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Article

Energy, Economic and Environmental Analysis of Alternative, High-Efficiency Sources of Heat and Energy for Multi-Family Residential Buildings in Order to Increase Energy Efficiency in Poland

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Abstract: The article presents energy, economic and environmental analyses of the possibilities of using alternative, high-efficiency sources of heat and energy for the multi-family residential building located in Wrocław, Poland, in the temperate climate zone characteristic of Central Europe. For conventional, alternative and hybrid heating systems based on renewable energy sources, comparative analyses of final energy demand, demand for non-renewable primary energy, CO_2 emissions, investment costs and life cycle costs were carried out. The detailed comparative analyses of the research results led to the formulation of conclusions and recommendations which may serve as guidelines for designers of multi-family residential buildings and investors. The solutions of heating and hot water preparation systems recommended in the article will enable the design and construction of buildings with no negative impact on the environment. Taking into account the economic and environmental analyses, the optimal sources of heat and energy are alternative heating systems based on highly efficient heat pumps supplied from a photovoltaic installation. Such solutions, however, have both technical and legal limitations related to the possibility of their implementation and are generally associated with higher investment costs.

Keywords: energy efficiency of buildings; environmental analyses; economic analyses; alternative energy sources; renewable energy sources; reduction of greenhouse gas emissions; reduction of carbon dioxide emissions

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1. Introduction

Human activity has led to a sharp increase in CO_2 emissions. According to report [1], the construction industry was responsible for 38% of total CO_2 emissions into the atmosphere in 2019 and 35% of total final energy consumption. The ambition of European countries is to achieve zero pollution levels. The European Green Deal (EGD) [2] assumes that the European Union will have been transformed into a climate-neutral area by 2050. Increasing energy efficiency will not only improve the competitiveness on the European market, but will also result in a direct reduction in energy demand. It will also increase energy security and, in the long run, help to minimize the negative impact on the environment and financial burdens. Another important argument to step up efforts to increase energy efficiency in the construction industry is the armed conflict started by Russia in Ukraine and the policy of blackmail against the European Union countries regarding the export of raw materials there. Increasing energy efficiency of buildings and the development of alternative, renewable energy sources will lead to independence from Russia, which was once the main supplier of fossil fuels, i.e., hard coal, crude oil and natural gas, to Poland and the neighboring countries.

The European Union's plan to upgrade to a competitive, low-emission economy by 2050 is associated with a dramatic fall in greenhouse gas emissions in the construction sector by approx. 90% compared to 1990. One practical way of achieving these ambitious goals was the adoption of the Directive on the Energy Performance of Buildings [3]. Its implementation results in the requirement to build "nearly zero-energy buildings" (NZEB), which is defined as a building with very high energy efficiency. An increased interest in Nearly Zero Energy Buildings (NZEB) is a worldwide phenomenon [4–9]. According to the directive [10], energy should predominantly originate from renewable sources, including energy from renewable sources produced on site or in the immediate vicinity.

In 2014, the Ministry of Infrastructure and Development devised the National Plan whose aim was to increase the number of buildings with low energy consumption [11]. The basis for the development of 'The National Plan to Increase the Number of Low-Energy Buildings' was the act [12]. According to the plan, a nearly zero-energy building (NZEB)—as defined in the Polish legal system—is a building that meets the requirements for thermal protection of buildings that has been in force since 1 January 2021; in the case of buildings occupied and owned by public authorities, it has been in place since 1 January 2019. The maximum values of the demand for non-renewable primary energy for the purposes of heating, cooling, ventilation and hot water preparation—and in the case of collective housing, public utility, industrial and warehouse buildings, built-in lighting—are presented in Table 1.

Table 1. Maximum values of demand for non-renewable primary energy in Poland [13].

