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Comparison of methods for determining the demand for final energy for heating on the example of a single-family residential building

***Abstract**. For an example single-family residential building, actual energy consumption for heating was estimated using gas consumption data for five heating seasons. Then the demand for usable and final energy for heating was estimated based on eight calculation methods, such as methods contained in the methodology for determining the energy performance of buildings from 2008, 2015 and 2023, methods described in PN-B 02025 and EN 832, as well as the thermal method based on PN-66/B-02419. Then, a comparative analysis of the method based on the actual energy consumed with the calculation methods for standard climatic conditions was carried out by determining the values of relative estimation errors. This made it possible to select the methods that give the results of estimating the final energy consumption for heating the building, which are closest to the actual values.*

***Streszczenie.** Dla przykładowego budynku mieszkalnego jednorodzinnego oszacowano rzeczywiste zużycie energii na ogrzewanie wykorzystując dane o zużyciu gazu za pięć sezonów grzewczych. Następnie oszacowano zapotrzebowanie na energię użytkową i końcową na ogrzewanie w oparciu o osiem metod obliczeniowych, takich jak: metody zawarte w metodologii wyznaczania charakterystyki energetycznej budynków z lat 2008, 2015 i 2023, metody opisane w normach PN-B 02025 oraz EN 832, a także metodzie termicznej bazującej na normie PN-66/B-02419. Następnie przeprowadzono analizę porównawczą metody opartej na faktycznie zużytej energii z metodami obliczeniowymi dla standardowych warunków klimatycznych, wyznaczając wartości względnych błędów oszacowania. Pozwoliło to wyłonić metody, które dają wyniki oszacowania zużycia energii końcowej na ogrzewanie budynku najbardziej zbliżone do wartości rzeczywistych. **(Porównanie metod wyznaczania zapotrzebowania na energię końcową do ogrzewania na przykładzie budynku mieszkalnego jednorodzinnego**).*

Keywords: building energy performance, building heating, real energy consumption, final energy, heating season degree days.
Słowa kluczowe: charakterystyka energetyczna budynku, ogrzewanie budynków, rzeczywiste zużycie energii, energia końcowa, stopniodni sezonu grzewczego.

