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Correlations Between Domestic Hot Water Consumption and Changes in Outdoor Temperature

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Abstract. Residential–household energy consumption accounts for almost one-third of total energy consumption in Hungary. The second-largest factor in household energy costs in most European countries is domestic hot water (DHW) production. According to several studies, DHW consumption is influenced by the physical environment and climatic conditions, including changes in climatic conditions in the long run.

The present study demonstrates how DHW consumption is affected by changes in outdoor temperature through the example of a housing estate built with prefabricated (panel) technology in Hungary, Budapest. The model estimating the DHW consumption constructed by regression analysis explains 74% of the values ($R^2 = 0.7415$). The independent variable of the model is the outdoor temperature. The modeling data source was the National Meteorological Service and the district heating provider supplying the housing estate.

The study also presents the DHW consumption changes expected to cause climate change, based on the data from one projection of two regional climate models, the ALADIN-Climate and the RegCM model.

The developed model and the projections'results can contribute to sustainable resource management and help plan the domestic hot water supply operation.

Keywords. Budapest, climate, domestic hot water, household, mean outdoor temperature, statistical data analysis, water consumption

1. Introduction

Residential energy consumption amounted to 26.3% of total energy consumption in the EU (27) and 32.6% of Hungary's total energy consumption in 2018. Thus, according to analyses traditionally considering four sectors (industry, transport, commercial and public services, households), this sector is the second-largest energy consumer, behind the industry, commercial and public services [1]. However, there are very high energy saving potentials in this sector and their energy supplyfrom a different perspective.

Domestic hot water (hereinafter: DHW) production is the second largest item in households'total energy consumption in most countries after heating and air conditioning [2, 3]. In the United States and the United Kingdom, the share of DHW consumption in total energy consumption is 20% [4, 5], and in Germany, 14% [6]. This proportion is typically higher in northern European countries than in other European countries due to the short summer and extreme winter [7]. Examining household's average consumption structure in Hungary, DHW production accounts for 10–15 percent [8, 9]. DHW production accounts for a significant share of residential buildings'total energy consumption. Still, it is worth noting that this share's size depends on several parameters, as consumption profiles are very complex and variable over time [10].

In Hungary, in the case of buildings with district heating, it is common to measure heat and DHW consumption. Therefore, with the help of consumption data from service providers, it is possible to analyze consumption patterns in detail. District-heated buildings are mostly multi-apartment residential buildings built with prefabricated reinforced concrete (panel) technology. In other building types, such studies are challenging to implement [11].

Among the factors influencing DHW consumption, the present study analyzes the relationship between mean outdoor temperature and DHW consumption, using statistical methods through the case study of a housing estate built with prefabricated technology in Hungary.

The research aims to gain a deeper understanding of the factors influencing DHW consumption. This is because more in-depth knowledge makes it possible to design innovative regulatory-operational strategies based on consumption patterns that consider various factors.

2. Background

2.1. Factors influencing DHW-consumption of households

Factors influencing households'energy consumption can be grouped and organized into models in several ways. These models aim to show the relationship between different factors and energy consumption. The models typically show the factors that influence energy use in general. Given that DHW consumption is part of total energy consumption [12], it is influenced by a significant part of the models and factors presented below.

The most common model is the three-dimensional model of Kowsari and Zerrifi (2011), which focuses on a complex series of decisions affecting households' energy system. This series of decisions is influenced by various factors, divided into three major groups. (I) endogenous household characteristics, (ii) external conditions, i.e., exogenous factors, (iii) and personal characteristics [13].