No.	Building Type	PE Value [kWh/(m^2·Year)]
1.	Single-family residential building (no cooling)	70
2.	Single-family residential building (with cooling)	$70 + 5 \cdot A_{f,c}/A_f$
3.	Multi-family residential building (no cooling)	65
4.	Multi-family residential building (with cooling)	$65 + 5 \cdot A_{f,c}/A_f$
5.	Collective residential building (no cooling)	75 + 25
6.	Collective residential building (with cooling)	$75 + 25 + 25 \cdot A_{f,c}/A_f$
7.	Public building (no cooling)	45 + 50
8.	Public building (with cooling)	$45 + 50 + 25 \cdot A_{f,c}/A_f$
9.	Storage building (no cooling)	70 + 50
10.	Storage building (with cooling)	$70 + 50 + 25 \cdot A_{f,c}/A_f$
11.	Industrial building (no cooling)	70 + 50
12.	Industrial building (with cooling)	$70 + 50 + 25 \cdot A_{f,c}/A_f$

where: A_f—surface with adjustable temperature—heated, $A_{f,c}$—surface with adjustable temperature—cooled.

Achieving the maximum rate of annual demand for non-renewable primary energy is possible through the use of alternative, renewable energy sources. According to the directive [10], renewable energy sources stand for energy generated from non-fossil based, renewable sources—namely, wind energy, solar energy, aerothermal, geothermal and hydrothermal energy, ocean energy, hydropower, energy obtained from biomass, gas from landfills, sewage treatment plants and from biological sources (biogas).

Designing buildings with nearly zero energy demand is based on an interdisciplinary approach that involves optimizing solutions at every stage. Projects carried out in accordance with the assumptions of BIM-based integrated design result in 30–50% energy savings while maintaining the assumed financial expenditures [14].

The literature [15] presents studies aimed at identifying the condition of residential buildings in terms of energy intensity and modernization in Poland against the EU background, as well as identifying factors and activities that increase the interest of households in buildings with net zero energy consumption. The authors of the article suggest that most of the buildings occupied in Poland are not energy efficient and depend on fossil fuels. According to the research results presented, 92.84% of all residential buildings were constructed before 2011 and are in desperate need of modernization, as insulated buildings require less energy. It was also found that buildings whose inhabitants declared reliance on renewable energy sources had been modernized and are generally more modern.

On the other hand, the paper [16] presents the comparative analysis of the carbon footprint, energy demand and life cycle costs of a building model located in the central European climate zone. The article includes the analyses performed based on a single-family house intended for a family of four over 25 years of operation. Based on the information contained in the article, general conclusions, guidelines and recommendations for investors and designers of energy-saving and environmentally friendly houses were listed.

Our article presents energy, economic and environmental analyses of the possibilities of using various energy sources for a multi-family residential building. The heat source solution, most efficient in terms of energy, economy and environment, should be technically feasible. The most efficient solutions in terms of energy means that the adopted approach should be characterized by the minimum value of the primary energy indicator (PE) in accordance with the technical conditions [13]. For economic reasons, the most efficient solution is a variant whose investment costs are reasonable, while maintaining the lowest possible operating costs. The LCC is a very popular parameter that can be applied as an objective function when optimizing buildings and their systems [17–29]. For environmental reasons, it is recommended that technical solutions guaranteeing the minimum level of CO_2 emissions should be used.

In Poland, energy performance is measured using the methodology specified in the resolution [28]. In accordance with the above resolution, to determine the annual demand for non-renewable primary energy (PE), the annual demand for final energy (FE) should be calculated, taking into account the non-renewable primary energy factor (w_i), which depends on the energy carrier or fuel used and is determined according to Table 2. As for the methodology for preparing the energy performance of buildings, the final energy is determined considering the efficiency of heating systems, cooling systems, hot water preparation systems and the annual demand for usable energy (UE). When determining the demand for usable energy, heat losses due to penetration through building partitions and those resulting from heating the ventilation air are considered, as well as internal heat gains including those from solar radiation.

Table 2. Coefficients of non-renewable primary energy input w_i [28] and EC CO_2 emission indicators applicable in Poland.