Introduction

Energy consumption in the European construction sector accounts for about 45% of the European Union's total energy needs, and 50% of the pollutants entering the ambient air come from this sector [1]. According to [2], the building sector consumes 35% of final energy demand. In order to improve the efficiency of energy use for heating and air conditioning of buildings and to reduce greenhouse gas emissions, Directive 2010/31/EU [3] on the energy performance of buildings was adopted by the European Parliament and the Council of the European Union. Poland, as a full-fledged member of the European Union, was obliged to implement the provisions of the directives on the energy performance of buildings [3]. The general basis for the development of energy certificates was the Energy Performance Law [4], and the detailed methodology for preparing energy performance certificates for buildings, parts of buildings, and dwellings was established successively in the Regulations of 2008, 2014, and 2023 [5-7]. The energy performance of a building includes, among other things, the estimation of the demand for usable energy and final energy. Usable energy (EU) is the most important from the point of view of the building designer. It is the energy efficiently used to heat and ventilate spaces. It informs us about the standard of the solutions used. The lower the demand for usable energy for heating and ventilation (EU), the better insulated partitions, more efficient ventilation system, and greater tightness of the building. Designing energy-efficient buildings involves, among other things, achieving the lowest possible coefficient of demand for usable energy. Final energy (FE) is the most important for the user of the facility, as the cost of operating the building matters most. It is the energy supplied to the building, for example, from the gas or electricity grid, taking into account the energy inputs required to cover losses incurred in installations and equipment. Thus, it is the energy that must be bought and paid for. The methods presented in the regulations for estimating the indices of demand for usable and final energy for heating buildings are as follows: In 2008, two methods of estimating energy demand were introduced, based on standard usage and climate data accepted from the nearest weather station. For new buildings, this was a monthly balancing method, while for existing buildings a simplified seasonal method was allowed. The 2015 methodology also introduced two ways of estimating energy performance. The first method, concerning the calculation of energy consumption for heating and ventilation, did not significantly differ from the provisions of the previous regulation, i.e. the monthly balancing method. However, some changes were made, such as the method of estimating the ventilation flux, which was related to the usable area of the building and determined by the index method (previously, the provisions of PN-B/83-03430 [8] were used to estimate the size of the ventilation air flux), and the values of the efficiency of heat generation, accumulation, distribution and transfer were modified. The second way of estimating energy demand was a method based on the actual amount of energy consumed, which could be applied to existing buildings. The method of calculation presented in the regulations did not assume conversion of the obtained values of energy consumption to the conditions of the standard season, and only the average value of the three years preceding the performance of the energy performance certificate was used. In the methodologies of 2008 and 2015, the assessment of the amount of usable and final energy demand for heating and ventilation was made on the basis of the balance method according to PN-EN ISO 13790:2008 [9]. In 2023, the regulations on how to determine the energy performance of buildings were amended, introducing two methods of calculating the demand for usable and final energy based on the standard PN - EN ISO 52016-1:2017 [10]. The energy performance of designed buildings, newly put into operation, and existing buildings can be determined using two energy balancing methods: the hourly method and the monthly method. These two methods are closely related, as they contain almost the same calculation assumptions and input data. Analogous to EN ISO 13790 [9] (now obsolete), the hourly method allows the determination of averaged parameters of a building and its systems. PN-EN ISO 52016-1:2017 [10] introduces more detailed calculation models and allows for more accurate determination of indicators than the monthly method, which allows for simplification of energy demand calculations where possible or required. The hourly method takes into account the thermal dynamics of the opaque building envelope and the variability over time of internal and external heat gains, especially from central heating and hot water systems and solar radiation. The monthly method, in its shape and assumptions, is similar to the calculation method contained in the 2008 regulations. Before the introduction of regulations specifying the methodology for calculating the demand for usable and final energy for heating buildings, it was possible to make calculations using industry standards, the most common of which were PN-66/B-02419 [11] and PN-B 02025 [12], where the energy balance was performed using the seasonal method, and the EN 832 standard [13], in which usable and final energy were balanced according to the monthly method.

Purpose and scope of work

The purpose was to compare methods for estimating final energy demand for heating using a single-family residential building as an example. For the example residential building, actual energy consumption for heating was estimated using gas consumption data for five heating seasons. Then, the demand for usable and final energy for heating was estimated based on eight calculation methods, such as the methods contained in the methodology for determining the energy performance of buildings from 2008, 2015, and 2023; the methods described in PN-B 02025 and EN 832; as well as the thermal method [14] based on PN-66/B-02419. The next step was to perform a comparative analysis of the method based on the actual consumed energy converted to standard season conditions with the calculation methods, determining the values of relative estimation errors.

Study object and calculation methodology

The calculations were made for a single-family residential building with a usable attic, built in 2017 and located in the city of Krakow. The building is equipped with a central heating system with underfloor water heating, featuring central and local control with a proportional controller. The heat source is a condensing gas boiler with modulating power ranging from 3-18 kW. In the analyzed building, gas is consumed for heating, hot water preparation, and cooking. The basic data for the analyzed building are summarized in Table 1.

Table 1. Basic data of the building

specification		value
heated area of the building A_f [m^2]		92,6
volume of the heated part of the building V_e [m^3]		417,71
partition heat transfer coefficient U [W/(m^2·K)]	external walls	0,167
	floor on the ground	0,22
	ceiling over usable attic	0,123
	insulated roof	0,135
	windows	1,1
	front door	0,53
surface area of all external building partitions A[m^2]		321,64
shape coefficient of buildings A/V_e [m^{-1}]		0,77

The building, built in 2017, meets the current technical requirements of the regulations (WT2022 [15]) for the heat transfer coefficient for the external envelope Umax. Monthly gas readings from the gas meter were carried out starting in 2018 (the readings are confirmed by gas invoices), allowing for an accurate determination of the final energy consumption for heating, hot water preparation, and meals. Table 2 summarizes the annual consumption of natural gas over a five-year period for heating purposes.