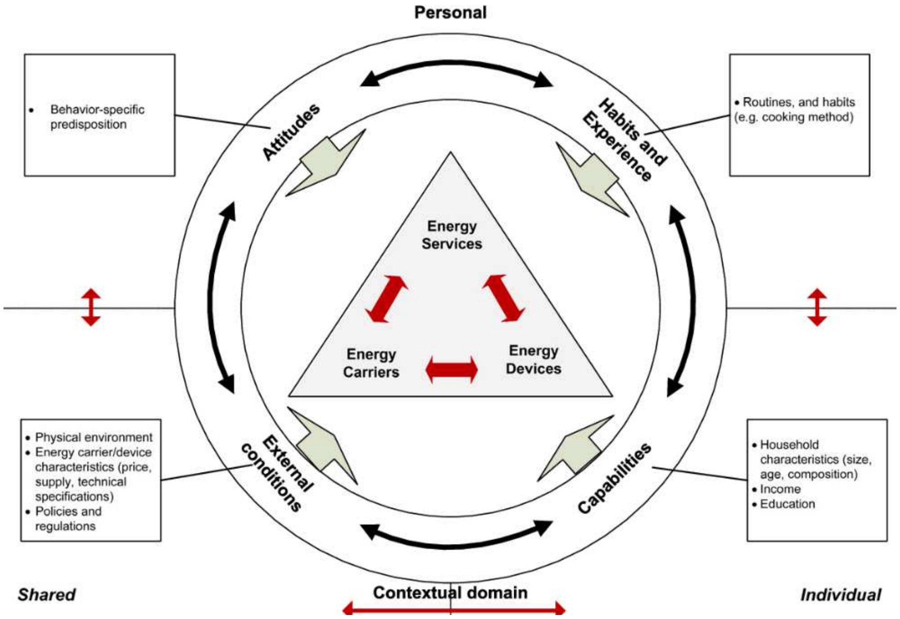

Fig. 1. The three-dimensional model of Kowsari and Zerriffi[13]

Additional groups are identified within the factors. Within the endogenous factor, economic characteristics (e.g., income) and non-economic features (e.g., size and composition of the household, age) appear. The model separates conditions related to the physical environment, energy policy and energy supply, and energy devices' characteristics within the exogenous factor. Personal features include behaviors related to energy use and habits and experiences. It is essential that influencing factors affect final energy consumption and interact with each other [13]. The model is shown in Fig. 1.

Relying on the holistic model of Kowsari and Zerriffi (2011), Putzer and Pavluska (2013) presented a model for Hungarian energy profile, in which all factors that show a significant correlation with household energy consumption based on the results of various researches were classified [13, 14]. Their model is shown in Fig. 2.

