energies

Article

Application of a Thermal Performance-Based Model to Prediction Energy Consumption for Heating of Single-Family Residential Buildings

Tomasz Szul

Faculty of Production and Power Engineering, University of Agriculture, 30-149 Krakow, Poland; t.szul@urk.edu.pl; Tel.: +48-662-46-47

Abstract: Energy consumption for heating of single-family residential buildings is a basic item in energy balance and significantly affects their operating costs. Accuracy of heat consumption assessment in existing buildings to a large extent determines the decision on taking actions aimed at heat consumption rationalization, both at the level of a single building and at regional or national level. In the case of energy calculations for the existing buildings, a problem often arises in the form of lack of complete architectural and construction documentation of the analyzed objects. Therefore, there is a need to search for methods that will be suitable for rapid energy analysis in existing buildings. These methods should give satisfactory results in predicting energy consumption when there is limited access to data characterizing the building. Therefore, the aim of this study was to check the usefulness of a model based on thermal characteristics for estimating energy consumption for heating in single-family residential buildings. The research was conducted on a group of 84 buildings, for which the energy characteristics were determined based on the actual energy consumption. In addition, information was collected on variables describing these buildings in terms of construction technology and building geometry, from which the following were extracted for further calculations: cubic capacity, heated area, and year of construction. This made it possible to build a prediction model, which enables the application of a fast, relatively simple procedure of estimating the final energy demand index for heating buildings. The resulting calculations were compared with actual values (calculated from energy bills) and then evaluated according to the standards for evaluating model quality proposed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). In this way, it was possible to determine whether, in the absence of building documents, the indicative method gives good results when estimating the energy demand for heating single-family residential buildings.

Keywords: energy efficiency; energy consumption; forecasting of energy consumption; single-family residential buildings

check for updates

Citation: Szul, T. Application of a Thermal Performance-Based Model to Prediction Energy Consumption for Heating of Single-Family Residential Buildings. *Energies* **2022**, *15*, 362. https://doi.org/10.3390/en15010362

Academic Editors: Francesco Nocera and Gianpiero Colangelo

Received: 29 November 2021
Accepted: 23 December 2021
Published: 5 January 2022

1. Introduction

The buildings sector (residential and tertiary) is a huge consumer of energy—it consumes more than 40% of the total final energy and emits 40% of CO_2 in the EU [1]. The residential sector accounts for approx. 76% of final energy consumed in the buildings segment [2], and the Polish residential building sector is characterized by some of the worst energy consumption and CO_2 emission indicators. In Europe, CO_2 emissions range widely from 5 kg $CO_2 \cdot m^{-2}$ in Norway to 120 kg $CO_2 \cdot m^{-2}$ in Iceland. With the average emission in Europe being 54 kg $CO_2 \cdot m^{-2}$ in Poland, it exceeds 110 kg $CO_2 \cdot m^{-2}$ [2]. Single-family buildings are a very important part of the Polish housing market. Statistical data on this building segment is poor and often divergent. According to the Central Statistical Office, by the end of 2020, there were over 6.82 million buildings in Poland, of which over 6.63 million were inhabited buildings. In this set of buildings, 6.06 million are single-family buildings and 577,000 are multi-family buildings [3]. In the total structure of inhabited buildings, the share of single-family houses is dominant, both in urban and rural areas. Most single-family buildings are in rural areas—3.99 million, compared to 2.06 million in urban areas. These buildings contain about 6,350,000 dwellings, in which about 19.5 million inhabitants live; of these inhabitants, almost 6.5 million are in urban areas and over 13 million in rural areas. In percentage terms, almost 90% of rural residents and almost 30% of urban residents live in single-family buildings, most of which are equipped with individual heat sources. In contrast to the European average, over 90% of these houses are detached houses (in Europe, the average is less than 60%). There are far fewer terraced and semi-detached houses, which undoubtedly increases energy intensity and thus maintenance costs. This means that the housing stock is quite old and characterized by low energy standards [4]. Buildings constructed in the last few decades in Poland were designed based on various changing building regulations, including thermal protection parameters of buildings. Most of these regulations referred to the thermal properties of the envelope, and the initial regulations on thermal requirements were dictated only by the need to avoid condensation on the envelope. It was not until the early 1980s that the main objective, including the requirements of the standard, was to reduce energy consumption. Current standards mandate that buildings be designed with minimum envelope U-value requirements. The U-value considers the material parameters of the envelope, thus it relates directly to the material properties of the building. The quality and energy consumption of the housing stock is very much influenced by the year of construction, modernization, or repair of the building. This results from the technologies used in that period and the building standards in force. Table 1 presents values of heat transfer coefficients for buildings erected, along with periods of validity of standards and regulations [5].

Table 1. Required maximum thermal transmittance value for external walls, storage ceilings (roofs), floor over unheated basement (and on the ground) and windows.

Years	**U_{max}—Thermal Transmittance of, $W\cdot m^{-2}\cdot K^{-1}$**			
	Walls Components	**Ceiling (Roof) Components**	**Floor over Unheated Basement**	**Windows**
Until 1952	**No Requirements**	**No Requirements**	**No Requirements**	**No Requirements**
1953–1966	1.163 (eastern and central Poland) 1.4 (western Poland)	0.87	1.16	no requirements
1967–1975	1.163	0.87	1.16	no requirements
1976–1982	1.163	0.70	1.16	no requirements
1983–1991	0.75	0.45	1.16	2.6
1992–1997	0.55	0.30	1.16	2.6
1998–2008	0.30	0.30	0.5	2.6
2009–2013	0.30	0.25	0.3	1.8
2014–2017	0.25	0.20	0.25	1.3
2017–2021	0.23	0.18	0.25	1.1
after 2021	0.20	0.15	0.25	0.9

The data in the table summarize the condition of single-family buildings and indicate that about 70% of single-family buildings are characterized by low or very low standards of thermal protection of the envelope. The performed thermal improvement measures (thermo-modernization) of buildings built before 2000 allowed to reduce the heat demand by about 23% on average [6], thus this segment has the potential to improve the energy performance.