No.	Method of Supplying the Building or Its Part with Energy	Type of Energy Carrier or Energy	w_i	EC CO_2 Emission Indicators [kg/kWh]
1	Local energy generation within the building	Heating oil	1.10	0.267
2		Natural gas	1.10	0.199
3		Liquefied gas	1.10	0.227
4		Coal	1.10	0.341
5		Lignite	1.10	0.402
6		Solar energy	0	0
7		Wind energy	0	0
8		Geothermal energy	0	0
9		Biomass	0.20	0
10		Biogas	0.50	0
11	District heating from cogeneration	Coal or natural gas	0.80	0.337/0.199
12		Biomass, biogas	0.15	0
13	District heating from a heating plant	Coal	1.30	0.341
14		Natural gas or heating oil	1.20	0.199/0.267
15	System power grid	Electrical power	3.00	0.708

2. Research Methodology

2.1. Description of the Analysed Building

The comparative analyses of conventional heating systems, alternative heating systems based on renewable energy sources, as well as of hybrid heating systems, understood as a combination of conventional and alternative systems, were performed for the project of a multi-family residential building with an area of 1051 m^2 located in Wrocław, Poland. It is a rectangular, 3-storey, two-staircase building with an unheated underground garage. It consists of 18 residential units and is intended for 50 residents (Figures 1 and 2). Its external walls were designed of sand lime bricks thermally insulated with mineral wool slabs. The flat roof consists of the reinforced concrete ceiling thermally insulated with extruded polystyrene panels. Inter-floor ceilings are designed as reinforced concrete. The windows are made of aluminum profiles with double-chamber glazing units. There are aluminum exterior doors. The heating is by means of surface water heat pump with hot utility water prepared centrally.

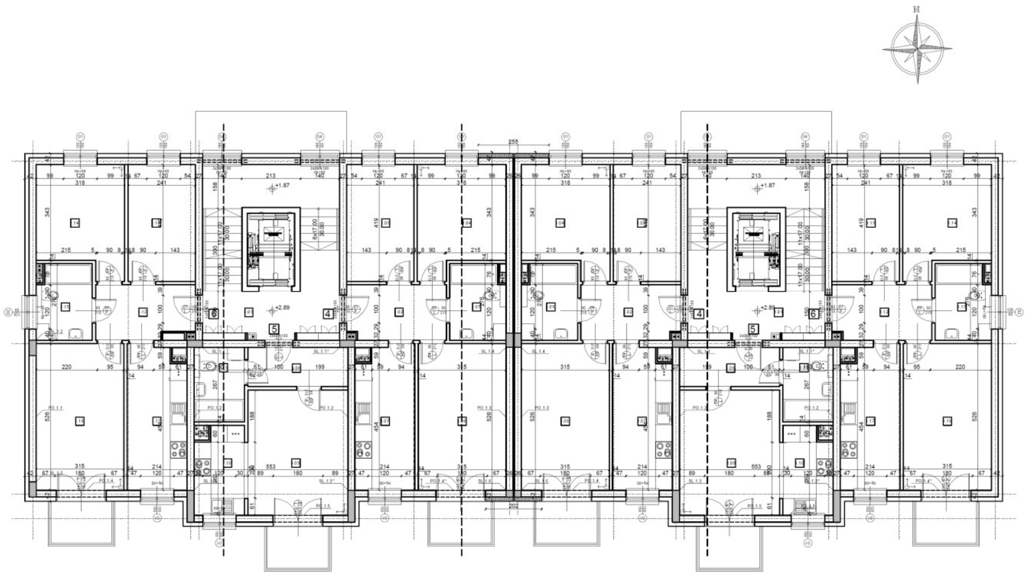


Figure 1. Repetitive floor plan of the building.

Figure 2. Elevation of the building.

2.2. Energy Analysis

The article presents the comparative analyses of demand for final energy, demand for non-renewable primary energy, CO_2 emissions, investment costs and costs in the life cycle. Energy calculations were made based on the CERTO 2015 simulation software, enabling energy modelling of buildings. The software is intended for the development of energy performance certificates in Poland and for the assessment of energy performance of residential buildings (e.g., single-family houses, blocks of flats), buildings, public buildings, schools, hospitals, production buildings and warehouses. The software makes it possible to simulate the demand for usable energy for heating purposes for the respective calculation zones and rooms and to assess the annual demand for final and primary energy, taking into consideration the applied heat and energy sources as well as energy carriers.

For the building in question, calculations of the annual demand for usable energy were made using the monthly balances method: the balances of internal and solar radiation gains were taken into account, as well as heat losses through external partitions and those attributed to heating the ventilation air. The standard schedule for the use of rooms as for this type of buildings and normative internal temperatures of rooms were adopted (rooms θi = 20 °C, kitchens θi = 20 °C, bathrooms θi = 24 °C, staircases θi = 8 °C) in accordance with [30]. The calculations assumed a external design temperature of θe = −18 °C [30] and an average annual external temperature of 8.1 °C for the city of Wrocław. The number of days in the heating season equals 130 (according to the calculations of the CERTO 2015 energy modelling software).

