012 to December 2013.

3.2 Analysis method

Basing on the measurement data, the analysis of the correlation between the number of users and the floor area of the apartments and the daily consumption of hot water was performed. For each of the apartments the annual consumption of domestic hot water was calculated (V_{DHW}, m^3/year), as a difference between the measured values at the beginning and at end of the year. Then, on the basis of the equation 1, the daily water consumption ($V_{d,DHW}$) was calculated for each apartment.

$$V_{d,DHW} = V_{DHW} / 365 \text{ [m}^3\text{/day]} \quad (1)$$

The main part of the analysis was focusing not only on the apartments themselves, but on the whole buildings and their hot water consumption model. The annual and daily hot water consumption was determined for each of the 16 buildings. Because all the 16 buildings came from the same residential complex, a new database was created in order to simulate buildings of unusual distributions of housing. The database was created using the measurements of water consumption of 626 apartments. The database consists of randomly simulated buildings, each consisting of randomly selected flats in different configurations. To produce the additional sample data, the bootstrap method was used. As a result, the authors obtained the sample buildings consisting of 4 to 60 flats (in the range of the buildings area from 150 to 3000 m^2).

3.3 Results discussion

In the paper, the ability to describe the daily consumption of hot water in an apartment building by the number of users or by the housing area was analyzed. Basing on the data provided in Table 1 it can be concluded that the average daily consumption of hot water in apartments increases with the number of users, where the number of people does not exceed 3. For the flats with four users, the increase of the consumption of hot water was not observed. However, due to the very small sample size, the apartments with four users cannot be taken as authoritative in this analysis.

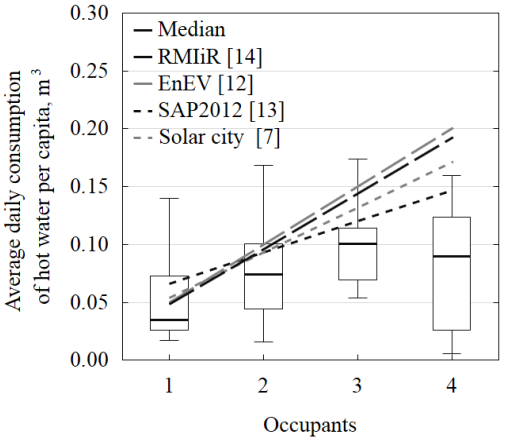

Fig. 1. Occupancy and average daily DHW consumption.

Table 1. Occupancy and average daily DHW consumption.

Occupants	Number of homes	Median	Average
1	15	0.035	0.052
2	41	0.076	0.083
3	17	0.101	0.102
4	5	0.089	0.081
Total	78	0.035	0.081

In the literature, we can find many attempts to describe the DHW demand as depending on the number of users. Figure 1 shows the selected models applied to the measured data. The RMIiR model [14] and the [12] model describe well only the apartments with one user.

This function assumes that each additional person in the household uses exactly the same amount of hot tap water. It does not take into account the fact that some part of the water is consumed on common goals, i.e. housekeeping or cooking. The hot water consumption in flats is well described by the relationship shown in SAP2012 [13], which was developed in order to analyze the energy being consumed to prepare hot tap water in homes in the UK. Similar results were also obtained using the model developed with the data from the Canadian housing in the Solar City [7].

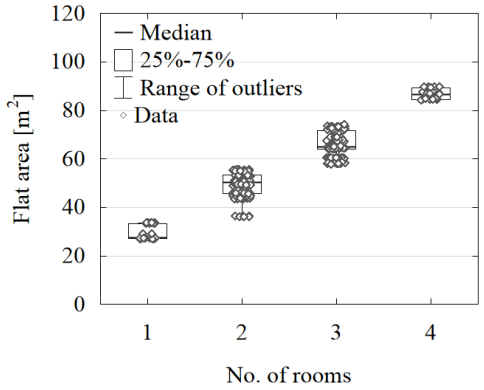

Fig. 2. Correlation between the flat area and the number of rooms.

Table 2. Correlation between the flat area and the number of rooms.

