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Article

Energy Analyses of Multi-Family Residential Buildings in Various Locations in Poland and Their Impact on the Number of Heating Degree Days

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Abstract: Reducing energy demand and greenhouse gas emissions in the construction industry is one of the daunting challenges to be addressed in the context of global warming. The purpose of these analyses was to examine how the energy class of a multi-family residential building regarding thermal insulation and type of ventilation affects the usable energy demand for heating and ventilation purposes, the length of the heating season, and the amount of demand for energy consumed by auxiliary devices. This article presents the energy analyses of multi-family residential buildings with identical technical parameters located in different locations in Poland. For research purposes, a total of 354 energy balances were compiled, covering 59 meteorological stations, 3 types of ventilation systems, and 2 building insulation standards. This article presents the ways in which the location and energy class of buildings affect the length of the heating season and the demand for energy required for heating and ventilation purposes. The results of the analyses carried out in this article show that the location and the energy class of the building have a significant impact on the demand for primary energy (EP). As a result, it was concluded that when designating a reference building for the energy rating system, its location should be taken into account and reference buildings should be designated considering climate zones.

Keywords: energy efficiency of buildings; length of the heating season; number of heating degree days (HDDs); energy certification; energy efficiency; residential buildings

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1. Introduction

The European Union countries plan to achieve climate neutrality by curbing CO_2 emissions by 55% by 2050 [1]. It is thus necessary to take critical steps that will increase the energy efficiency of buildings and reduce the consumption of fossil fuels. Energy expenditures in the construction industry currently account for nearly 40% of the total energy consumption in the EU, which translates into greenhouse gas emissions at the level of 35% [2]. The recommendations of the European Commission on the renovation of buildings reveal that 27% of the energy consumption in the EU is attributed to the residential sector [3].

The COVID-19 pandemic has had a noticeable impact on our lives and habits. It has also dramatically changed the perception and functioning of our places of residence. More frequent and longer home stays, as well as remote work, have prompted us to pay attention to the technical condition and energy consumption of our dwellings. We started to take heed of the prevailing microclimate and air quality of our rooms. The extended home stays have also brought economic and environmental consequences. The increased consumption of electricity and thermal energy for heating and hot water preparation, as well as the energy required by air conditioning and refrigeration devices, has resulted in larger emissions of pollutants. Recent geopolitical events have made us think more often about the direction of development that would enable us to become independent from external energy carriers. We had made the first steps in this direction even before the world was struck by the coronavirus pandemic and the crisis related to the military operations in Ukraine. The widespread thermal modernization of buildings is not only an opportunity to improve the quality of life in our homes, but there are also a number of macroeconomic aspects at work, which could give the economy a huge development boost. Regarding the environmental issues related to the emission of greenhouse gases, the problem of low emissions and smog are equally significant. Paper [4] presents research on the state of the energy intensity of residential buildings in Poland. The authors investigated what influences increases in interest in energy-saving construction among people. The authors of the study found that a significant number of buildings in Poland are energy-intensive, and heating is carried out using heat sources dependent on fossil fuels. According to their analyses, buildings whose inhabitants admitted to using RES are more energy-efficient and modern.

In line with the assumptions of the European Green Deal (EGD) [5], the European Union is to transform into a climate-neutral area by 2050. In order to reduce CO_2 emissions in the construction sector, the idea of promoting "nearly zero-energy buildings" (NZEBs), which are defined as buildings with very high energy efficiency, was put forward. The increased interest in nearly zero-energy buildings (NZEBs) can be observed around the world [6–12].

In order to promote low-energy-demand buildings, the European Commission made a decision to introduce a system of energy labeling for buildings in the Member States. The energy performance certificate system varies from country to country. The purpose of energy certification is to enable comparing and assessing the energy performance of various buildings and encourage their owners and tenants to improve them. The certification allows for a comparison of the technical condition of the assessed building against the values required by law. In works [13–16], comparative analyses of different ways of expressing energy performance in selected EU countries were carried out. Table 1 includes the main methods of expressing energy performance.

Table 1. Methods of presenting energy performance.

No.	Methods of Presenting Energy Performance
1.	Classes from A++ to G—primary energy
2.	Primary Energy—continuous scale
3.	Classes A to G—primary energy Continuous scale—CO_2 emissions
4.	Classes from A++ to G—energy efficiency ratio, primary energy, heating energy demand, CO_2 emissions

A significant number of buildings in Poland are energy-intensive, and heating is carried out using heat sources relying on fossil fuels. The policy of the European Union countries is aimed at reducing CO_2 emissions, primarily in the construction sector. In Poland, work is underway to define a reference building for the energy standard of multi-family residential buildings in order to determine energy classes and a new methodology for calculating the energy performance of buildings. An important aspect is also determining the carbon footprint for the building and installation components applied. It should be noted that climate change will result in an increase in external temperatures, which also affects the length of the heating season (Ld), the number of heating degree days (HDDs) [17–20], and indirectly affects the operation time of auxiliary devices in the heating system.

In studies on the energy consumption of buildings, the aspect that the length of the heating season affects the demand for energy consumed by auxiliary devices in the heating system is generally overlooked. Based on the current legal status in Poland, in accordance with the regulation on the methodology for determining the energy performance of buildings [21], in energy models of buildings, the value of the operation time of circulation pumps is constant regardless of the energy standard of the building. This type of approach greatly simplifies the energy assessment of buildings. The operating time of auxiliary devices within the heating system will also have a significant impact on the planned building assessment system based on the life cycle assessment (LCA).

The decision was made to inquire into how the length of the heating season will affect the demand for the final and primary energy of buildings. The authors of the paper believe that this issue may have an important impact that should be investigated.

Publication [16] presents studies that were carried out for multi-family residential buildings with different aspect ratios and ventilation systems in three locations in Poland, depending on the climate. The impact of these components on the energy class of the building was assessed. The research in press [16] was aimed at estimating the limits of the energy efficiency classes of multi-family buildings in Poland. The article does not discuss how the energy class of a building and its standard affect the demand for final energy (EK) and primary energy (EP). In our study, however, the decision was made to extend the research to 59 different locations throughout Poland to include different energy classes of buildings, depending on the ventilation system and the thermal insulation of external partitions. The decision was made to investigate whether the adopted energy class of the building and its location affect the length of the heating season (Ld). It was ascertained whether this significantly affects the consumption of electricity in buildings by auxiliary devices of the heating system (pumps), and thus, whether it can have a significant impact on the energy performance of the building and also, indirectly, on determining the carbon footprint.