The calculation of the energy performance of buildings can be carried out using different methods, which can be divided into engineering calculations, statistical and data-driven models, and hybrid models [7–36]. Figure 1 presents the techniques for modeling and predicting energy consumption in buildings with a breakdown of each calculation method. The presented scheme includes citations of works in which the authors used a particular method to predict energy consumption for heating or to determine energy performance in different types of buildings, which were mostly offices, hotels, schools, universities, and multifamily buildings [7,22,34].

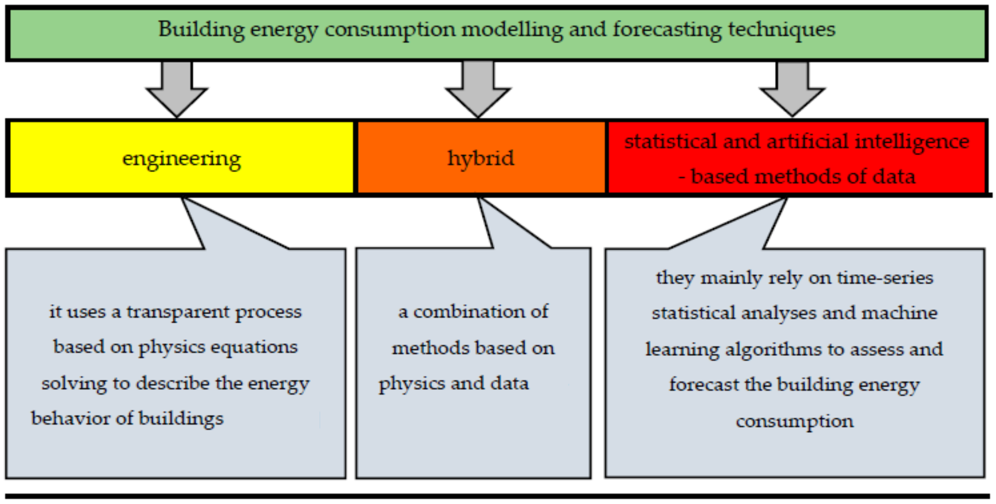

Figure 1. Classification of methods for forecasting energy consumption in buildings [7–36].

The literature analysis has shown that the most used methods are statistical and artificial intelligence models based on neural networks, fuzzy logic, and rough set theory. These models are mainly focused on estimation of energy consumption and thermal comfort in simulated or existing energy-efficient or passive objects as well as multi-family residential buildings [12,26,34,36,37]. Few works deal with single-family residential buildings [6]. There is a lack of research on actual buildings [7,34], for which it is difficult to obtain reliable and accurate data. It is therefore advisable to test new methods based on a small amount of general data, such as a method based on the thermal performance of buildings. Thus far, this method has been applied to estimate the power demand for heating buildings that do not have complete building documentation. This quantity was determined empirically based on statistical data performed over several decades [38,39]. The thermal characteristic of a building is equal to thermal power losses of 1 m^3 of the heated volume of the building, related to unit temperature difference of the air inside and outside the building [38]. The method presented in papers [38–40] has been combined and used with relations contained in PN-66/B-02419 [41], which was used for calculations of seasonal demand for fuel. Introduction of modifications allowed estimating the energy consumption for heating using only two variables describing the building, i.e., heated cubature, year of construction (time interval in which it was built), and type of heat source. This method—according to the literature review—has not been used so far for energy consumption forecasting in buildings [7–36], which is a novelty in this type of research. To evaluate the quality of the developed predictive model, evaluation metrics such as [42] *MAPE*, *MBE*, *CV RMSE*, and R^2, which are adopted as statistical calibration standards by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) [43], were used.

2. Materials and Methods

2.1. Description of the Research Subject

The study was conducted on peripheral areas located within the administrative area of the City of Krakow, which is in the southern part of Poland. According to the Central Statistical Office [3], there are 43.7 thousand single-family residential buildings within the administrative area of the City of Krakow. These buildings are 96% heated by gas boilers. On this basis, the minimum sample size has been determined, which amounts to 81 objects (for the confidence level α = 0.95 and maximum error of 10%), in which the research should be carried out. The survey was conducted in 84 single-family residential buildings heated with gas boilers, within which information was collected on heated area, heated and ventilated volume, and gas consumption for heating purposes, among others. Information was also collected on possible thermomodernization activities in the buildings. The structure of buildings in terms of their year of construction according to the data contained in the Central Statistical Office and the buildings in which the research was carried out is shown in Figure 2. At the same time, the age ranges were determined in accordance with the binding legal regulations concerning the maximum values of heat transfer coefficients U_{max} by external partitions, i.e., in periods when norms and sector regulations of the Ministry of Construction were in force.

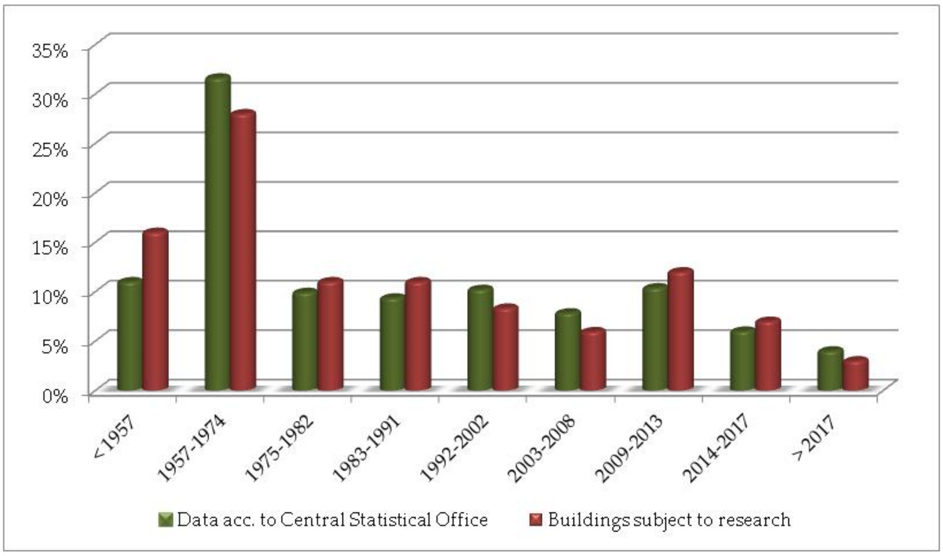

Figure 2. Age structure of single-family residential buildings in the Krakow area.