Symbol	No. of rooms	Area flat
M1	1	≤ 35 m^2
M2	2	35.1 – 56.5 m^2
M3	3	56.5 – 79 m^2
M4	4	≥ 79.1 m^2

Additionally, the ability to describe the daily consumption of hot water by the size of the apartments was analyzed. For individual residential units, it is not a good analytical approach. Most of the models assume a linear relationship between the consumption of hot water and the floor area of the flat. For more detailed information about the relationship between the consumption of hot water and the size of a dwelling (which presumably could be correlated with population growth) the relationship between the floor area of flats and the number of rooms in 259 apartments was examined. The data shown in Figure 2 illustrate a strong correlation between the area of a flat and the number of rooms. For further analysis, the classification of housing presented in Table 2 was adopted.

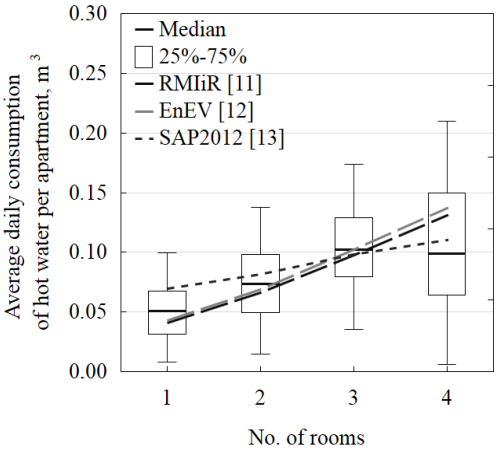

Fig. 3. Number of rooms and average daily DHW consumption.

Table 3. Number of rooms and average daily DHW consumption.

No. of rooms	Number of homes	Median	Average
1	57	0.051	0.051
2	327	0.074	0.074
3	200	0.102	0.104
4	42	0.099	0.105
Total	626	0.082	0.084

Then, the correlation between the number of rooms and the daily consumption of hot water was examined. The results are shown in Table 3 and in Figure 3. The analysis of the average daily hot water consumption shows that with the increase of the number of rooms, and thus with the increase of the floor area of the housing, the consumption of hot water also increases. However, in three- and four-room apartments, this value is stable. This phenomenon may be related to the constant average number of users in the apartments of this size. In addition, figure 3 shows the relationship that is currently being used to calculate the DHW consumption for the purposes of estimating the demand for energy in buildings in Poland, Germany and the UK. The results are shown for an average housing area in each group. The first two models: [11] and [12] do not take into account the fact that in 4-room apartments the water consumption does not differ from 3-room apartments. The method presented in SAP2012 [13] describes the actual average daily consumption of hot water significantly better.

The conducted analysis shows that both variables similarly describe the change in the daily consumption of hot water. Unfortunately, the number of users, which is the most common variable in all sorts of analyzes, is difficult to determine. Therefore, the later studies were focusing mostly on the area and the number of rooms in apartments.

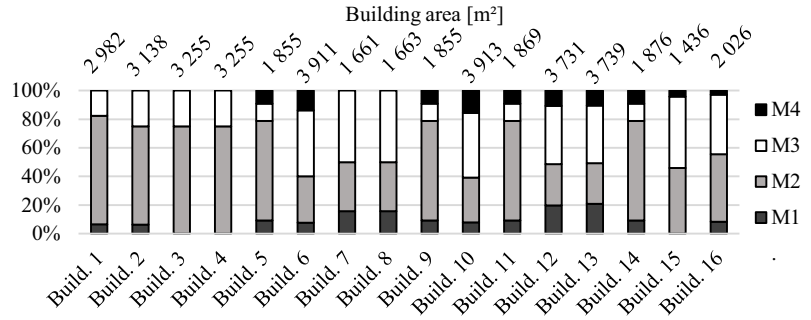

Fig. 4. Specification of the areas and the structures of flats in the analyzed buildings.

The analysis of hot water consumption was performed for 16 buildings located in Wroclaw, Poland. In Figure 4 the buildings' mix of the flat types and their area were presented. Additionally, in Figure 5 the dependency between the daily hot water consumption and the building area was presented. The results were related to the dependency function from the actual Polish procedure of certification. As one can see on the graph, the dependency function from the procedure fits the trend of the data, but significant differences are also visible: from 2% to even 37%. This discrepancy may be a result of the structure of flats in buildings. This is particularly visible in the buildings 1, 2, 3, 7 and 8. In these buildings there are no 4-room apartments. In such cases, the daily hot water consumption is often higher than in other buildings.