Table 2. Volume of natural gas consumption by month in m^3

specification	year				
	2018	2019	2020	2021	2022
	natural gas consumption [m^3]				
January	133,5	152,8	148,2	138	126,4
February	145	105	128,5	124,1	99,4
March	130,2	92,4	108,2	105,8	104,4
April	71,3	68,4	72,4	85,3	81,7
May	28	52,9	28	49	32,2
June	23	24,3	26,8	19,9	19,2
July	23,7	22,3	26	20	20,3
August	25,7	20,4	18,1	29	20,9
September	32,9	38,4	34,1	38,6	48,1
October	64	75,9	67	70,3	54,8
November	104,6	100,1	99,9	96	101,7
December	129,6	125,3	130,5	133,3	128,5
total	912,2	878,8	888,2	909,9	837,9

The annual gas consumption of the building varies from 837 to 912 m^3, with an average of 885 m^3. To determine the annual final energy demand for heating the building, it was necessary to separate the gas flow for heating from the part related to the preparation of hot water and meals. Therefore, it was assumed that in the summer months (June, July, and August), natural gas was consumed exclusively for the preparation of domestic hot water and meals, and the final energy consumption for this purpose could be accurately estimated. In the calculations, it was assumed that in the months of the heating season, the final energy for the preparation of domestic hot water and meals would be the average value of the three summer months. This allowed the calculation of the final energy consumption for heating the building in accordance with the methodology contained in Regulation [6]. In the method based on actual energy consumed, the heat of combustion of the gas supplied to the building (conversion factor) was assumed based on information from gas invoices for the individual months of the billing period, which averaged 11,082 kWh/m^3 for the years analyzed. Although the methodology does not assume conversion (correction) of actual energy consumption for heating and ventilation to standard season conditions, such calculations were made in the paper. Using the data of the Institute of Meteorology and Water Management - National Research Institute on the average monthly outdoor temperatures for the city of Krakow (climate station Krakow-Balice) in 2018-2022, the values of heating season degree days were calculated, amounting to 3240; 3204,8; 3236,4; 3267,9; 3086,6 Kd, respectively, and then compared with the reference value for the climate station Krakow-Balice, which is 3748,4 Kd. On this basis, the values of the final energy consumption for heating the building for each year were converted to standard season conditions, as shown in Table 3.

Seasonal final energy consumption for heating, converted to standard season conditions, varies between 8021 and 8387 kWh/year, with an average value of 8202 kWh/year. The coefficient of variation for the analyzed period is 1.9%, so it can be assumed that final energy consumption for heating in individual heating seasons is characterized by a slight variation. The next step was to calculate the consumption of usable and final energy for heating the building using the methods written in the methodologies for determining the energy performance of the building written in the regulations of 2008, 2015 (using PN-EN ISO 13790:2008 [9]) and 2023 (based on PN-EN ISO 52016-1:2017 [10]). In addition, calculations of seasonal energy consumption for heating were made based on PN-B 02025 [11] and EN 832 [12], as well as the thermal method [12] based on PN-66/B-02419 [13].

Table 3. The amount of final energy consumption for heating the building in [kWh]

specification	year				
	2018	2019	2020	2021	2022
	final energy consumption [kWh]				
January	1212,1	1446,3	1379,4	1275,5	1177,6
February	1383,8	941,2	1201,2	1152,5	878,3
March	1219,9	800,8	975,7	950	933,9
April	567,6	535,5	578,9	722,2	682,7
May	87,6	363,5	86,8	319,9	133,5
September	142,2	202,5	154,6	205	309,8
October	486,4	617,7	519,4	556	384,3
November	936,3	885,9	884,5	841,3	904
December	1213,6	1166,1	1223,8	1254,6	1200,8
total (for 9 months)	7249,5	6959,5	7004,3	7277	6604,9
seasonal final energy consumption for heating converted to standard season conditions	8387	8139,9	8112,3	8346,9	8021