These buildings were characterized by high variability in characteristic dimensions such as area and heated volume as shown in Table 2.

Table 2. Average values of surface area and heated cubic capacity for the analyzed group of buildings.

Years	Mean Values of Parameters	
	A_h—Area of Temperature-Controlled Rooms (Heated Surface), m^2	V_e—Heated Volume of the Building, m^3
until 1957	68	182
1957–1974	94	274
1975–1982	145	514
1983–1991	127	341
1992–2002	132	412
2003–2008	157	459
2009–2013	163	469
2014–2017	169	579
after 2017	139	407

Average heated area of the analyzed buildings is 132 m^2 and heated volume is 404 m^3. The analyzed buildings, especially those constructed before 2003, were subjected to thermo-modernization activities—their share is 39%, while thermal improvement in 73% consisted of external wall thermal insulation. In the remaining part, the ceilings were additionally insulated. The average thickness of thermal insulation of external walls in the analyzed group of buildings is 7.6 cm, while the average thickness of thermal insulation of ceilings is 9.2 cm.

In 76% of the buildings, windows were replaced with new ones, mainly PVC with single glazing units. Unfortunately, since only a small part of them had building documentation, it was not possible to calculate heat transfer coefficients of partitions before and after thermal improvement.

The heating needs (heating, preparation of domestic hot water, and preparation of meals) in the analyzed buildings are realized with the use of natural gas boilers. Therefore, information about the actual gas consumption in three seasons covering the years 2017–2019 was obtained. This allowed us to calculate the actual final energy consumption for heating the buildings.

2.2. Calculation Method for Energy Demand for Heating a Building

Energy consumption for heating buildings depends on many factors, the most important of which are the thermal insulation and airtightness of the envelope of the external heated space of the building, the thermal accumulation of the building and its heating method, and the efficiency of the thermal processes in the building.

In order to determine the above-mentioned factors, various calculation methods are applied, which are summarized in Figure 1. One of them is a method using simplified relations describing the final energy demand in a building, which is based on an assumption that the thermal load of the building at a given external temperature is proportional to temperature difference between the heated space of the building and its surroundings, which can be determined from relations [13]:

$$\varnothing_{h(\theta_e)} = \varnothing_{ho} \cdot \frac{\theta_i - \theta_e}{\theta_i - \theta_{eo}} \tag{1}$$

where: $\varnothing_{h(\theta e)}$ is instantaneous heat load of the building at a given temperature, kW; $\varnothing_{ho}$ is design heat load of the building for heating, kW; θ_i is design value of internal temperature, °C; θ_e is design value of external temperature, °C; θ_{eo} is instantaneous value of outdoor temperature, °C.

Theoretical value of the amount of heat transferred from the building to the environment during the whole heating season is determined by the relation:

$$\varnothing_h = \varnothing_{ho} \cdot \frac{\theta_i - \theta_{e,ave}}{\theta_i - \theta_e} \cdot n \cdot 24 = \frac{\varnothing_{ho}}{\theta_i - \theta_e} \cdot HDD \cdot 24 \tag{2}$$

where: $\varnothing_h$ is the amount of heat transferred from the building to the surroundings during the heating season, kWh; $\varnothing_{ho}$ is design heat load of the building for heating, kW; θ_i is design value of internal temperature, °C; θ_e is design value of external temperature, °C; $\theta_{e,ave}$ is average value of external temperature in the heating season, °C; n is number of days in the heating season, depending on the local climatic conditions; HDD is number of heating degree-days for the building location, °Cd.

Equations (1) and (2) have been derived on the assumption that the same internal temperature θ_i is maintained in all heated compartments. In this method of calculating the heat demand for building heating, no account is taken of the heat gains (solar and internal) generated in heated compartments which reduce the amount of heat that is actually required for building heating. Additionally, no account is taken of the heating system efficiency. The mentioned parameters have been considered in PN-66/B-02419 [41], which has been used for calculations of seasonal demand for fuel. The seasonal energy consumption for heating can be calculated from the formula:

$$\varnothing_{H,d} = \frac{y \cdot 24 \cdot \varnothing_{ho} \cdot HDD}{\eta_{H,tot} \cdot (\theta_{i,ave} - \theta_e)} \tag{3}$$

where: $\varnothing_{H,d}$ is calculated seasonal energy consumption for heating the building, kWh; $\varnothing_{ho}$ is design heat load of the building for heating, kW; HDD is number of heating degree-days for the location of the building, °Cd; $\theta_{i,ave}$ is average value of the internal temperature (temperature in heated rooms) in the heating season, °C; θ_e is design value of the external temperature, °C; $\eta_{H,tot}$ is total efficiency of the heating system in a given building; y is reducing coefficient due to the occurrence of heat gains in the building, taken in the range of 0.67–1. According to [13], for single-family buildings it equals 0.57.

The presented relation has been decided to be used for calculations of seasonal heat demand in single-family buildings.

In the original form of the relation discussed (3), it was assumed that the design heat load of a building $\varnothing_{ho}$ (demand for power for heating) should be calculated according to the standard, which is currently PN-EN ISO 12831-1:2017-08. 2017 [35]. The calculation of the design heat load requires detailed data on the materials of the partitions, the surface areas through which heat losses occur, and the volumes (heated and ventilated). While obtaining these data is not a major problem for the design of heating in a new building, in the case of existing buildings, especially those without construction documentation, obtaining the information will be extremely difficult and time-consuming. Therefore, it was decided to use the relation, which was applied to estimate the demand for power for heating buildings, in which the so-called thermal characteristic is used [38,39]. This quantity was determined empirically based on statistical data made [38]. In the case of single-family buildings whose heated volume is less than 1000 m^3, this relation can be written in the following form [40]:

$$\varnothing = 0.064 \cdot \sqrt[6]{V_e^5} \cdot w \tag{4}$$

where: $\varnothing$ is approximate power demand for heating of the building, kW; V_e is cubic capacity of the building calculated according to external dimensions, m^3; w is correction factor dependent on the period of construction of the building.