In the first stage of the research, the demand for usable energy of the building was compared for the building with natural ventilation, mechanical exhaust ventilation and mechanical supply and exhaust ventilation with heat recovery; the thermal insulation of partitions meeting the minimum legal requirements and partitions meeting thermal insulation in the calculations imposed on buildings with passive energy characteristics were also taken into account. In the next stage, detailed tests were carried out for various heating systems, considering the fact that mechanical supply-exhaust ventilation with heat recovery had been installed in the multi-family residential building. External partitions that meet the thermal insulation requirements for buildings with passive energy characteristics were designed.

2.3. Economic Analysis

In the economic analysis of life cycle costs (LCC), investment costs were assessed based on cost estimates taking into account the costs of heat and energy sources, costs of labor, costs of power, gas and heating connections. The operating costs include the costs of energy carriers, personnel costs, costs of sweeping chimneys, costs of technical and service inspections. The prices of energy carriers were adopted based on the prices of energy carriers currently in force for residential buildings: hard coal PLN 0.41/kWh; pellets-biomass PLN 0.63/kWh; natural gas PLN 0.62/kWh; heat substation supplied from the municipal network PLN 0.25/kWh; electricity PLN 1.05/kWh.

2.4. Environmental Analysis

The environmental analysis involved comparing the CO_2 emission calculations for the analyzed variants of the heating systems. When performing environmental analyses, the following CO_2 emission factors were adopted for the respective energy carriers: hard coal 0.341 kg/kWh; pellets-biomass 0 kg/kWh; natural gas 0.199 kg/kWh; heat substation supplied from the municipal network 0.337 kg/kWh; electricity 0.708 kg/kWh.

3. Analysis of Alternative Sources of Energy and Heat

This article presents the issues related to the energy, economic and environmental analysis of the possibility of implementing alternative energy and heat supply systems for multi-family residential buildings. The analysis of alternative energy and heat sources is required in accordance with Polish regulations. It is contained in the order on the scope and form of a construction project [17]. The selected energy source should be most efficient economically and environmentally method possible and be technically feasible. The analysis of the optimal energy source should include:

- the assessment of the annual demand for usable energy for heating, ventilation, hot water preparation;
- the list of energy carriers available on a given plot;
- the selection of two energy supply systems for analysis: a conventional system and an alternative system or a conventional system and a hybrid system, understood as a combination of the conventional and the alternative systems;

- the optimization and comparative calculations for selected energy supply systems;
- the results of the comparative analysis and the choice of the building's energy supply system.

Conventional systems are based on heat sources involving energy carriers based on fossil fuels, natural gas, electricity from the power grid.

Alternative systems include:

- systems based on energy from renewable sources, e.g., photovoltaic installations;
- systems that involve the use of high-efficiency cogeneration, i.e., the simultaneous generation of heat and electricity;
- heating or cooling systems based on energy from renewable energy sources or heat pumps;
- systems using waste energy from technological processes, e.g., from production processes, as alternative sources of heat.

The balances of the annual demand for usable thermal energy of the multi-family residential building for heating and ventilation purposes, as well as the preparation of domestic hot water, were drawn, taking into account the following cases:

- Class A1—a building with mechanical supply and exhaust ventilation with heat recovery and with designed external partitions, meeting the requirements for buildings with passive energy characteristics and with minimized effects of thermal bridges, in accordance with [13];
- Class A2—a building with mechanical exhaust ventilation and designed external partitions, meeting the requirements for buildings with passive energy characteristics and with minimized effects of thermal bridges, in accordance with [13];
- Class A3—a building with natural ventilation and with designed external partitions, meeting the requirements for buildings with passive energy characteristics and with minimized effects of thermal bridges, in accordance with [13];
- Class B1—a building with mechanical supply and exhaust ventilation with heat recovery and with designed external partitions meeting the minimum requirements of technical conditions [13];
- Class B2—a building with mechanical exhaust ventilation and designed external partitions meeting the minimum requirements of technical conditions [13];
- Class B3—a building with natural ventilation and with designed external partitions meeting the minimum requirements of technical conditions [13].