In publication [22], the authors focused on presenting how the thermal insulation class and the ventilation system affect the demand for primary energy and CO_2 emissions for several selected heat sources in one location (Wrocław). In the research project, the decision was made to analyze for one assumed heating system how the location of the building in different regions of Poland (59 meteorological stations) affected the value of demand for non-renewable primary energy (EP). This article, however, analyzes the impact of the location of the building in Poland on the demand for usable energy (EU_H), the demand for electricity consumed by auxiliary devices, the length of the heating season, and the number of heating degree days.

2. Research Methodology

2.1. Description of the Analyzed Building

Comparative analyses of the demand for energy for heating purposes and preparation of hot utility water were carried out for the project of a multi-family residential building with an area of 1051 m^2, in which 18 apartments are included. Detailed assumptions regarding solutions for the construction of building partitions and central heating installations are included in publication [22]. According to the design concept, it is a rectangular, 3-story, 2-staircase building with an unheated underground garage. In accordance with the design assumptions, the following were designed: external walls made of lime-sand blocks and thermally insulated with mineral wool boards; flat roofs made of reinforced concrete slabs and thermally insulated with extruded polystyrene, reinforced concrete interfloor ceilings; windows made of aluminum profiles, with a two-chamber glazing unit; external aluminum doors. The facade of the building is shown in Figure 1.

Figure 1. Building [22].

2.2. Usable Energy Demand Analysis

This article presents comparative analyses of the demand for usable energy for heating and ventilation in various locations in Poland. Energy calculations were made based on the CERTO 2015 simulation program, enabling the energy modeling of buildings for the respective calculation zones and rooms. The study incorporates the monthly method, which is used in Poland to determine the energy characteristics in accordance with [21,23]. Depending on the latitude and longitude, Europe has different types of climates. Poland is dominated by a temperate climate, but its three main subtypes can be distinguished: a warm climate, a mild climate, and a cold climate. Due to the division of the territory of Poland into five climate zones according to [24] and the different values of external temperatures and insolation for individual meteorological stations located in the country, the balance of demand for usable energy for heating and ventilation purposes was prepared for identical multi-family residential buildings located in 59 places in Poland, coinciding with the locations of meteorological stations. The territory of Poland, according to [24], is divided into five climate zones, in which the design external temperature, depending on the zone, ranges from −16 °C to −24 °C. The division of the climate zones is shown in Figure 2. The values of the design external temperature for the individual climate zones and average annual external temperatures are presented in Table 2.

Figure 2. Polish territory divided into climate zones based on the Polish standard [24].

Table 2. External temperatures and average temperatures based on the Polish standard [24].

Climate Zone	Design Outdoor Temperature θ_e (°C]	Average Annual Outdoor Temperature of the Climate Zone $\theta_{e(r)}$ (°C]
I	−16	7.7
II	−18	7.9
III	−20	7.6
IV	−22	6.9
V	−24	5.5

According to the research work of Alsabry et al. [22], a standard schedule for the use of rooms was adopted for this type of building, with the following normative internal temperatures of rooms: rooms θ_i = 20 °C, kitchens θ_i = 20 °C, bathrooms θ_i = 24 °C, staircases θ_i = 8 °C, in accordance with [24].

In each location, calculations were made for 6 energy classes of buildings (A1, A2, A3, B1, B2, and B3), in accordance with the assumptions presented in the work of Alsabry et al. [22].

Ventilating air streams were calculated considering the Polish standard on the requirements for ventilation installations in residential buildings [25] and the regulation on the development of energy performance [21]. The authors of this article carried out analyses for buildings with three types of ventilation, namely natural ventilation, mechanical exhaust ventilation, and mechanical supply and exhaust ventilation with heat recovery in a counter-current exchanger (average annual heat recovery of 75%). The air tightness of the buildings with natural ventilation was adopted in accordance with [26] at level n_{50} = 2.9 1/h, while with mechanical ventilation, it was assumed to be n_{50} = 1.4 1/h. In the calculations, internal heat gains were assumed at the level of q_{int} = 7.1 W/m^2 for residential premises and at the level of q_{int} = 1.0 W/m^2 for staircases, which correspond to the methodology for determining the energy performance of buildings in Poland in accordance with the regulation [21].

2.3. Analysis of the Length of the Heating Season

This article presents comparative analyses of the length of the heating season in 59 surveyed locations in Poland. It includes a comparison of how the energy class of the building according to [22], as well as the meteorological data of the analyzed locations, affect the length of the heating season (Ld) and the number of heating degree days (HDDs) calculated on the basis of [17–20]. In accordance with the methodology adopted, the length of the heating season for individual locations and energy classes of buildings depends on the balance of profits, heat losses, heat capacity, the building mass, and its location. The calculation of the number of heating degree days was made based on the formula:

$$\mathrm{HDD} = \sum_{i=1}^{12} (\theta_i - \theta_e(m)) \cdot \mathrm{Ld}(m)$$

where

HDD—number of heating degree days (K·day);
Ld(m)—number of heating days in the m-th month (day);
θ_i—internal operating temperature [°C], in accordance with standard [24];
$\theta_e(m)$—average long-term outdoor air temperature in the m-th month for meteorological stations [°C].

Using CERTO 2015 software (Version: 1.4.8.0.—Lower Silesian Energy and Environment Agency, 11 Pełczyńska Str., 51-113 Wrocław, Poland), simulation analyses of the heat balances of individual locations and energy classes of buildings were performed, which allowed for determining the length of the heating season. The value of the number of heating days in a month (Ld(m)) depends on the balance of heat gains, heat losses, heat capacity, the mass of the building, and its location.

2.4. Analysis of the Demand for Final Energy and Primary Energy

Additional tests were carried out to compare the demand for the final energy (EC) and the primary energy (EP). A hybrid heat supply system, based on an air–water heat pump and a natural gas condensing boiler house as the peak heat source, was tested. In accordance with the design concept, analyses were carried out for a water heating system, a pump heating system with underfloor heating, and a heat buffer for heating purposes. Hot utility water is prepared using a heat pump and a natural gas condensing boiler. A thermally insulated hot and circulating water installation is provided. Table 3 presents the parameters of the efficiency of the heating system and the preparation of domestic hot water.

Table 3. Efficiency of the heating system and preparation of domestic hot water based on [21].