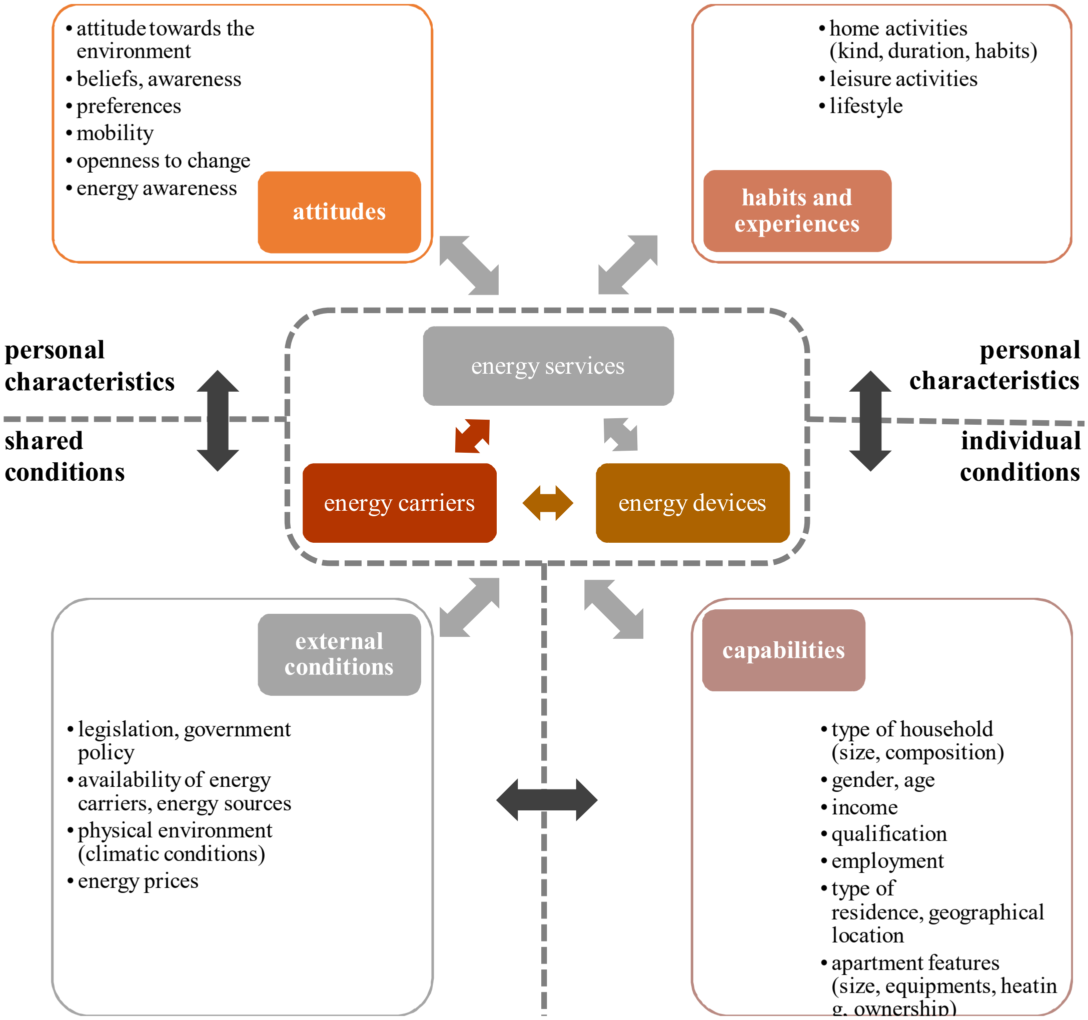

Fig. 2. Model of Putzer and Pavluska (2013): factors influencing energy use of households Figure by the author based on [15]

The physical environment and climatic conditions' impact appears in the international literature as a factor influencing DHW consumption [16-21]. As a counterpoint, it should be noted that Romano et al. (2016) study of climatic and geographical conditions showed that the only altitude has an influencing effect on DHW use, the outdoor temperature has no [22].

Several studies in the literature with different temporal details dealing with seasonality significantly influence DHW consumption [16, 23-29].

The present research uses the Putzer–Pavluska model [14], the advantage is that it contains several statistically exact measurable parameters, and this model has been developed for Hungarian conditions. The research examines the effect of climatic conditions, within this the impact of outdoor temperature influencing the DHW consumption of households.

2.2. The climate of Hungary

Hungary is located in the northern continental climate zone, and its climate is characterized by high variability over time. One of the main reasons for this variability is that its climate is equally affected by (i) the rainy oceanic effects; (ii) continental effects with extreme temperatures; and (iii) Mediterranean climate, which is dry in summer and rainy in winter. These climate effects can become dominant in the country for a longer or shorter period of time [30].

Due to the changeable climate, it is not easy to classify the country according to a global climate classification system. However, according to the Köppen–Geiger climate classification system, most of Hungary is classified as Dfb (Cold (continental), no dry season, warm summer) [31]. The mean annual temperature is around 11 °C, with the warmest month being July and the coldest January [30].

Most of the capital, Budapest, is classified as Dfb. The Füredi housing estate, which is the case study area of the present study, is classified partly as Dfb and partly as Dfa (Cold (continental), no dry season, hot summer) [31].

Fig. 3. shows the climate classification map of the case study area in different spatial resolutions.

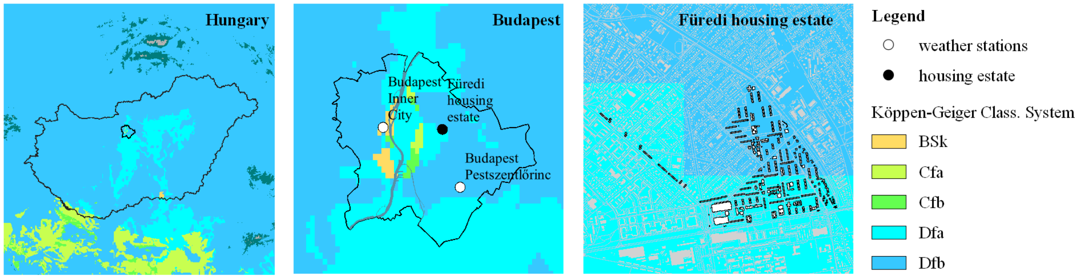

Fig. 3.Köppen-Geiger climate classification map of Hungary, Budapest and the case study area[31]