Figure 6 shows the hot water demand in the buildings with an unusual distribution of flats. To generate such data the bootstrap method was used, utilizing the measured data of the appropriate apartments. The first chart shows only the buildings with 1-room apartments, the second chart – the buildings with 2-room apartments, third – 3-room apartments and the last – 4-room apartments. For the buildings with 3-room flats, the function proposed in the Regulations [11, 12] coped with the estimation of the hot water consumption quite well. However, in case of the buildings with 1, 2- and 4-room flats, the slope of the function is not as expected. These comparisons suggest that it would be useful to develop a method of estimating the consumption of hot water, which takes into account the structure of a building. Such a method will be proposed later in the study.

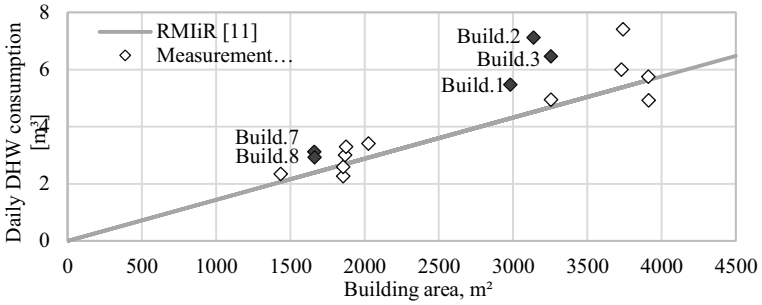

Fig. 5. Building area and average daily DHW consumption.

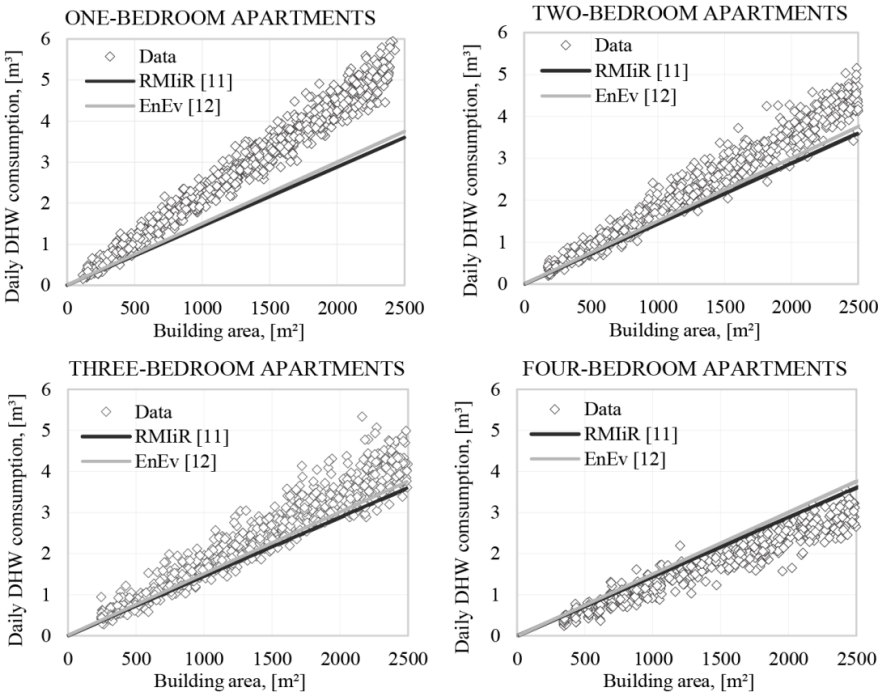

Fig. 6. Consumption of hot water in buildings of unusual size apartments.

4. Average daily model of hot water consumption

After the examination of the measurement data, a refinement of the model of hot water consumption in apartment buildings was proposed. The model is indented to determine the daily average consumption of hot water in the buildings with the desired structure. The model assumes that the number of apartments in a building is more than 4. Smaller buildings and individual flats must be considered separately.