The values of the correction factor "w", which correlates with the period of construction of buildings, were presented by the author of this paper in [40] and updated for buildings built after 2017. The average values of the correction factor according to the age of the building are presented in Table 3.

Table 3. Values of the correction factor depending on the age of the building.

Years	"w" Correction Factor
until 1957	1.92
1957–1974	1.78
1975–1982	1.58
1983–1991	1.34
1992–2002	1.21
2003–2008	1
2009–2013	0.92
2014–2017	0.74
after 2017	0.65

Formula (3) after transformation took the following form:

$$Q_{H,d} = \frac{0.876 \cdot HDD \cdot \sqrt[6]{V_e^5} \cdot w}{\eta_{H,tot} \cdot (\theta_{i,ave} - \theta_e)} \tag{5}$$

where: $\Phi_{H,d}$ is calculated seasonal energy consumption for heating the building, kWh; HDD is number of heating degree-days for the building location, °Cd; V_e is heated volume of the building (calculated by external dimensions), m^3; θ_e is design value of outdoor temperature, °C; $\theta_{i,ave}$ is average value of indoor temperature in the heating season (temperature in heated compartments), °C; w is correction factor dependent on the period of construction of the building; $\eta_{H,tot}$ is total efficiency of heating system in the given building.

The index of final energy demand for heating was calculated according to the formula:

$$FE = \frac{Q_{H,d}}{A_h} \tag{6}$$

where: FE is index of final energy demand for heating, kWh·(m^2·year)$^{-1}$; A_h is area of temperature-controlled rooms (heated surface), m^2.

A new paradigm is to evaluate the quality of a model based on empirical formulas for estimating energy consumption in actual single-family residential buildings (Figure 3).

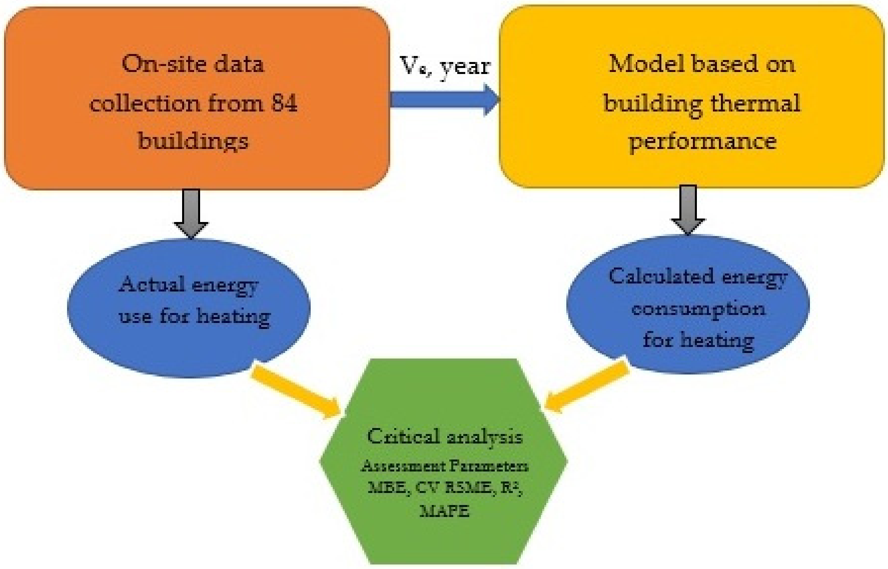

Figure 3. Methodological scheme of the performed activities.

The quality assessment of the developed models was based on the mean bias error (MBE), coefficient of variance of the root mean square error ($CV\ RMSE$), and coefficient of determination (R^2), which are accepted as statistical calibration standards by ASHRAE Guideline 14-2014 [43]. Other metrics frequently used in the literature such as $MAPE$ were also used for quality assessment [42].

$$MBE = \frac{\sum_{m=1}^{n_g}\left(y_i - y_i^P\right)}{\sum_{m=1}^{n_g} y_i}\cdot 100\% \quad m = 1, 2, 3\ldots, n_g \tag{7}$$

$$CV\ RMSE = \frac{\sqrt{\sum_{m=1}^{n_g}\frac{\left(y_i - y_i^P\right)^2}{y_i}}}{\frac{1}{n_g}\ \sum_{m=1}^{n_g} y_i}\cdot 100\% \quad m = 1, 2, 3\ldots, n_g \tag{8}$$

$$R^2 = \left(\frac{n_g\cdot\sum_{m=1}^{n_g} y_i\cdot y_i^P - \sum_{m=1}^{n_g} y_i\cdot\sum_{m=1}^{n_g} y_i^P}{\sqrt{\left(n_g\cdot\sum_{m=1}^{n_g} y_i^2 - \left(\sum_{m=1}^{n_g} y_i\right)^2\right)\cdot\left(n_g\cdot\sum_{m=1}^{n_g} y_i^{P\,2} - \left(\sum_{m=1}^{n_g} y_i^P\right)^2\right)}}\right)^2 \tag{9}$$

$$MAPE = \frac{1}{n_g}\sum_{m=1}^{n_g}\left|\frac{y_i - y_i^P}{y_i}\right|\cdot 100\% \quad m = 1, 2, 3\ldots, n_g \tag{10}$$

where: y_i is the actual value (quantity) in the facility i, and $y^p{}_i$ is the forecast value (quantity) in the facility i. The difference between y_i and $y^p{}_i$ is divided by the actual value y_i and m the number of the test object (m = 1, 2, 3, . . . , n_g).

According to ASHRAE Guideline 14 criteria [43], for the model to be considered well-calibrated, the value of the evaluation indices should not exceed:

- MBE index ± 5%,
- $CV\ RMSE$ index 15%,

However, the value of the coefficient of determination should be $R^2 \geq 0.75$.

3. Results and Discussion

3.1. Real Energy Consumption for Heating Buildings

The study was conducted for 84 single-family residential buildings located in the southern part of Poland in the city of Krakow. For the analyzed buildings, data were collected on natural gas consumption in three seasons covering the years 2017–2019.