	Gas Boiler Room	Heat Pump Air-Water
Heating system		
Production efficiency	0.95	3.00
Accumulation efficiency	0.95	0.95
Transport efficiency	0.90	0.90
Regulation and use efficiency	0.85	0.85
Domestic hot water preparation system		
Production efficiency	0.88	2.60
Accumulation efficiency	0.85	0.85
Transport efficiency	0.70	0.70

It was assumed that the heat pump and auxiliary devices were powered from the power grid and a 22.5 kWp photovoltaic PV installation. The primary energy demand calculations took into account that the non-renewable primary energy factor adopted from [21] for natural gas $w_i = 1.1$, electricity $w_i = 2.5$, and solar energy $w_i = 0$.

3. Results and Analysis

For the purposes of this research, the values of the average annual outdoor temperatures of the climate zones were compared with the 30-year average temperatures recorded at meteorological stations located in various places in Poland. In the first (I) climate zone in Poland, there are 11 meteorological stations, at which the average annual outdoor temperature $\theta_{i(r)}$ ranges from 7.9 °C to 8.9 °C. According to [24], the average annual outdoor temperature of the climate zone $\theta_{i(r)}$ is 7.7 °C. In the second (II) climate zone in Poland, there are 15 meteorological stations, at which the average annual outdoor temperature $\theta_{i(r)}$ ranges from 7.1 °C to 9.0 °C. According to [24], the average annual outdoor temperature of the climate zone $\theta_{i(r)}$ is 7.9 °C. In the third (III) climate zone in Poland, there are 24 meteorological stations, at which the average annual outdoor temperature $\theta_{i(r)}$ ranges from 7.2 °C to 9.0 °C. According to [24], the average annual outdoor temperature of the climate zone $\theta_{i(r)}$ is 7.6°C. In the fourth (IV) climate zone in Poland, there are seven meteorological stations, at which the average annual outdoor temperature $\theta_{i(r)}$ ranges from 6.9 °C to 8.1 °C. According to [24], the average annual outdoor temperature of the climate zone $\theta_{i(r)}$ is 6.9 °C. In the fifth (V) climate zone in Poland, there are two meteorological stations, at which the average annual outdoor temperature $\theta_{i(r)}$ ranges from 5.4 °C to 6.3 °C. According to [24], the average annual outdoor temperature of the climate zone $\theta_{i(r)}$ is 5.5 °C. A detailed comparative summary is presented in Table S1.

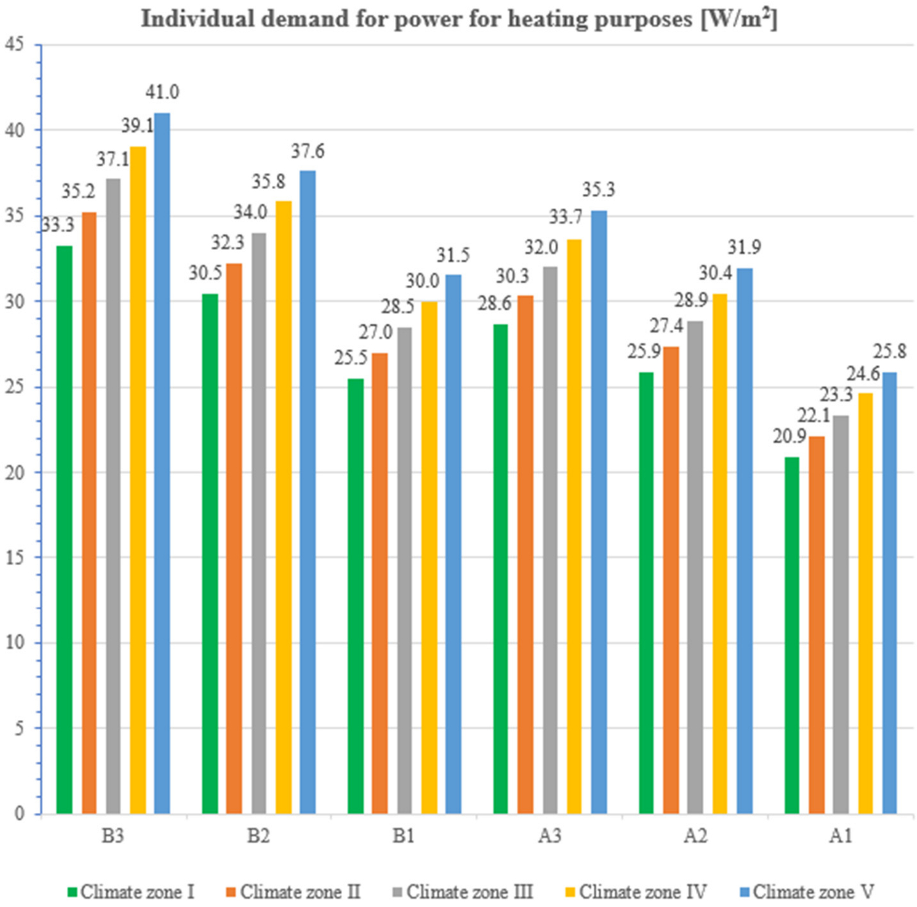
Performing the energy, economic, and environmental analyses of the possibility of implementing alternative energy and heat supply systems for multi-family residential buildings in accordance with [27] required estimating the annual demand for usable energy for heating, ventilation, and hot water preparation.

Based on the calculations carried out for the buildings of various energy classes and located in five climate zones in Poland, the values of the design heat load for heating and ventilation were estimated. The calculation results are presented in Table 4. The maximum demand for heat power for the purposes of heating was 43.09 kW, which corresponds to a B3 class building located in climate zone V ($\theta_e = -24$ °C). The minimum value of the design heat load for heating purposes was 21.93 kW, which corresponds to an A1 class building and location in climate zone I ($\theta_e = -16$ °C). The authors discovered that the energy class of the building and its location may even double the power demand for heating, which translates into the amount of investment costs related to the construction of the heating system and heat source.

Table 4. Comparison of the design heat load for heating and ventilation calculated according to the standard in [24] for different energy classes of buildings and climate zones in Poland.