Calculations were performed based on climatic data for the Krakow-Balice station. Then, the unit energy demand indices and final energy demand for heating related to the heated area of the building (A_f) were calculated. For comparison purposes, the different methods were labeled as follows:

A - method based on standard building use, monthly balancing according to 2008 methodology;
B - method based on standard building use, seasonal balancing according to 2008 methodology;
C - method based on standard building use, monthly balancing according to 2015 methodology;
D - method based on the actual amount of energy consumed in the building according to the 2015 methodology;
E - method based on standard building use, monthly balancing according to the 2023 methodology;
F - method based on standard building use, hourly balancing according to the 2023 methodology;
G - method based on standard building use, seasonal balancing according to PN-B 02025;
H - seasonal method using a thermal model based on PN-66/B-02419 standard;
I - method based on standard building use, monthly balancing according to EN 832; and:
J - method based on the amount of energy actually consumed, converted to standard season conditions, which is the benchmark for the compared methods.

Calculation Results and Discussion

The calculations made it possible to determine the seasonal final energy demand for heating for the analyzed building and their results are summarized in Figure 1.

Depending on the calculation method used, the seasonal final energy demand for heating ranges from 6211 to 10745 kWh. The three estimation methods "C", "D", and "F" indicated values lower than the actual consumption (which is the baseline - method "J") from 524 kWh (F) to 1991 kWh (C). The remaining methods indicated higher values of final energy consumption for heating from 434 kWh (E) to 2543 kWh (G).

The next step was to calculate the values of indices of specific demand for usable and final energy for heating the building. The indicator values are summarized in Table 4.

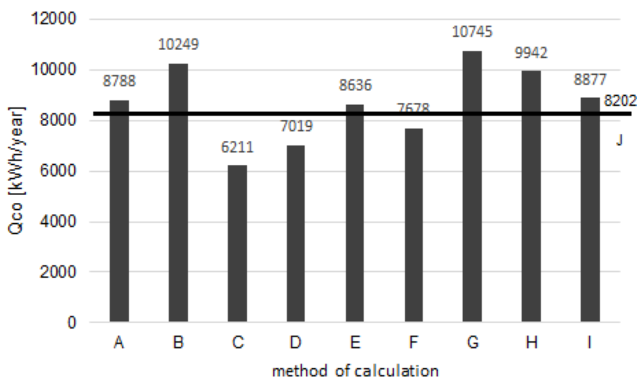

Fig.1. Value of final energy consumption for heating depending on the estimation method adopted

Table 4. Comparison of utility and final energy demand indicators for heating depending on the estimation method adopted

specification	energy demand index	
	utility [kWh/(m²·year)]	final [kWh/(m²·year)]
A	81,6	94,9
B	92,2	110,7
C	55,0	67,1
D	-	75,8
E	74,1	93,3
F	66,3	82,9
G	96,3	116,1
H	88,3	110,4
I	79,6	95,8
J	-	88,6

The values of the index of usable energy demand for heating, depending on the calculation method used, range from 55 kWh/(m^2·year) (C) to 96,3 kWh/(m^2·year) (G). The final energy demand index for heating determined based on actual energy consumption converted to standard seasonal conditions (J) is 88,6 kWh/(m^2·year), which is 12,8 kWh/(m^2·year) higher than the index determined solely on the basis of the average energy consumption for heating (D).