Since the acquired data included total heat consumption for heating, preparation of domestic hot water, and preparation of meals, it was therefore necessary to separate the consumption only for heating of the buildings. For this purpose, it was assumed that the heating season lasts 9 months a year, that is from January to May and from September to December. However, in the three summer months, i.e., June, July, and August, energy is consumed exclusively for preparation of domestic hot water and meals. This allowed us to calculate the average monthly energy consumption for the mentioned purposes (domestic hot water, preparation of meals). The energy consumption for heating buildings was calculated as the difference between the total energy consumption in the individual months of the heating season and the calculated average value of the three summer months. On this basis, the final energy demand for heating was calculated. To exclude seasonal variations, the obtained actual values of energy consumption for heating were recalculated (corrected) to standard season conditions (multi-year average). Data on heating season degree-days (from 2017–2019, where HDD_{2017} = 3615.3 °Cd; HDD_{2018} = 3405.4 °Cd; HDD_{2019} = 3073.8 °Cd), based on which the calculations were carried out, were taken from the climate database of the Institute of Meteorology and Water Management—National Research Institute (IMWM–NRI) for the Krakow region. The amount of final energy consumption for heating was calculated according to the formula:

$$Q_{H,f} = \sum_{i=1}^{3} \frac{HDD(t_b)_i}{HDD(t_b)_0} \cdot Q_{H,f_i} \cdot \frac{1}{3} \tag{11}$$

where: $Q_{H,f}$ is the final energy demand for the heating season, kWh; $HDD_{(t_b)_0}$ is the number of degree days in a standard heating season, °Cd; $HDD_{(t_b)_i}$ is the number of degree days for the "*i*" of this year, °Cd; Q_{H,f_i} is final energy consumption for heating in a measurement period for the "*i*" of this year, kWh.

The results obtained allowed to determine the annual energy consumption in the studied group of buildings divided into heating as well as domestic hot water and meal preparation, which is presented in Figure 4.

The average energy consumption for heating in the analyzed group of buildings was 20,440 kWh·year^{-1}, with the variability coefficient of 32%, which gives an average value in the range of 19,110 to 21,770 kWh·year^{-1}. The energy consumption for preparation of domestic hot water and meals was on average 5480 kWh·year^{-1}, for which the variability coefficient is 19.6%. It can be assumed that in the studied group of buildings, the energy consumption for this purpose is between 5250 and 5760 kWh·year^{-1}.

The values of final energy consumption for heating per FE_0 surface unit are presented in Table 4.

The average value of the final energy consumption for heating in the analyzed group of buildings was 176 kWh·(m^2·year)$^{-1}$. The average final energy consumption for heating for the "average building" in Poland was determined based on standard reference calculations based on EN-ISO 13790:2008 [44,45] for single-family residential buildings is 182.3 kWh·(m^2·year)$^{-1}$. Comparing the average values of the index in the analyzed group of buildings with theoretical values [45], it can be observed that they are similar and, therefore, the group of buildings adopted for the analysis can be considered representative.

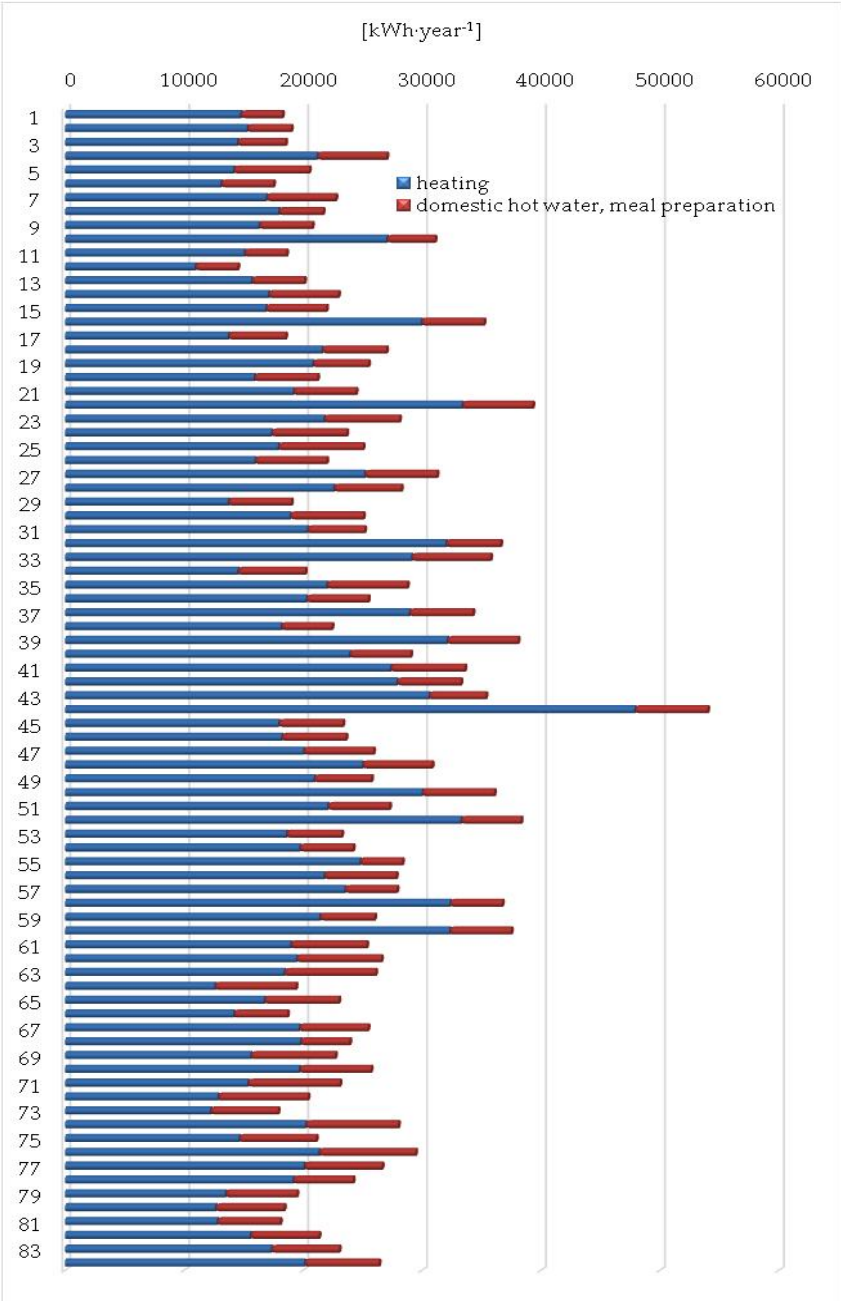

Figure 4. Summary of energy consumption for heating and hot water preparation for the analyzed group of buildings.