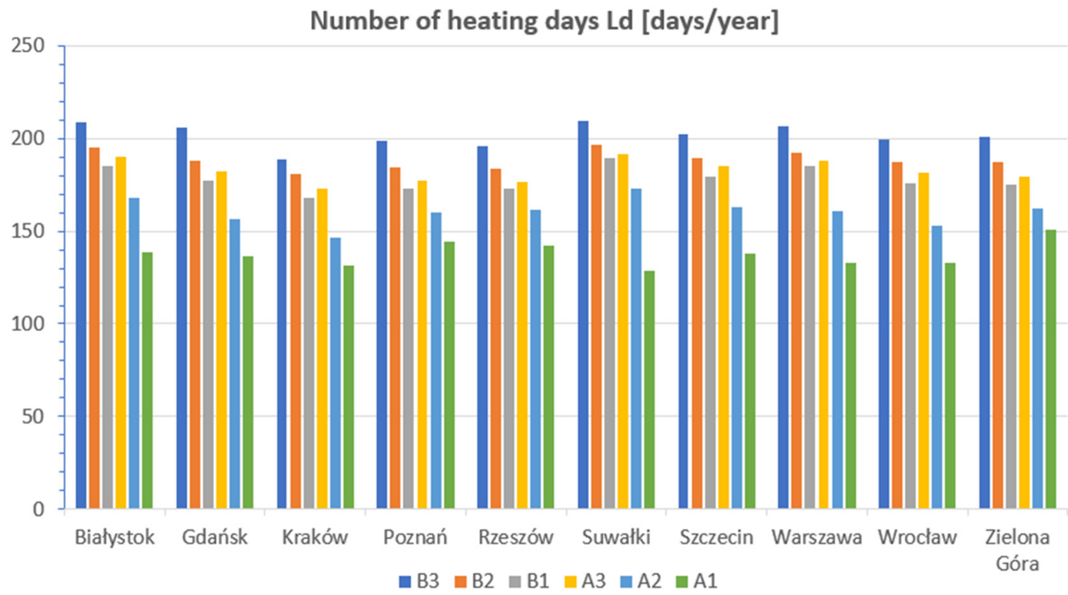
Climate Zone	Design Heat Load for Heating and Heating the Ventilating Air					
	Class B3 (kW)	Class B2 (kW)	Class B1 (kW)	Class A3 (kW)	Class A2 (kW)	Class A1 (kW)
I	34.95	32.02	26.78	30.10	27.17	21.93
II	36.98	33.90	28.37	31.85	28.77	23.24
III	39.02	35.77	29.95	33.61	30.36	24.54
IV	41.06	37.65	31.54	35.37	31.96	25.85
V	43.09	39.52	33.12	37.12	33.55	27.16

The analysis of the calculated indicators of the unit power demand for the heating purposes of buildings shows that the buildings designed in class A1, with mechanical supply and exhaust ventilation with heat recovery and partitions, corresponding to buildings with passive energy characteristics, have a lower demand for heat power for heating purposes. Due to the power of the heat sources, it was worth analyzing whether it is more advantageous economically to design I building in energy class A3 or B1. The analysis of the data shows that in the case of buildings located in climate zones IV and V, designing building partitions with higher thermal resistance than buildings located in climate zones I and II should be considered. The unit power demand for the heating purposes of buildings designed in energy classes B3, B2, B1, A3, A2, and A1 in Poland, depending on their location, is shown in Scheme 1.



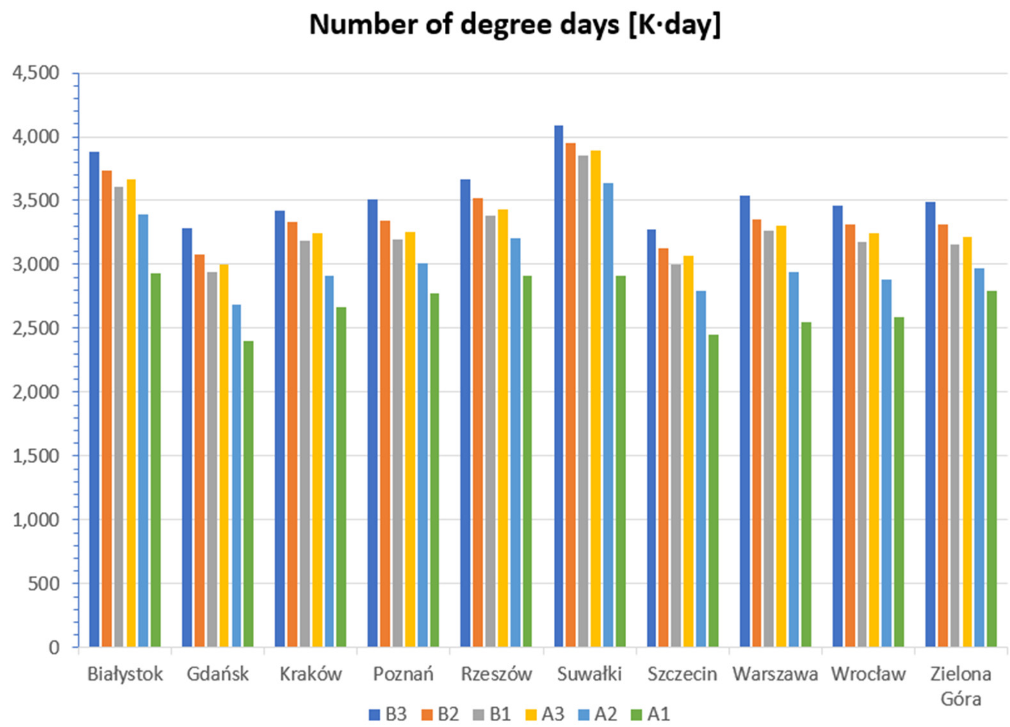
Scheme 1. Individual demand for power for heating purposes $[\mathrm{W/m^2}]$.

Based on the calculated heat balances for individual buildings located in Poland and designed in energy classes A1, A2, A3, B1, B2, and B3, the length of the heating season was determined, which depends on the balance of heat gains and losses, as well as the heat capacity of the building. The maximum length of the heating season for buildings in the B3 class located in Piła is 230.3 days per year. The minimum length of the heating season for the A1 building located in Tarnów is 109.4 days per year. According to the comparative analysis, for the same location, a longer heating season occurs in the case of a building with higher heat transfer coefficients U for external partitions and natural ventilation than in the case of buildings with designed external partitions with increased thermal insulation and natural ventilation. A shorter heating season occurs when a building is designed in the A1 energy class. The length of the heating season, therefore, affects the amount of auxiliary energy used for the operation of circulation pumps in the heating system. To sum up, the shorter the heating season, the lower the demand for auxiliary energy in the building. A detailed summary of the length of the heating season is presented in Table S2. For selected meteorological stations, Scheme 2 presents the graphical representation of the number of heating days of buildings.