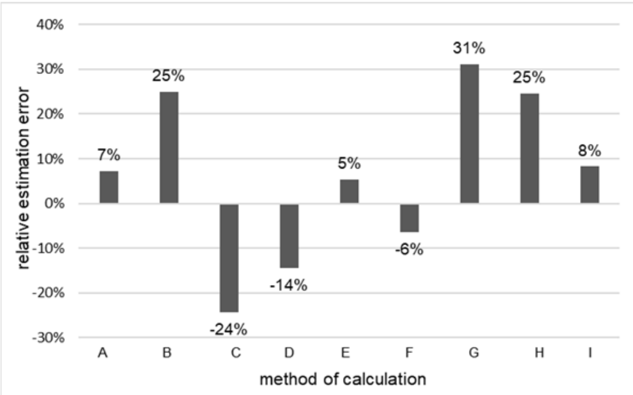

Fig. 2. Relative error values depending on the method adopted for estimating final energy demand for heating

The values of final energy demand indicators for heating, determined on the basis of the calculation models, range from 67,1 kWh/(m^2·year) (C) to 116,1 kWh/(m^2·year) (G). The results closest to the reference value were obtained for methods "F" (82,9 kWh/(m^2·year)) and "E"

(93,3 kWh/(m^2·year)), which differ by 5,7 kWh/(m^2·year) and 4,7 kWh/(m^2·year), respectively. Method "F" indicates lower consumption than the reference, while "E" yields higher index values. Slight differences from the reference value were still obtained from two methods: "A" (higher by 6,8 kWh/(m^2·year)) and "I" (higher by 7,2 kWh/(m^2·year)).

The final step in the calculation was to calculate the value of the relative error [16]. The absolute error indicates by what percentage the calculated value differs from the actual value. The values of actual energy consumption converted to standard season conditions (J) were used as a reference level, and the values obtained from each method were compared with it in turn. The obtained relative error values are summarized in Figure 2.

By analyzing the values of relative error, one can see a wide variation in the results obtained depending on the method adopted for estimating the final energy demand for heating for the analyzed building. Three methods indicate lower than actual energy consumption from 6% (F) up to 24% (C). Six methods overestimate the amount of final energy consumption in the range of 5% (E) to 31% (G). The largest values of relative error were obtained for methods that balance energy consumption on a seasonal basis, namely methods "G", "B" and "H", with the final energy consumption values obtained being higher than the reference value (thereby overestimating the energy consumption of the building). Monthly balancing methods "E" and "A" yield error values (overestimating consumption) of 5 to 7%. The "C" method, which also belongs to the group of hourly methods, underestimates energy consumption by as much as 24%. The results obtained from the hourly method (F) have a relative error of 6%, which indicates that the results obtained through this method are slightly lower than the reference value. The relative error for the method based on the actual amount of energy consumed (without correcting for standard season conditions) is 14%.

Conclusions

The analysis carried out to compare methods of determining the final energy demand for heating of an example single-family residential building with a heated area of 92,6 m^2 allowed for the drawing of the following conclusions:

- The actual energy consumption for heating the building expressed by the final energy demand indicator for the standard heating season is 88,6 kWh/(m^2·year).
- The values of final energy demand indicators for heating for the analyzed calculation methods range from 67,1 kWh/(m^2·year) (method based on standard building use, monthly balancing according to the 2015 methodology) to 116,1 kWh/(m^2·year) (method based on standard building use, seasonal balancing according to the PN-B 02025 standard). The results closest to the reference value were obtained for the method based on standard building use, monthly balancing according to the 2023 methodology (82,9 kWh/(m^2·year)) and the method based on standard building use, hourly balancing according to the 2023 methodology (93,3 kWh/(m^2·year)). Both methods are based on the PN-EN ISO 52016-1:2017 standard. With respect to the actual final energy consumption (reference value), the monthly balancing method overestimates energy consumption by 5%, while the hourly method underestimates consumption by 6%.
- The second method that gives results close to the actual value is the method, based on the calculation algorithm, with monthly balancing written in the 2008 methodology for estimating the energy performance of buildings. The calculated final energy consumption for heating expressed by the FE index is 94,9 kWh/(m^2·year), thus differing from the actual value by about 7%.
- The largest values of relative error were obtained for methods that balance energy consumption on a seasonal basis (PN-EN ISO 13790:2008, PN-66/B-02419, PN-B 02025), which overestimate energy consumption from 25 to 31%.

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