Table 4. Values of the correction factor depending on the age of the building.

***FE*₀—Index of Final Energy Demand for Heating, kWh·(m²·Year)⁻¹**				
min	max	average	standard deviation	confidence interval
81	298	176	57.5	164–188

3.2. Calculation of Energy Consumption for Heating of Buildings

The collected data describing the buildings, such as year of construction and heated volume of the building V_e, were entered into model (5) through which the seasonal energy consumption for heating was calculated. The buildings are in climate zone III for which the design outdoor temperature θ_e is equal to −20 °C and the annual average outdoor temperature is 7.6 °C. The calculations assume that the average design indoor temperature $\theta_{i,ave}$ for the rooms in the residential buildings is +20 °C. The number of heating season degree-days *HHD* for the given location (meteorological station Kraków–Balice) is 3748.4 °Cd. All buildings were equipped with central heating installations with gas boilers, therefore the total efficiency of the heating system $\eta_{H,tot}$ has been assumed for the calculations, in accordance with the provisions contained in the regulations concerning the calculation of the energy performance of buildings [46], which for this type of installation amounts to 0.81.

The calculated seasonal energy consumption for heating was then used to determine the final energy demand for heating *FE*. The indicator values obtained based on the calculations have been compared with the actual values, which is shown in Figure 5.

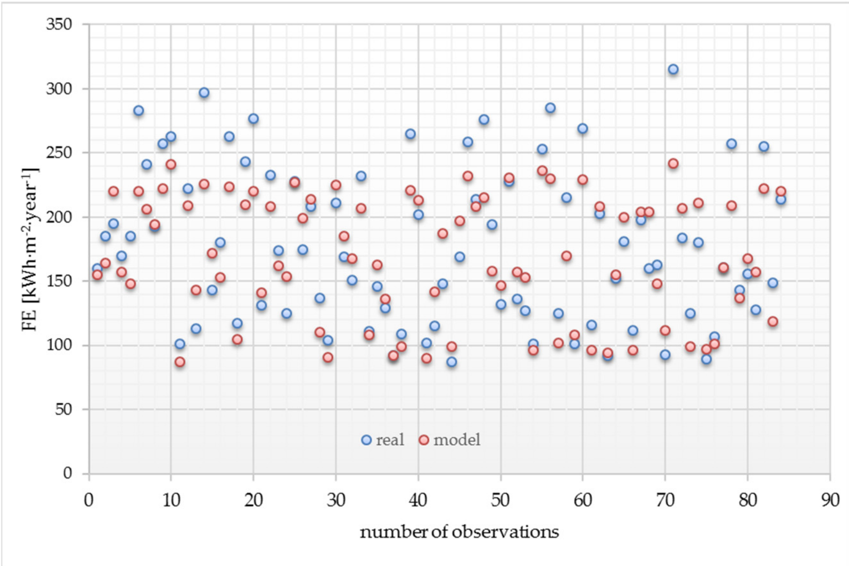

Figure 5. Comparison of actual final energy demand rate for heating with values obtained from model calculations.

By analyzing the results shown in Figure 5, it can be concluded that the model calculations differ from the actual data in the range of 1 to 73 kWh·(m^2·year)$^{-1}$, with the most common value in the range of 19 to 26 kWh·(m^2·year)$^{-1}$.

The next step of the study was to calculate metrics to evaluate the quality of the developed predictive model such as *MBE*, *CV RMSE*, R^2, and *MAPE*, which are adopted as statistical calibration standards by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers). The calculation results are summarized in Table 5.

Table 5. Comparison of mean bias error (*MBE*), coefficient of variation root means square error (CV RMSE), coefficient of determination (R^2), and mean absolute percentage error (*MAPE*) values for the analyzed energy consumption model.

Assessment Parameters	
MBE (%)	3.8
CV RMSE (%)	12.1
R^2 (−)	0.78
MAPE (%)	12.9

The results presented in Table 5 indicate that the model of energy demand for heating buildings, based on the so-called thermal characteristics, which is based on the formula provided in PN-66/B-02419 [41], is of acceptable quality despite the use of a limited set of variables. According to the adopted methodology, acceptable models were those for which R^2 was above 0.75, *MBE* within ±5%, and *CV RMSE* below 15%. The obtained error values provide a basis for the statement that in the absence of building documentation, the approximation method gives good results in estimating the energy demand for heating single-family residential buildings.

4. Conclusions and Perspectives

Based on research carried out in 84 single-family residential buildings, energy consumption data were collected for a three-year period of exploitation. Based on the analysis of the actual energy consumption, it can be stated that the buildings consumed between 19.1 and 21.7 MWh·year^{-1} of energy for heating, while for other purposes related to the preparation of domestic hot water and meals, an average of 5.25 to 5.7 MWh·year^{-1} is consumed. The average value of the unit energy demand for heating FE for the studied group of buildings is 164 to 188 kWh·(m^2·year)$^{-1}$. Since only a small part of the studied group of buildings had building documentation, the variables which characterized the buildings in terms of heat demand were separated: the year of construction and heated cubic capacity. These variables were used to build a model based on thermal characteristics for prediction of heat demand for heating. The obtained computational results were compared with the actual values and then evaluated in accordance with the standards for assessing the quality of the model proposed by ASHRAE, in which the predictive model must meet the calibration conditions, which were set so that *MBE* is within ±5%, *CV RMSE* is less than 15%, and R^2 is above 0.75, in order to be considered acceptable in quality.