3. Data and method

3.1. Description of the case study area

In Hungary, more than a third of the prefabricated buildings are located in the capital, so Budapest's case study area was selected: the Füredi housing estate (with an apartment number of almost 12,000) is the fifth-largest housing estate in the capital. More than 90% of the dwellings here are one and a half or two rooms, with an average floor area of 50 m² [32].

3.2. Climatic data

The monthly mean temperature data source is the Hungarian Meteorological Service's weather stations: Budapest-Pestszentlőrinc and Budapest-Belterület. The averages of the two weather dataset were used in this study. The stations'air distance from the case study area is ~ 9.00 km. Fig. 3. shows the location of the weather stations within the capital.

The data used to estimate future consumption in DHW use come from the National Adaptation Geo-information System (NAGiS) [33]. The database was created based on CarpatClim-HU data from projections of ALADIN-Climate [34] and RegCM[35] climate models. Regarding radiation constraint, the ALADIN-Climate model was created with the scenario RCP8.5, RegCM was created with RCP4.5. Naturally, the simulations are burdened with uncertainties resulting from approximating the description of physical processes and the unpredictability of specific processes [33, 36].

Table 1 shows the expected changes in Hungary's yearly mean temperature for the period between 2021–2050 and 2071–2100 based on the projection of the two models mentioned above. The reference period is 1961–1990. The values are the differences in the two periods'annual mean temperatures.

Table 1. Expected mean temperature changes in Hungary based on climate model projections (° C) [33]

model	**ALADIN-Climate (RCP8.5)**		**RegCM (RCP 4.5)**	
period	**2021–2050**	**2071–2100**	**2021–2050**	**2071–2100**
year	1,5-2,0	3,0-3,5	1,0-1,5	3,0-3,5
winter	1,0-1,5	2,0-2,5	1,0-1,5	3,0-3,5
spring	1,5-2,0	3,0-3,5	1,5-2,0	2,5-3,0
summer	2,0-2,5	4,0-4,5	0,5-1,0	3,5-4,0
autumn	1,5-2,0	3,0-3,5	0,5-1,0	3,0-3,5

3.3. Domestic hot water consumption data

Data on the DHW consumption of the case study area were provided by the district heating provider supplying the housing estate. The basic unit of the data is the primary heat receiver of the buildings, and the period is 2010-2016, broken down by month. (If there are several heat receivers in a building, their data has been merged.) The data is the basis for the billing, validated by the district heating provider.

There are 84 multi-residential buildings in the housing estate, of which 72 buildings participate in the studies (see Figure 4. - buildings highlighted in red). In the case of buildings excluded from the examination, either the DHW consumption dataset was incomplete, or the energy status differed significantly from other buildings (e.g., they are equipped with solar panels).

As regards the DHW supply system, buildings can be considered identical.

A total of 11,211 apartments in the 72 buildings are involved in the studies, divided into different building types. Although each building type has apartments of different sizes, each condo is uniform in hot water taps: each apartment has a bathroom sink, a bathtub, and a kitchen sink. The average dwelling size in the housing estate is 50 m^2, and the average density is 1.53 persons per dwelling.

The DHW consumption data were available in m3/building/month units from district heating providers. The data set was normalized to the number of dwellings (to minimize differences between building types) and the number of days (due to the different length of months) and converted into liters, as in other research [37]. Thus, this study's basic unit is the daily consumption of DHW per liter per apartment [l/apartment/day].

3.4. Statistical parameters of the dataset

The descriptive statistical characteristics of the 7-year monthly datasets are presented in Table 2. After the normality analysis of the data based on the Kolmogorov–Smirnov test, it can be stated that the distribution of the sample elements does not significantly deviate from the normal distribution.