Scheme 2. Length of the heating season (Ld (days/year)) for selected meteorological stations and energy classes of buildings**.**

For the analyzed buildings, the value of heating degree days (HDDs) was calculated, taking into account the estimated number of heating days. The maximum value of degree days (HDDs) occurred for a building with natural ventilation and external partitions located in Zakopane, in accordance with [26] (class B3), and it was 4280.62 K·day. The minimum HDD value was for an A1 building located in Tarnów, and it was 2167.28 K·day. Based on a detailed analysis of the number of heating degree days (HDDs), it was concluded that the better the thermal insulation of the external partitions, the lower the number of heating degree days for the assessed building and the lower the HDD value in the case of mechanical supply and exhaust ventilation with heat recovery. The detailed list is presented in Table S3. For selected meteorological stations, Scheme 3 presents a graphical comparison of the number of heating degree days for the assessed buildings.



Scheme 3. Number of heating degree days (HDDs (K·day)) for selected meteorological stations and energy classes of buildings**.**

For buildings designed in energy classes A1, A2, A3, B1, B2, and B3, calculations of the demand for usable energy for heating and ventilation were performed for 59 locations in Poland. The comparative analysis shows that for buildings designed in the B3 energy class, the minimum indicator of the annual demand for usable energy for heating and ventilation EU_H was calculated for Tarnów (the southern region of Poland) and was 31.12 kWh/(m^2 · year), and the highest indicator of the annual demand for usable energy for heating and ventilation EU_H was calculated for Suwałki (north-eastern region of Poland) and was 51.50 kWh/(m^2 · year). The average value of the demand for usable energy for heating and ventilation for a building designed in the B3 energy class was 37.48 kWh/(m^2 · year). A detailed summary of buildings in energy class B3 is presented in Table S4.

For buildings designed in energy class B2, the minimum indicator of the annual demand for usable energy for heating and ventilation EU_H was determined for Świnoujście (north-western region of Poland) and was 19.35 kWh/(m^2 · year), and the highest indicator of the annual demand for usable energy for heating and ventilation EU_H was calculated for Suwałki (north-eastern region of Poland) and was 36.99 kWh/(m^2 · year). The average value of the demand for usable energy for heating and ventilation for a building designed in the B2 energy class was 25.55 kWh/(m^2 · year). A detailed summary of buildings in energy class B2 is presented in Table S5.

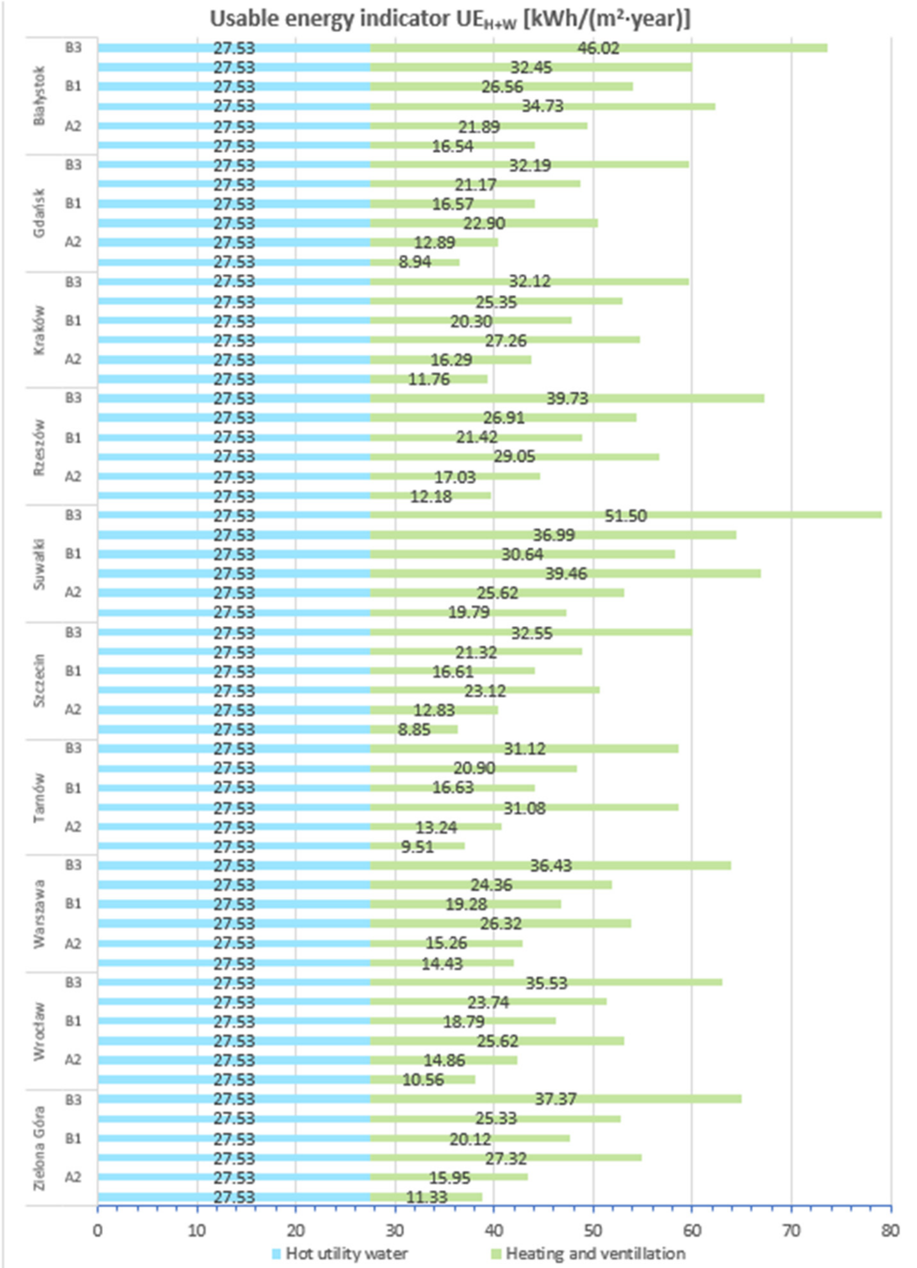
The research shows that for buildings designed in the B1 energy class, the minimum indicator of the annual demand for usable energy for heating and ventilation EU_H was calculated for Świnoujście (north-western region of Poland) and was 15.01 kWh/(m^2 · year), and the highest indicator of the annual demand for usable energy for heating and ventilation EU_H was calculated for Suwałki (north-eastern region of Poland) and was 30.46 kWh/(m^2 · year). The average value of the demand for usable energy for heating and ventilation for a building designed in the B1 energy class was 20.32 kWh/(m^2 · year). A detailed summary of buildings in energy class B1 is presented in Table S6.