For the model analyzed, the values of the indices are as follows: *MBE* = 3.8%, *CV RMSE* = 12.1%, and R^2 = 0.78. Thus, in the case of incomplete data or lack of building documentation for existing buildings, it is possible to express the belief that the modified method presented in this paper based on the so-called thermal characteristics can be successfully used to estimate energy consumption for heating of single-family residential buildings.

In the future, the author plans to use the studied group of objects again for testing hybrid forecasting methods based on the rough set theory (RST). It is also planned to introduce to the model a coefficient which characterizes the influence of thermomodernization actions on the decrease of energy consumption. Additionally, the author plans to extend the existing database with analogous objects heated by other heat sources, as well as buildings used in other climatic zones.

Funding: This research was funded by University of Agriculture in Krakow, Poland.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We are grateful to Thomas G. Mathia from Laboratoire de Tribologie et Dynamique des Systèmes, École Centrale de Lyon, France, for very fruitful scientific discussions on mathematical modelling.

Conflicts of Interest: The author declares no conflict of interest.

References

1. International Energy Agency; United Nations Environment Programme. 2018 Global Status Report: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. 2018. Available online: https://wedocs.unep.org/20.500.11822/27140 (accessed on 28 November 2021).
2. BPIE. Europe's Buildings under the Microscope. A Country-by-Country Review of the Energy Performance of Buildings. 2011. Available online: https://www.bpie.eu/publication/europes-buildings-under-the-microscope (accessed on 21 September 2021).
3. Statistics Poland. 2021. Available online: https://bdl.stat.gov.pl/BDL/dane/podgrup/wymiary (accessed on 29 September 2021).
4. Praca Zbiorowa. Stan Energetyczny Budynków w Polsce, Raport, BuildDesk Polska. 2011. Available online: http://www.builddesk.pl/files/BuildDesk/Consultancy/PL%20BD%20Analytics/2010-12-stan-energetyczny-budynkow.pdf (accessed on 2 October 2021).
5. Pawłowski, K. *Projektowanie Przegród Zewnętrznych Budynków o Niskim Zużyciu Energii*; Wydawnictwo Grupa Medium: Warszawa, Poland, 2021; ISBN 978-83-64094-71-2.
6. Szul, T. Analysis of heat source selection for residential buildings in rural areas. *BIO Web Conf.* **2018**, *10*, 1–6. [CrossRef]

7. Bourdeau, M.; Zhai, X.-Q.; Nefzaoui, E.; Guo, X.; Chatellier, P. Modelling and forecasting building energy consumption: A review of data-driven techniques. *Sustain. Cities Soc.* **2019**, *48*, 101533. [CrossRef]
8. Seyedzadeh, S.; Rahimian, F.; Glesk, I.; Roper, M. Machine learning for estimation of building energy consumption and performance: A review. *Vis. Eng.* **2018**, *6*, 5. [CrossRef]
9. Zhao, H.; Magoulès, F. A review on the prediction of building energy consumption. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3586–3592. [CrossRef]
10. Fumo, N. A review on the basics of building energy estimation. *Renew. Sustain. Energy Rev.* **2014**, *31*, 53–60. [CrossRef]
11. Foucquier, A.; Robert, S.; Suard, F.; Stéphan, L.; Jay, A. State of the art in building modelling and Energy performances prediction: A review. *Renew. Sustain. Energy Rev.* **2013**, *23*, 272–288. [CrossRef]
12. Costanzoa, V.; Fabbrib, K.; Piraccini, S. Stressing the passive behavior of a Passivhaus: An evidence-based scenario analysis for a Mediterranean case study. *Build. Environ.* **2018**, *142*, 265–277. [CrossRef]
13. Kasperkiewicz, K. *Termomodernizacja Budynków. Ocena Efektów Energetycznych*; Wydawnictwo Naukowe PWN: Warszawa, Poland, 2018; ISBN 978-830-119-61-34.
14. Mat Daut, M.A.; Hassan, M.Y.; Abdullah, H.; Rahman, H.A.; Abdullah, M.P.; Hussin, F. Building electrical energy consumption forecasting analysis using conventional and artificial intelligence methods: A review. *Renew. Sustain. Energy Rev.* **2017**, *70*, 1108–1118. [CrossRef]
15. Fan, C.; Xiao, F.; Wang, S. Development of prediction models for next-day building energy consumption and peak power demand using data mining techniques. *Appl. Energy* **2014**, *127*, 1–10. [CrossRef]
16. Ahmad, T.; Chen, H.; Guo, Y.; Wang, J. A comprehensive overview on the data driven and large scale based approaches for forecasting of building energy demand: A review. *Energy Build.* **2018**, *165*, 301–320. [CrossRef]
17. Tardioli, G.; Kerrigan, R.; Oates, M.; O'Donnell, J.; Finn, D. Data Driven Approaches for Prediction of Building Energy Consumption at Urban Level. *Energy Procedia* **2015**, *78*, 3378–3383. [CrossRef]
18. Cieśliński, K.; Tabor, S.; Szul, T. Evaluation of Energy Efficiency in Thermally Improved Residential Buildings, with a Weather Controlled Central Heating System. A Case Study in Poland. *Appl. Sci.* **2020**, *10*, 8430. [CrossRef]
19. Wang, J.; Srinivasan, R.S. A review of artificial intelligence-based building energy use prediction: Contrasting the capabilities of single and ensemble prediction models. *Renew. Sustain. Energy Rev.* **2017**, *75*, 796–808. [CrossRef]
20. Deb, C.; Lee, S.E. Determining key variables influencing energy consumption in office buildings through cluster analysis of pre-and post-retrofit building data. *Energy Build.* **2018**, *159*, 228–245. [CrossRef]
21. Štefko, J.; Osvald, A.; Makovická Osvaldová, L.; Sedlák, P.; Štefková, J. *Model Fire in a Two-Storey Timber Building*; Springer International Publishing: Cham, Switzerland, 2021; ISBN 978-3-030-82205-7. [CrossRef]
22. Chang, C.; Zhu, N.; Yang, K.; Yang, F. Data and analytics for heating energy consumption of residential buildings: The case of a severe cold climate region of China. *Energy Build.* **2018**, *172*, 104–115. [CrossRef]
23. Szul, T.; Nęcka, K.; Mathia, T.G. Neural Methods Comparison for Prediction of Heating Energy Based on Few Hundreds Enhanced Buildings in Four Season's Climate. *Energies* **2020**, *13*, 5453. [CrossRef]
24. Fayaz, M.; Kim, D. A Prediction Methodology of Energy Consumption Based on Deep Extreme Learning Machine and Comparative Analysis in Residential Buildings. *Electronics* **2018**, *7*, 222. [CrossRef]
25. Castelli, M.; Trujillo, L.; Vanneschi, L.; Popovič, A. Prediction of energy performance of residential buildings: A genetic programming approach. *Energy Build.* **2015**, *102*, 67–74. [CrossRef]
26. Szul, T.; Kokoszka, S. Application of Rough Set Theory (RST) to Forecast Energy Consumption in Buildings Undergoing Thermal Modernization. *Energies* **2020**, *13*, 1309. [CrossRef]
27. Lu, H.; Cheng, F.; Ma, X.; Hu, G. Short-term prediction of building energy consumption employing an improved extreme gradient boosting model: A case study of an intake tower. *Energy* **2020**, *203*, 117756. [CrossRef]
28. Chou, J.S.; Bui, D.K. Modeling heating and cooling loads by artificial intelligence for energy-efficient building design. *Energy Build.* **2014**, *82*, 437–446. [CrossRef]
29. Cheng, M.Y.; Cao, M.T. Accurately predicting building energy performance using evolutionary multivariate adaptive regression splines. *Appl. Soft Comput.* **2014**, *22*, 178–188. [CrossRef]
30. Wang, Z.; Wang, Y.; Zeng, R.; Srinivasan, R.S.; Ahrentzen, S. Random Forest based hourly building energy prediction. *Energy Build.* **2018**, *171*, 11–25. [CrossRef]
31. Szul, T.; Tabor, S.; Pancerz, K. Application of the BORUTA Algorithm to Input Data Selection for a Model Based on Rough Set Theory (RST) to Prediction Energy Consumption for Building Heating. *Energies* **2021**, *14*, 2779. [CrossRef]
32. Nebot, À.; Mugica, F. Energy Performance Forecasting of Residential Buildings Using Fuzzy Approaches. *Appl. Sci.* **2020**, *10*, 720. [CrossRef]
33. Szul, T.; Nęcka, K.; Lis, S. Application of the Takagi-Sugeno Fuzzy Modeling to Forecast Energy Efficiency in Real Buildings Undergoing Thermal Improvement. *Energies* **2021**, *14*, 1920. [CrossRef]
34. Zhang, L.; Wen, J.; Li, Y.; Chen, J.; Ye, Y.; Fu, Y.; Livingood, W. A review of machine learning in building load prediction. *Appl. Energy* **2021**, *285*, 116452. [CrossRef]
35. *ISO 12831-1:2017-08*; European Standard: Heating Systems in Buildings. CEN: Brussels, Belgium, 2017.
36. Chalal, M.L.; Benachir, M.; White, M.; Shrahily, R. Energy planning and forecasting approaches for supporting physical improvement strategies in the building sector: A review. *Renew. Sustain. Energy Rev.* **2016**, *64*, 761–776. [CrossRef]