Building partitions in a multi-family residential building meeting the minimum legal requirements in accordance with the Technical Conditions [13] are presented in Table 3.

Table 3. Heat transfer coefficients U in accordance with the Technical Conditions [13].

No.	Partition Type	U [W/(m^2·K)]
1.	External wall	0.20
2.	Flat roof	0.15
3.	Ceiling above the garage	0.25
4.	Windows	0.90
5.	External door	1.30

Building partitions in a multi-family residential building meeting the requirements of buildings with passive energy performance, according to [31], are presented in Table 4.

Table 4. Heat transfer coefficients U for buildings with passive energy characteristics [31].

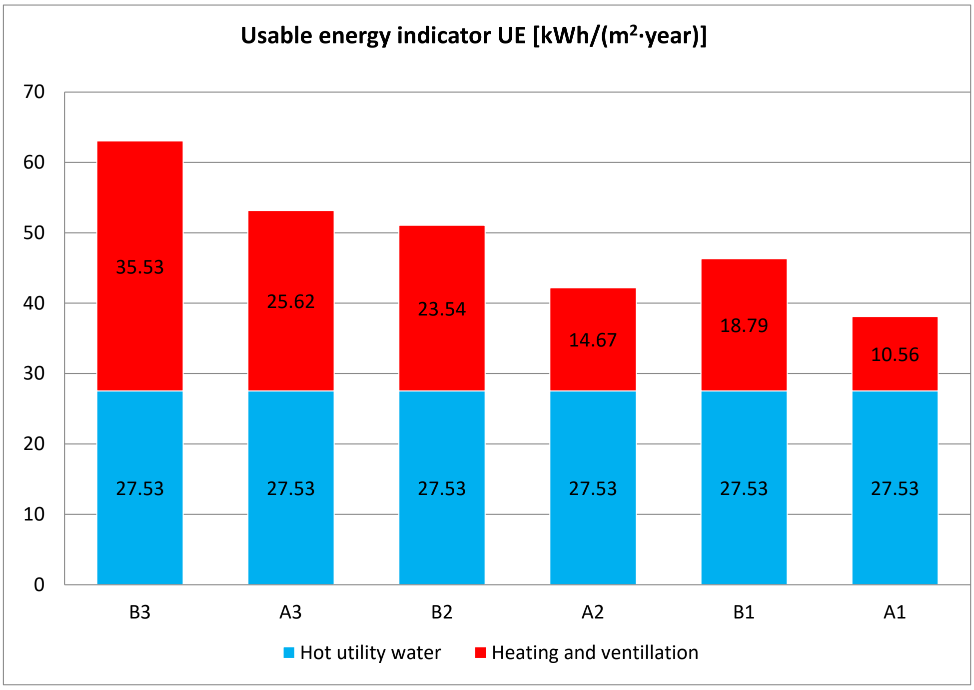
No.	Partition Type	U [W/(m^2·K)]
1.	External wall	0.12
2.	Flat roof	0.10
3.	Ceiling above the garage	0.20
4.	Windows	0.80
5.	External door	1.00

In the computational analyses, the decision was made to review the three ventilation systems:

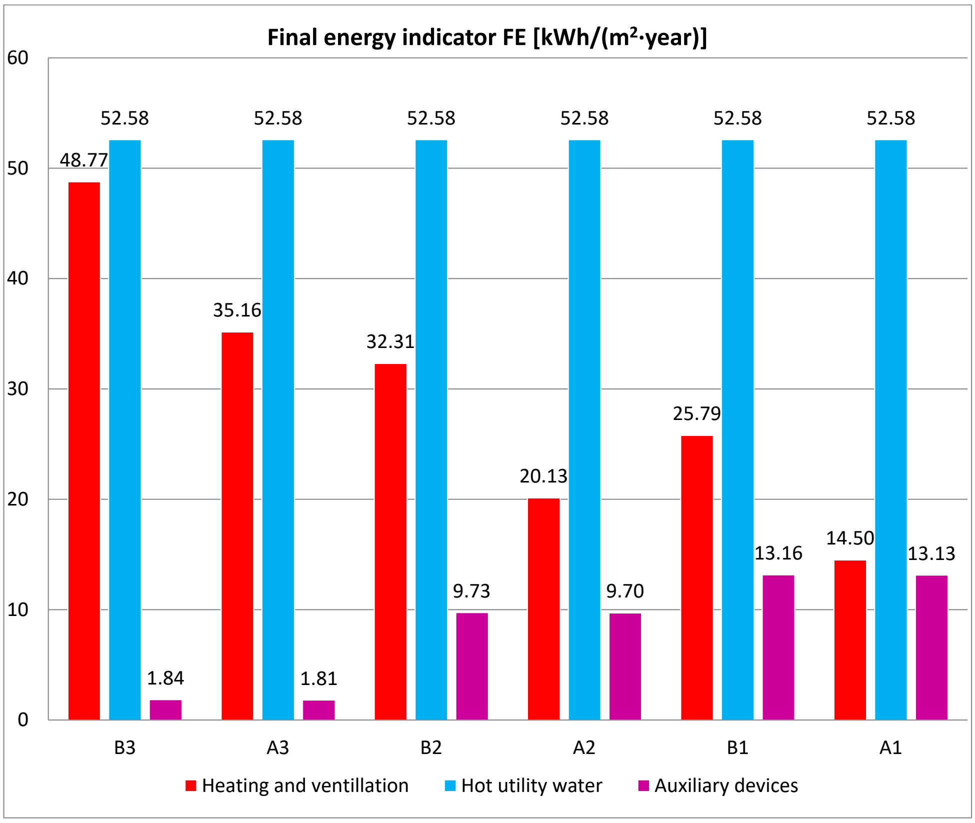
- Natural ventilation: air supply through window diffusers and exhaust through ventilation ducts,
- Mechanical exhaust ventilation: air supply through window diffusers and mechanical exhaust through fans installed on ventilation ducts,
- Mechanical supply and exhaust ventilation: implemented by the supply and exhaust ventilation unit with heat recovery. An average annual heat recovery of 75% was assumed for the calculations.

Energy analyses were performed for a building of a different energy class regarding usable energy and are presented in Scheme 1. When considering the balances of annual demand for usable energy, the highest indicator of demand for usable energy for heating and ventilation occurs in the case of a building with natural ventilation and with typically designed external partitions. The indicator of annual demand for usable energy EU_H for this is 35.53 kWh/(m^2·year). The high value of EU_H indicator of demand for usable energy for heating and ventilation suggests high energy consumption of the designed building. The lowest demand for usable energy for heating and ventilation occurs in the case of a building with mechanical supply and exhaust ventilation with heat recovery, with designed external partitions, meeting the requirements of buildings with passive energy characteristics. The annual demand for this usable energy is 10.56 kWh/(m^2·year). A facility designed with such principles in mind is a building that is able to achieve the zero-energy standard. It should be noted that the demand for usable energy for the preparation of hot utility water for all the variants is 27.53 kWh/(m^2·year). Depending on the energy class of the building, the demand for usable energy for the preparation of domestic hot water can vary from 43% to 72% of the total demand for usable energy in the building.

Comparative analyses of the demand for final energy and non-renewable primary energy in the case of heat supply from a natural gas condensing boiler house were performed for a building of various energy classes. Energy analyses of final and primary energy included energy demand for heating and ventilation, preparation of domestic hot water and auxiliary devices supporting technical systems. The results of the demand for final energy are presented in Scheme 2. The highest indicator of demand for final energy for heating and ventilation occurs in the case of a building with natural ventilation and with typically designed external partitions; the indicator of annual demand for final energy FE_H is 48.77 kWh/(m^2·year). The lowest indicator of demand for final energy for heating occurs in the case of a building with mechanical supply and exhaust ventilation with heat recovery, with designed external partitions, meeting the requirements of buildings with passive energy characteristics; the indicator of annual demand for final energy FE_H is 14.50 kWh/(m^2·year). The indicator of the demand for final energy to prepare domestic hot water FE_W for all variants is 52.58 kWh/(m^2·year). The calculations of the demand for the final energy FE also included the energy consumed by auxiliary devices such as circulation pumps or fans in air handling units. The smallest indicator of the demand for final energy consumed by the auxiliary devices of FE_{meas} occurs in the case of natural ventilation and amounts to 1.81 kWh/(m^2·year). In the case of mechanical ventilation, the energy consumed by the fans is established as well. The highest rate of demand for consumed energy occurs in the case of mechanical supply and exhaust ventilation with heat recovery, for which FE_{room} is 13.13 kWh/(m^2·year).