For buildings designed in energy class A3, the minimum indicator of the annual demand for usable energy for heating and ventilation $(\mathrm{EU_H})$ was calculated for Świnoujście (north-western region of Poland) and was 20.99 $\mathrm{kWh/(m^2 \cdot year)}$, and the highest indicator of the annual demand for usable energy for heating and ventilation $(\mathrm{EU_H})$ was calculated for Suwałki (north-eastern region of Poland) and was 39.46 $\mathrm{kWh/(m^2 \cdot year)}$. The average demand for usable energy for heating and ventilation for a building designed in the A3 energy class was 27.57 $\mathrm{kWh/(m^2 \cdot year)}$. A detailed summary for buildings in the A3 energy class is presented in Table S7.

For buildings designed in energy class A2, the minimum indicator of the annual demand for usable energy for heating and ventilation $(\mathrm{EU_H})$ was 11.55 $\mathrm{kWh/(m^2 \cdot year)}$, and the highest indicator of the annual demand for usable energy for heating and ventilation $(\mathrm{EU_H})$ was calculated for Suwałki (north-eastern region of Poland) and was 25.62 $\mathrm{kWh/(m^2 \cdot year)}$. The average demand for usable energy for heating and ventilation for a building designed in the A2 energy class was 16.32 $\mathrm{kWh/(m^2 \cdot year)}$. A detailed summary of buildings in the A2 energy class is presented in Table S8.

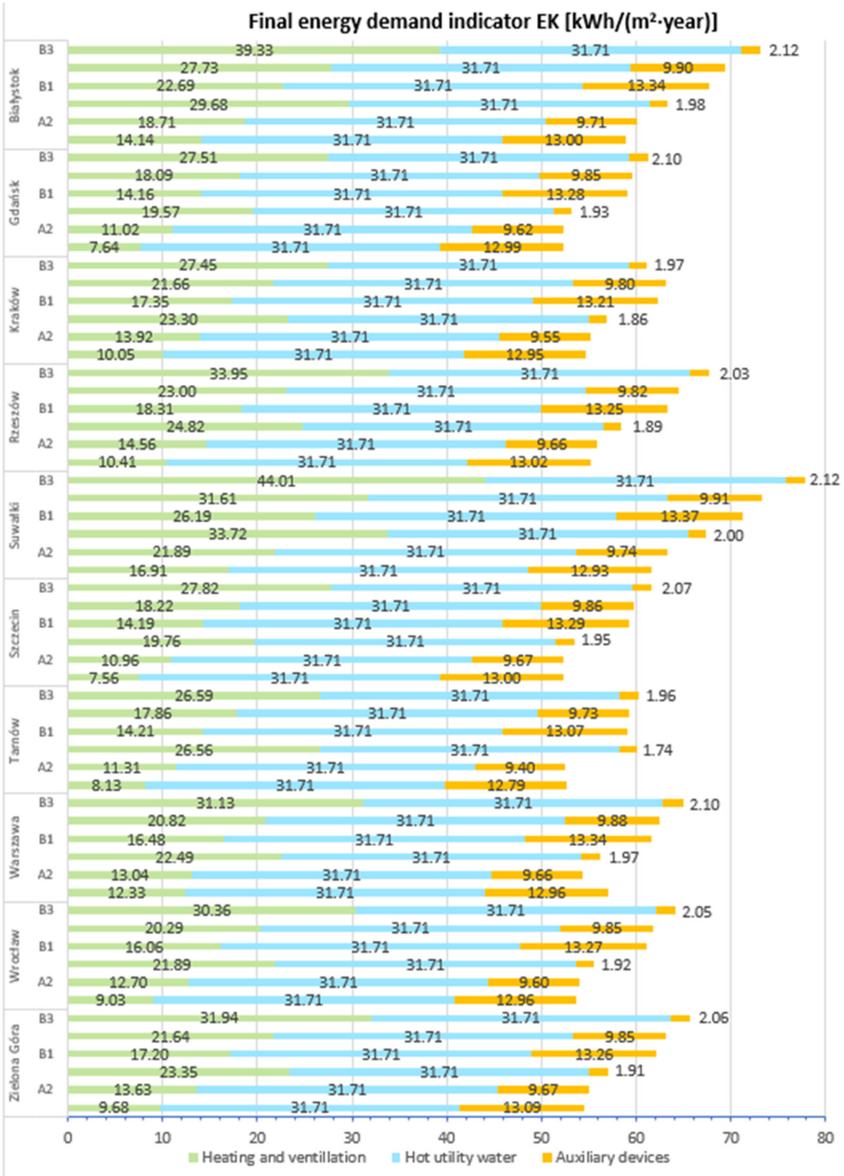
For buildings designed in energy class A1, the minimum indicator of the annual demand for usable energy for heating and ventilation $(\mathrm{EU_H})$ was determined for Świnoujście (north-western region of Poland) and was 7.82 $\mathrm{kWh/(m^2 \cdot year)}$, and the highest indicator of the annual demand for usable energy for heating and ventilation $(\mathrm{EU_H})$ was calculated for Suwałki (north-eastern region of Poland) and was 19.79 $\mathrm{kWh/(m^2 \cdot year)}$. The average value of the demand for usable energy for heating and ventilation for a building designed in the A1 energy class was 11.82 $\mathrm{kWh/(m^2 \cdot year)}$. A detailed summary of buildings in the A1 energy class is presented in Table S9.

In view of the above, the authors of the article decided to compare the indicators of the annual demand for usable energy for heating and ventilation as well as for the preparation of domestic hot water for the selected 9 locations of buildings. Regardless of the location of the building, the indicator of the annual energy demand for the preparation of hot utility water $(\mathrm{EU_W})$ was 27.53 $\mathrm{kWh/(m^2 \cdot year)}$. The analyses show that the better the thermal insulation of external partitions, the lower the value of the indicator of demand for usable energy for heating and ventilation. The use of mechanical ventilation with heat recovery and improved air tightness of the building improves the energy performance of the building. It was also noticed that higher values occurred for buildings located in climate zone V (in the north-western part of Poland). The lowest values of the indicator were found in the coastal belt (climate zone I) and in the region of southern Poland (Kraków, Tarnów), where insolation is greater. For buildings in energy class B3 located in climate zones IV and V, the demand for usable energy for heating purposes for buildings was up to 65%, and for buildings located in climate zone I, it was less than 54%. For buildings in energy class A1, which are characterized by low demand for usable energy for heating purposes, the demand for usable energy for preparing hot utility water was as much as 75% in climate zone I and in southern Poland, while in the north-east, it was less than only 58%. This is due to the more severe continental climate. The details are presented in Scheme 4.