To develop the model, 1600 cases (400 buildings with one-bedroom apartments, two-room apartments, three-room apartments and four-room apartments) obtained using the bootstrap technique have been used. The draws were repeated to check the influence of the randomly selected sample on the outcome of the model. No association was found. In all the consecutive draws the model parameters remained unchanged. For each designed case, the following calculations ware made: the total area of 1-room apartments, 2-room apartments, 3-room apartments and 4-room apartments (A_{M1}, A_{M2}, A_{M3}, A_{M4}) and the daily hot water consumption ($V_{d,DHW}$). The multiple regression analysis performed using

Statistica package estimated the model's parameters. The final model is described by the equation 2. The coefficient of determination of the model (R^2) is 0.95.

$$V_{d,DHW} = 0.0022 \cdot A_{M1} + 0.0018 \cdot A_{M2} + 0.0017 \cdot A_{M3} + 0.0012 \cdot A_{M4} + 0.00122 \ [m^3/day] \quad (2)$$

where: A_{m1} – area one-room apartments [m^2], A_{m2} – area two-room apartments [m^2], A_{m3} – area tree-room apartments [m^2], A_{m4} – area four-room apartments [m^2], $V_{d,DHW}$ [m^3/day] – daily hot water consumption.

The results of the model taking into account the building structure were shown in fig. 7. The relative error of the estimates of the proposed model equals to 10%, while the corresponding error of the model proposed in the Regulation [11] was at the level of 17%, and the model from the Regulation [12]: 14%. The verification was conducted using a sample from an independent draw. Also, when applied to the actual data (that are presented in Figure 5), the proposed model was showing better results, as its relative error was at the level of 12% comparing to 15% and 16% in case of the currently available models.

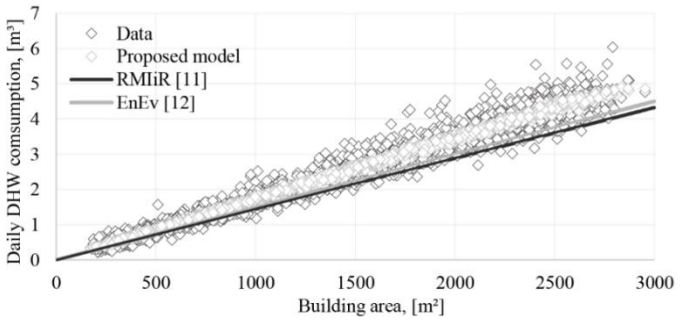

Fig. 7. Proposed model for daily average consumption of hot water.

Figure 8 presents the percentage change of the consumption of hot water in the buildings with different proportion of the floor area of four-room apartments comparing to the two-room apartments. The reference point is a building with 50% share of two-room apartments and 50% share of four-room apartments. Depending on the building's share, its estimated hot water consumption can vary by 20% despite of the same total building area. In case of one-room apartments, the analysis difference may be even greater.

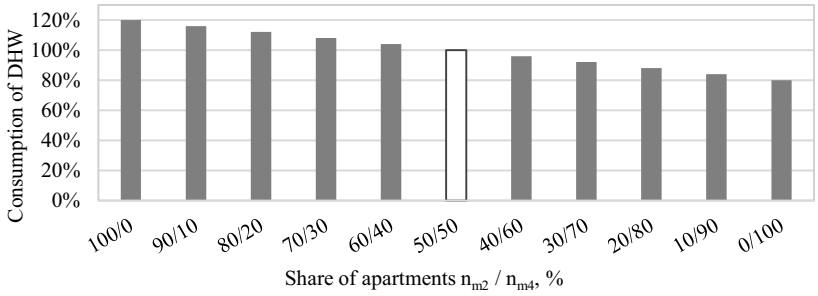

Fig. 8. The percentage change in the consumption of hot water depending on the share of two-bedroom apartments with respect to four-room apartments**.**

5. Conclusions

The article presents the results of measurements of the hot water consumption of 626 apartments of different sizes, number of rooms and number of users. The researchers have

demonstrated that it is possible to describe the daily consumption of hot water with the area of a housing and the number of users. However, the number of users of an apartment is often difficult to determine. Adopting the area of a building as the determining variable without regard to the number of users, e.g. as in the model described in [11], results in large inaccuracies in estimating the consumption of hot water. In this publication, the authors demonstrated the ability to describe the hot water consumption of a flat basing on the number of rooms in the flat and its area, considering that such information are much easier to obtain. As the final result of the data analysis, the authors proposed the calculation model of the hot water consumption of a building, where the variables are the total areas of 1-, 2-, 3- and 4-room flats. The model showed a better fit to the analyzed sample of data than the models proposed in the current Regulations in Poland [11] and Germany [12]. The relative error of the simulation was 10% compared to 17% error of the model from the Regulation [11].

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