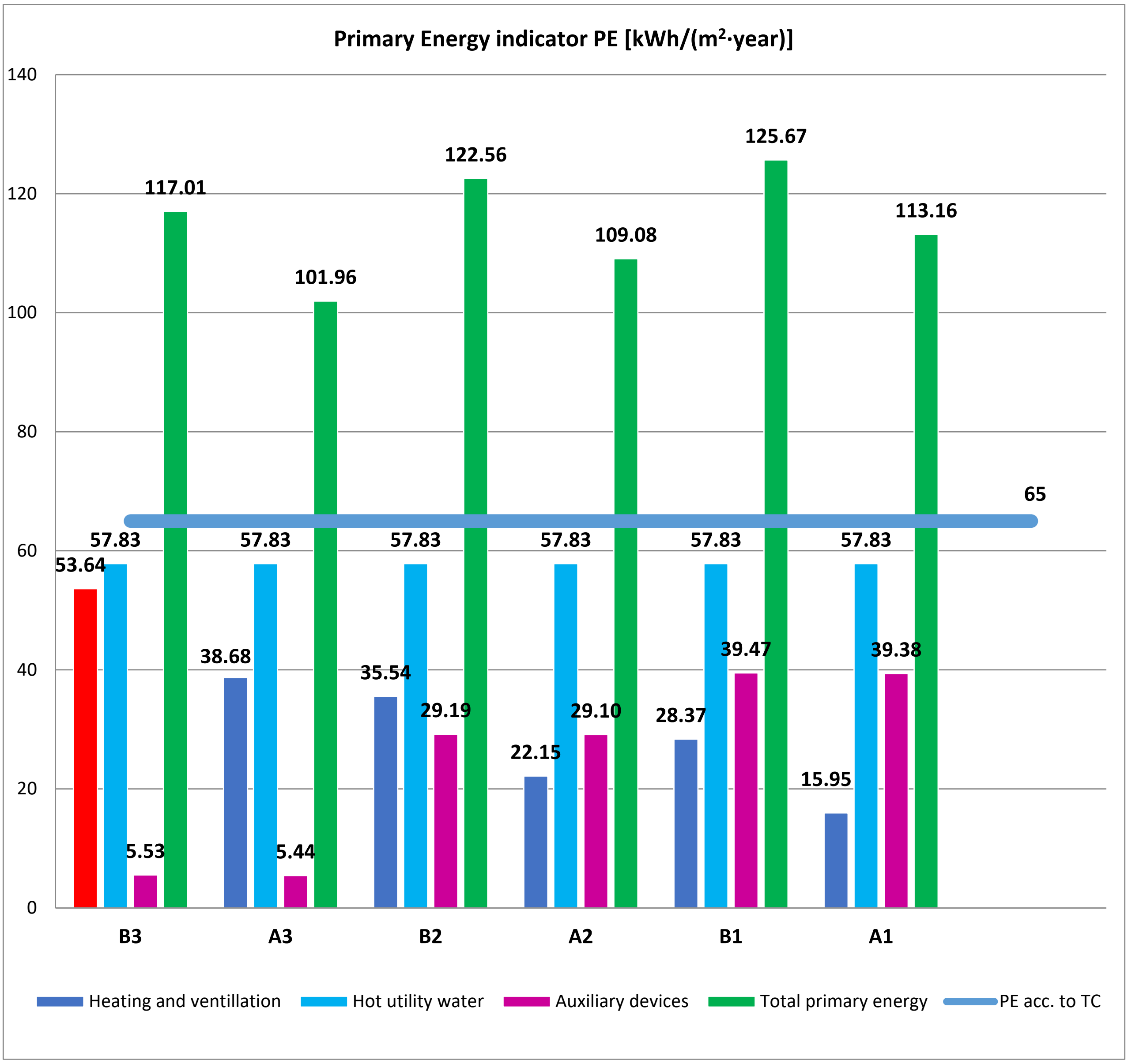


Scheme 1. Comparison of usable energy indicators for a building of a different energy class.