Scheme 4. Comparison of indicators of annual demand for usable energy for heating and ventilation purposes and preparation of hot utility water for buildings located in selected representative locations**.**

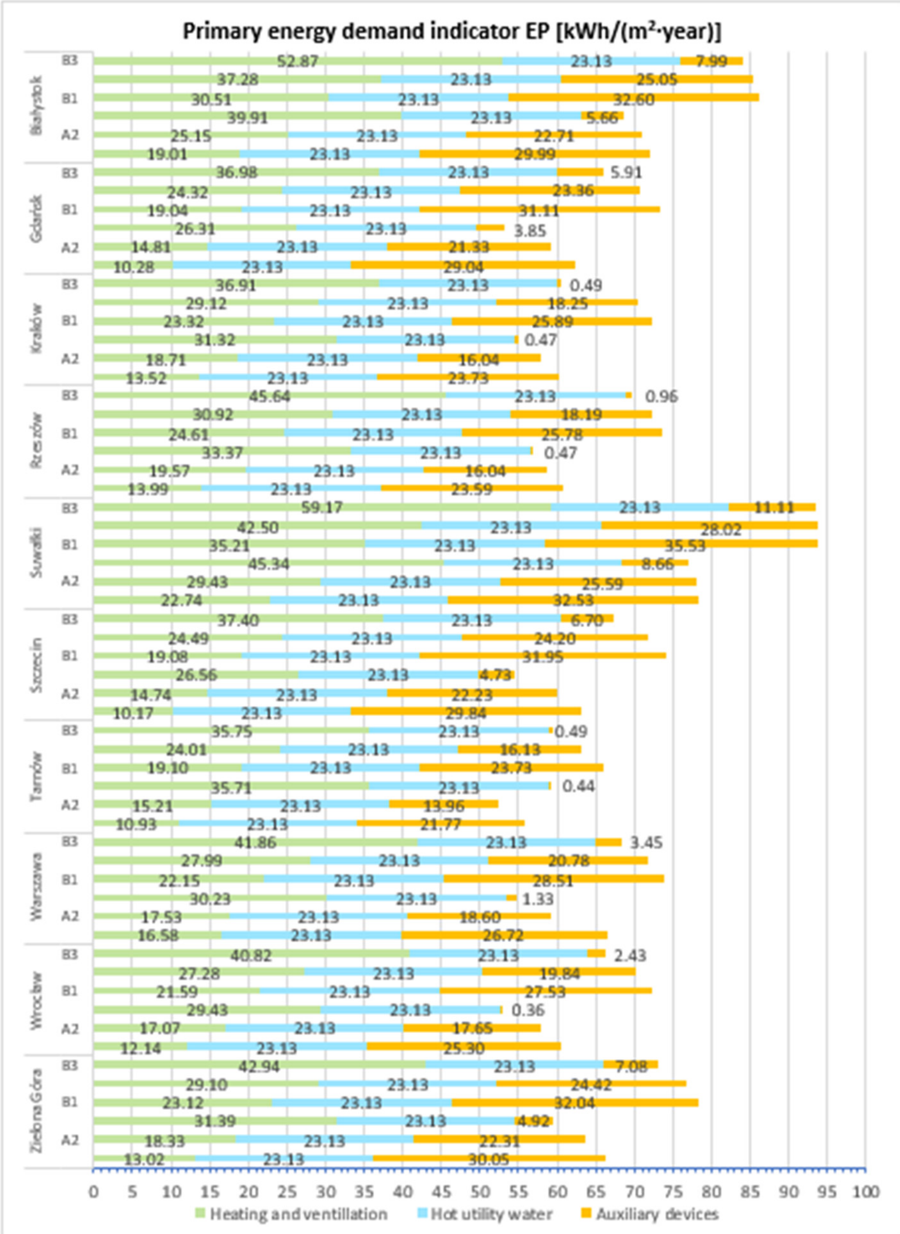
The calculations of the demand for final energy were made, which also included the demand for auxiliary energy to supply the heating system, mechanical ventilation, and the hot water system. The analyses show that higher demand for final energy occurred in buildings with a higher demand for usable energy for heating purposes. It should also be noted that a higher demand for final auxiliary energy occurred when mechanical ventilation is used. The length of the heating season had only a slight impact on the difference in auxiliary energy consumption. The details are presented in Scheme 5.



Scheme 5. Comparison of indicators of annual demand for final energy for heating and ventilation purposes as well as preparation of domestic hot water for buildings located in selected representative towns.

The demand for primary energy calculated for selected variants was compared with the maximum value of the EP according to [26], which was 65 $kWh/(m^2 \cdot year)$ in Poland for multi-family residential buildings.

The comparative analysis shows that meeting the legal requirements is possible with the suggested heating system only in the case of buildings with designed external partitions that meet the standards for buildings with passive energy characteristics. Regardless of the suggested energy class, a building with such a proposed heating system does not meet the requirements for the EP index according to [26] for buildings located in north-eastern Poland. It is also worth noting that the use of mechanical ventilation leads to an increase in the amount of energy consumed by auxiliary devices. This results in exceeding the maximum EP indicator. The details are presented in Scheme 6.



Scheme 6. Comparison of indicators of annual demand for primary energy for heating and ventilation purposes as well as preparation of domestic hot water for buildings located in selected representative towns**.**

4. Discussion and Works to Complete

The energy rating system for buildings introduced by the EPBD [28] is aimed at increasing the number of buildings with low energy consumption. In the energy assessment of buildings, the amount of energy for heating, hot water preparation, auxiliary devices, and, in the case of public utility buildings, internal lighting is assessed. The authors calculated the length of the heating season, the number of heating degree days (HDDs), and the demand for usable energy for heating (EU_H) for 59 building locations in Poland. In the energy assessment of buildings, it was examined how the energy class of buildings affects the length of the heating season. According to the EPBD [29], buildings with nearly zero-energy consumption (n-ZEB) should have very high energy efficiency. According to the authors of this article, in the energy assessment of buildings, it is necessary to take into account the operation time of auxiliary devices in accordance with the schedule of their use. The schedule for the use of circulation pumps and adjustments in the heating system depends on the energy class of the building and the location. Studies have shown that the schedule and duration of the use of circulation pumps and adjustments in the heating system depend on the energy class of the building and the location. The energy class of buildings and the length of the heating season affect the energy demand for heating purposes as well as the demand for primary energy. This will also have an impact on the introduction of a carbon footprint assessment method for buildings.