Table 2. Descriptive statistical parameters of datasets

	mean outdoor temperature [ºC]	**DHW consumption [l/apt/day]**
N	84	84
Sum	1059,60	7588,01
Mean	12,61	90,33
Median	13,00	93,33
Min	-1,20	71,76
Max	25,10	103,72
Deviation	7,97	8,76
Kurtosis	-1,29	-0,41
Skewness	-0,08	-0,77

3.5. Method

The available data were analyzed using MS Excel. The Kolmogorov-Smirnov test examines thenormality of the data sets.

The correlations between DHW consumption and temperature data were explored by bivariate linear and polynomial regression analysis: in the model, the independent variable was the monthly mean outdoor temperature [ºC], and the dependent variable was DHW consumption [l/apt/day].

4. Results and discussion

4.1. Regression statistics

Table 3 summarizes the parameters of the statistical models described below. The models are significant. It can be stated that the change of the outdoor temperature explains the change in DHW consumption in 74% in the case of the linear model, 85% in the case of the quadratic polynomial model, and 88% in the case of the cubic polynomial model.

Table 3. Regression statistics

	linear regression	**quadratic polynomial regression**	**cubic polynomial regression**
R	0.86	0.92	0.94
R^2	0.74	0.85	0.88
Adjusted R^2	0.74	0.85	0.88
The standard error of the estimation	4.48	3.40	3.03
N	84	84	84
F	235.23	235.37	203.84
Significance	< 0.001	< 0.001	< 0.001

4.2. A linear model describing the correlation between DHW consumption and outdoor temperature

As a result of the linear regression analysis, it can be seen from the coefficients that in case of an increase of the mean outdoor temperature by 1 ºC, the DHW consumption decreases by approximately one liter per day (0.95 liters). It can also be stated that the average DHW consumption per apartment at 0 ºC is 102.27 liters (see Table 4).

Table 4. Summary of coefficients – linear regression

	Coefficients	**Standard error**	***t***	***p***	**Lower 95%**	**Upper 95%**
constant	102.27	0.92	111.30	<0.001	100.44	104.10
outdoor temperature	-0.95	0.06	-15.34	<0.001	-1.07	-0.82

Based on the coefficients, the linear regression function is as follows:

$$y = -0.95 \times t + 102.27 \tag{1}$$

where:

y – estimated DHW consumption of the *j*th month [l/apt/day]
t – mean outdoor temperature of the *j*thmonth [ºC]

The values estimated by the linear model and the corresponding measured values are shown in Fig. 4.

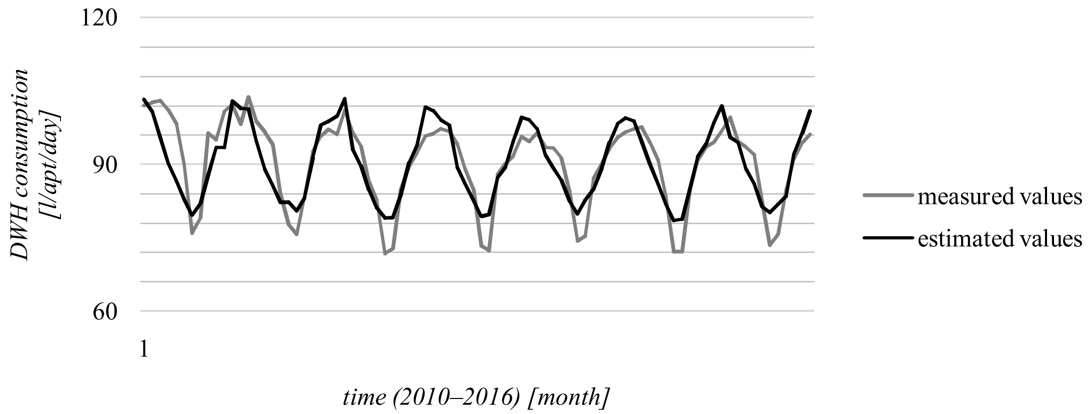

Fig. 4. Values estimated by the linear model of the monthly mean outdoor temperature and the corresponding measured values

4.3. Polynomial models describing the correlation between DHW consumption and outdoor temperature

In addition to fitting a linear function, polynomial fitting was also used to investigate the linear fittingefficiency.