37. Djamila, H. Indoor thermal comfort predictions: Selected issues and trends. *Renew. Sustain. Energy Rev.* **2017**, *74*, 569–580. [CrossRef]
38. Kamler, W. *Ciepłownictwo*; Państwowe Wydawnictwa Naukowe: Warszawa, Poland, 1976; ISBN 83-01-00218-2.
39. Krygier, K.; Klinke, T.; Sewrynik, J. *Ogrzewanie, Wentylacja, Klimatyzacja*; Wydawnictwa Szkolne i Pedagogiczne: Warszawa, Poland, 1991; ISBN 830-207-89-80.
40. Szul, T. Assessment of the accuracy of the approximate method used to estimate the heating power demand for single-family houses. *J. Res. Appl. Agric. Eng.* **2018**, *63*, 126–129.
41. CEN. Polish Standard: Central Heating. Calculation of Fuel Requirements for Heating Buildings (Centralne Ogrzewanie. Obliczanie Zapotrzebowania Paliwa do Ogrzewania Budynków) PN-66/B-02419. Available online: https://sklep.pkn.pl/pn-b-02419-1966p.html (accessed on 5 October 2021).
42. Ruiz, G.R.; Bandera, C.R. Validation of Calibrated Energy Models: Common Errors. *Energies* **2017**, *10*, 1587. [CrossRef]
43. American Society of Heating, Ventilating, and Air Conditioning Engineers (ASHRAE). *Guideline 14-2014, Measurement of Energy and Demand Savings*; American Society of Heating, Ventilating, and Air Conditioning Engineers: Atlanta, GA, USA, 2014; Available online: https://scholar.google.com/scholar_lookup?title=American+Society+of+Heating,+Ventilating,+and+Air+Conditioning+Engineers+(ASHRAE).+Guideline+14-2014,+Measurement+of+Energy+and+Demand+Savings&author=ASHRAE&publication_year=2014 (accessed on 5 October 2021)Technical Report.
44. *ISO 13790:2008*; European Standard: Energy Performance of Buildings-Calculation of Energy Use for Space Heating and Cooling. CEN: Brussels, Belgium, 2008. Available online: https://www.iso.org/standard/41974.html(accessed on 5 October 2021).
45. TABULA. Polish Building Typology. In *Scientific Report*; Narodowa Agencja Poszanowania Energii: Warszawa, Poland, 2012; Available online: https://episcope.eu/fileadmin/tabula/public/docs/scientific/PL_TABULA_ScientificReport_NAPE.pdf (accessed on 15 January 2021).
46. Ordinance of 27 February 2015 on the Methodology for Determining the Energy Performance of a Building or Part of a Building and Energy Performance Certificates. Available online: http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20150000376/O/D20150376.pdf (accessed on 2 October 2021).