Article [30] presents the results of calculations aimed at determining the reference energy standard of multi-family residential buildings for the purposes of determining their energy class. The results of the analyses showed that the value of the indicator of demand for energy for heating depended on the type of ventilation system used; it was the highest in the case of a building with exhaust ventilation, and the lowest in a building with heat recovery ventilation. It was also shown that the influence of the building shaped the A/V factor—the higher its value, the higher the value of the energy demand for heating. In the presented research results, the demand for final and primary energy consumed by auxiliary devices was calculated, taking into account the time of their operation on the basis of the regulation on the methodology of preparing energy characteristics [21]. In this article, the decision was made to show that it can significantly affect the energy performance of buildings.

Meteorological data have an impact on the energy performance of buildings, the length of the heating season, and the number of heating degree days. In the article [16], it was stated that in the context of the results of research calculations, it is important which meteorological data are used to determine the energy characteristics. The weather data used for the calculations were determined on the basis of measurements from the years 1970–2000. The use of more recent data could reduce the value of the length of the heating season, the number of heating degree days, and the demand for usable, final, and primary energy. It is, therefore, necessary to update the meteorological data for more accurate energy modeling of buildings.

Based on the presented research results, the following recommendations and guidelines for designers of energy-saving multi-family houses were formulated:

- For buildings located in eastern and north-western Poland, it is necessary to design partitions above the energy class A standard and apply ventilation with heat recovery;
- When designing an energy-saving building, the demand for usable energy for heating and ventilation should be reduced in the first place;
- Designing buildings in line with the standard of increased thermal insulation of external partitions reduces the length of the heating season and the amount of energy consumed by auxiliary devices—circulation pumps and regulators in the heating system;
- The location of buildings in Poland affects the fulfillment of EP requirements according to [26] and forces eastern Poland to apply solutions based on highly efficient heat sources and the use of renewable heat sources with greater power than those in western Poland.

The presented study includes only analyses of the demand for usable, final, and primary energy for multi-family residential buildings. At a later stage, additional calculations of investment and operating costs, as well as CO_2 emissions for various heating systems, should be made, which would complement a full technical, economic, and environmental analysis. Other categories of buildings should also be included in further research: single-family residential buildings, office buildings, commercial buildings, kindergartens and schools, and health care facilities.

5. Conclusions

The main purpose of the work was to examine how the energy class of a multi-family residential building regarding the thermal insulation and type of ventilation affects the demand for usable energy for heating and ventilation, the length of the heating season, and the number of heating degree days. The aim of the study was to determine whether energy analyses at the designing stage should take into account the operation time of auxiliary devices depending on the energy class of buildings and their location. The energy analyses carried out were aimed at presenting recommendations and guidelines for designers of multi-family residential buildings, which is why a calculation method was chosen that allowed for modeling the building in terms of energy. The analyses were performed for a typical multi-family building located in 59 towns in Poland. The analyses took into account several variables affecting the test results: the thermal insulation of partitions, the type of ventilation system, and climatic data. The work also shows whether a building with the same energy parameters located in different places in Poland met or did not meet the requirements for the maximum value of primary energy (EP) according to the technical conditions [26].

The authors of this research clearly reveal that designers must approach the design of buildings individually. Buildings designed according to the adopted standard in Suwałki and Białystok, regardless of the energy class, exceeded the maximum value of the demand for primary energy (EP) according to the technical conditions [26]. It is worth noting that for Suwałki (climate zone V), the maximum primary energy demand index (EP) occurred for class B3 and amounted to 93.41 $kWh/(m^2 \cdot year)$. For the same energy class of a building located in Wrocław (climate zone II), the primary energy demand index (EP) was 66.38 $kWh/(m^2 \cdot year)$. When the demand for primary energy consumed by auxiliary devices was analyzed in detail, it was noticed that for the B3 energy class of a building located in Suwałki, the annual demand for primary energy (EP) consumed by auxiliary devices was 7.99 $kWh/(m^2 \cdot year)$, while in Wrocław, the primary energy (EP) used by auxiliary devices was 2.43 $kWh/(m^2 \cdot year)$. A building in the A1 energy class located in Wrocław was characterized by the demand for primary energy (EP) at the level of 60.57 $kWh/(m^2 \cdot year)$ and met the requirements of WT [26], while the same building designed in Suwałki was characterized by the demand for primary energy (EP) at the level of 78.40 $kWh/(m^2 \cdot year)$ and did not meet the requirements of WT [26]. When analyzing the demand for primary energy consumed by auxiliary devices in detail, it was noticed that for the A1 energy class of the building located in Suwałki, the annual demand for primary energy (EP) consumed by auxiliary devices was 32.53 $kWh/(m^2 \cdot year)$, while in Wrocław, the primary energy (EP) consumed by auxiliary equipment was 25.30 $kWh/(m^2 \cdot year)$. The demand for primary energy used by auxiliary devices in buildings with mechanical supply and heat recovery exhaust ventilation (class B1 and class A1) located in Wrocław was analyzed. The annual demand for primary energy (EP) used by auxiliary devices for a building in the B1 energy class was 27.53 $kWh/(m^2 \cdot year)$, while for a building in the A1 energy class, it was 25.30 $kWh/(m^2 \cdot year)$. The analyses show that the energy class of buildings, the location of the building, and the climate data significantly affect the demand for primary energy of a building and its ability to meet the legal requirements.

If partitions are characterized by greater thermal insulation, it is possible to reduce the demand for usable energy for heating and ventilation purposes. The use of mechanical ventilation with heat recovery is also recommended. The use of energy-saving solutions that reduce usable energy is the first step to creating a building with nearly zero-energy performance. It also has a positive effect on shortening the length of the heating season, which, in turn, translates into a reduction in the operation time of the circulation pumps in the heating system. These solutions translate favorably into meeting the requirements of the EP index for the designed buildings.

According to the authors, the research also shows that the location of a building has a significant impact on its demand for energy for heating and ventilation purposes. The technical solutions adopted in this research make it possible to meet the EP requirements according to [26] in buildings located in climate zones I, II, and III. Still, it is impossible to meet the legal requirements in the case of buildings located in eastern and north-eastern Poland.

It is also worth considering whether, when adopting reference buildings for the energy rating system of buildings, regionalization resulting from various climatic conditions should not, perhaps, be taken into account.

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