As a result of the polynomial regression analysis, the coefficients'summary shows that the average DHW consumption per apartment at 0 ºC is between 97 and 99 liters.

The sum of the coefficients is shown in Table 5 for the quadratic regression and in Table 6 for the cubic regression. The values estimated by the models and the corresponding measured values are shown in Fig. 5 for the quadratic model and Fig. 6 for the cubic model.

Table 5. Summary of coefficients – quadratic polynomial regression

	Coefficients	**Standard error**	***t***	***p***	**Lower 95%**	**Upper 95%**
constant	97.38	0.93	104.24	<0.001	95.52	99.24
outdoor temperature	0.41	0.18	2.28	<0.001	0.05	0.76
(outdoor temperature)^2	-0.05	0.01	-7.84	<0.001	-0.06	-0.04

Based on the coefficients, the linear regression function is as follows:

$$y = -0.05 \times t^2 + 0.41 \times t + 97.38 \tag{2}$$

where:
y – estimated DHW consumption of the *j*th month [l/apt/day]
t – mean outdoor temperature of the *j*thmonth [ºC]

The values estimated by the quadratic polynomial model and the corresponding measured values are shown in Fig. 5.

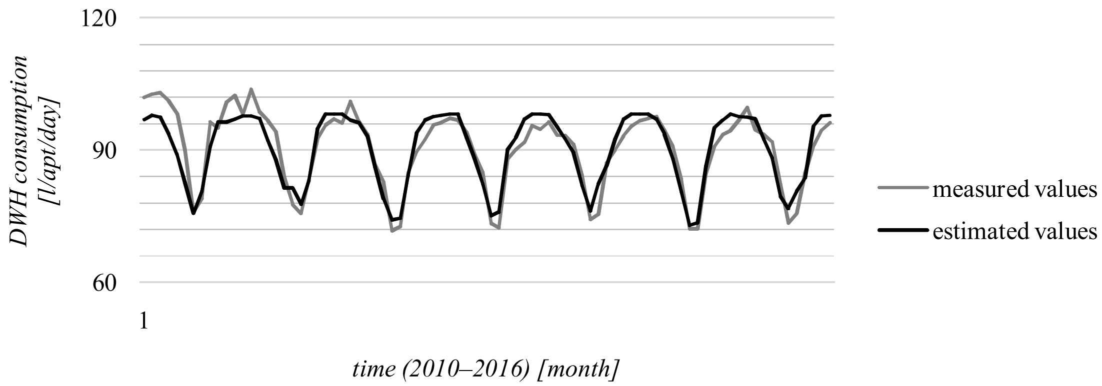

Fig. 5. Values estimated by the quadratic polynomial model of the monthly mean outdoor temperature and the corresponding measured values

Table 6. Summary of coefficients – cubic polynomial regression

	Coefficients	**Standard error**	***t***	***p***	**Lower 95%**	**Upper 95%**
constant	99.51	0.95	104.49	<0.001	97.62	101.41
outdoor temperature	-1.05	0.35	-2.98	<0.001	-1.75	-0.35
(outdoor temperature)^2	0.10	0.03	-2.98	<0.001	0.03	0.17
(outdoor temperature)^3	-0.004	0.00	-4.64	<0.001	-0.006	-0.002

Based on the coefficients, the linear regression function is as follows:

$$y = -0.004 \times t^3 + 0.10 \times t^2 - 1.05 \times t + 99.51 \tag{3}$$

where:
y – estimated DHW consumption of the jth month [l/apt/day]
t – mean outdoor temperature of the $j$thmonth [ºC]

The values estimated by the cubic polynomial model and the corresponding measured values are shown in Fig. 6.

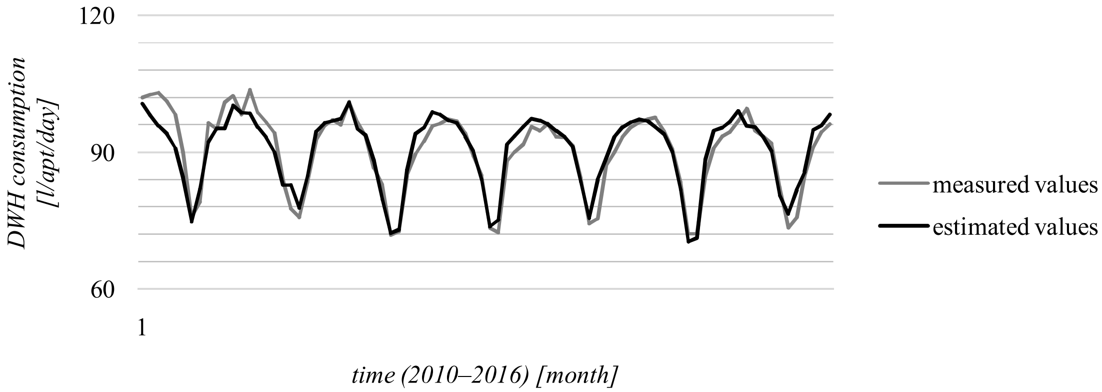

Fig. 6. Values estimated by the cubic polynomial model of the monthly mean outdoor temperature and the corresponding measured values

The explanatory force (R^2) of the polynomial regression functions was 11–14 percentage points higher than the 74% value of the linear fit. Although it means a better fit, it does not mean that the linear model should be discarded. In the case of a fast estimation, a linear, in the case of a more accurate estimate, a polynomial model is recommended. For all three models, it is essential to note that the regression functions'behavior can be questioned outside the experienced values of the mean outdoor temperature functioning as an independent variable (below -1.2 ºC and above +25.1 ºC).

Using the developed models, it is possible to estimate the DHW consumption based on outdoor temperature, which can helpplandistrict heating providers' control strategy.

4.4. Prediction of future values of DHW consumption

Based on the models presented in 4.2. and 4.3. and the climate model projections showedin 3.2., DHW consumption for future decades can be predicted. During the calculation of each period's expected consumption, in the first step, the average temperature between 2010 and 2016 was determined, and then the predicted temperature in the following decades based on the projections. The expected DHW consumption values for the linear model are shown in Table 7.

Table 7. Predicted DHW consumption for 2021–2050 and 2071–2100 based on climate model projections

model	**current DHW consumption [l/apt/day]**	**ALADIN-Climate (RCP8.5)**		**RegCM (RCP 4.5)**	
period	average of 2010–2016	2021–2050	2071–2100	2021–2050	2071–2100
year	90.34	88.44–88.92	87.02–87.50	88.92–89.39	87.02–87.50
winter	100.13	98.71–99.18	97.76–98.23	98.71–99.18	96.81–97.29
spring	90.04	88.15–88.62	86.73–87.20	88.15–88.62	87.20–87.68
summer	80.85	78.49–78.96	76.59–77.07	79.91–80.38	77.07–77.54
autumn	90.32	88.43–88.90	87.01–87.48	89.38–89.85	87.01–87.48

Given that climate model projections predict an increase for all periods, a decrease in DHW consumption is expected.

5. Conclusion and direction for future research

This study examined the correlations between mean outdoor temperature and DHW consumption using statistical methods on the example of district heated multi-residential buildings.

Based on the results, it can be concluded that the change in the outdoor temperature significantly influences DHW consumption. The linear regression models'explanatory force is 74%, and that of the polynomial models is 85–88%. It can also be stated that if the outdoor temperature increases by 1 ºC, the DHW consumption decreases by approximately 1 liter per day per apartment. This value can be used as a rule of thumb.

In the future, it will be possible to examine how the relationship between DHW consumption and outdoor temperature develops in housing estates with similar climatic conditions (e.g., other housing estates in the Hungarian capital). The study's spatial resolution can be refined in the future if not only a building but also apartment-level DHW consumption data are available.

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Comments

The map shown in Fig. 3 and Fig. 4 was edited using official primary data. Permit for using the data: FF/947/1/2017 by the FöldművelődésügyiMinisztérium (Ministry of Agriculture). Source of further data: OpenStreetMap.

The present study used the Hungarian Meteorological Service datasets. Registration number: GFO-456-2/2018, code: H/27.

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