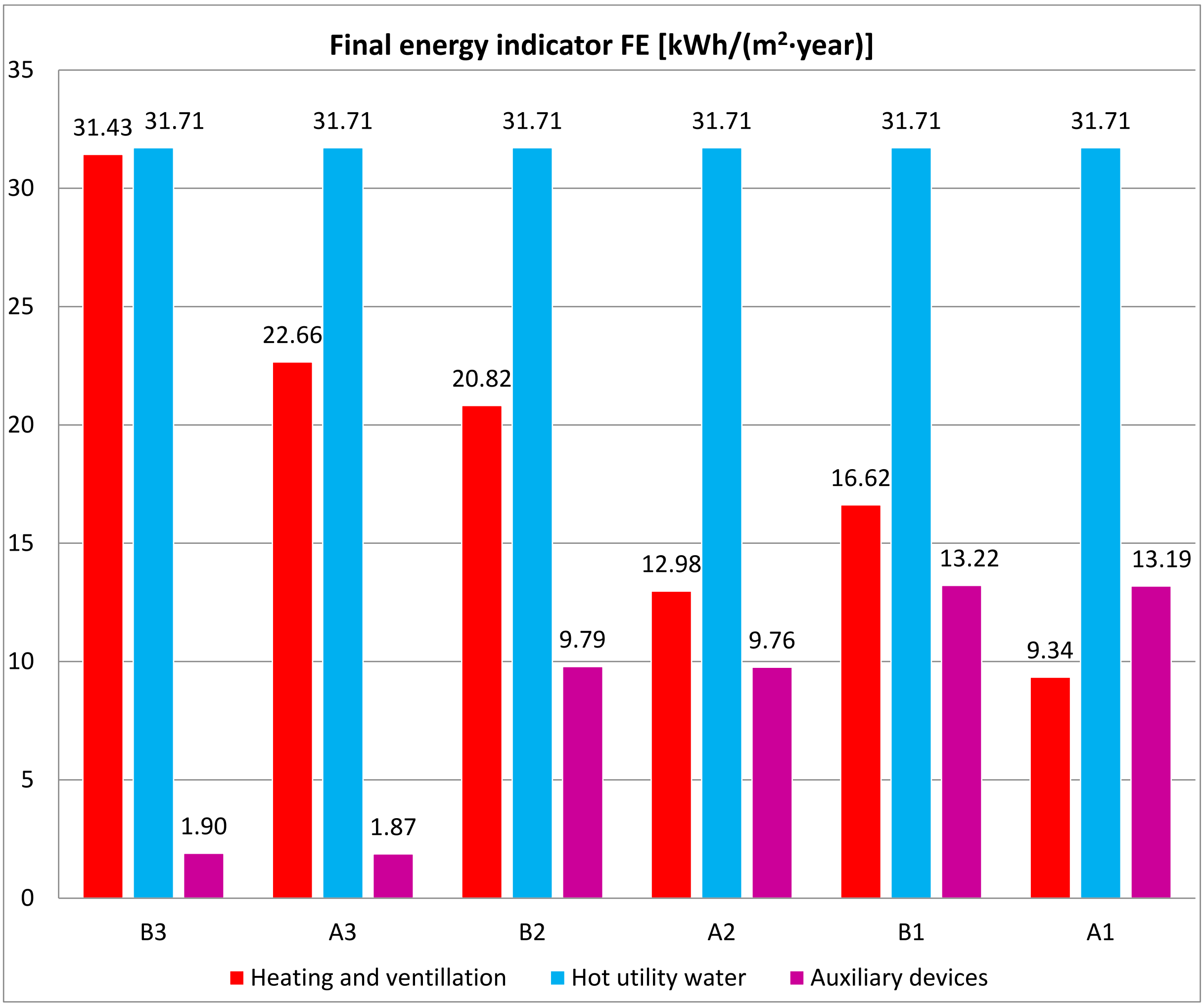
Scheme 2. Comparison of FE indicators for a building of a different energy class for the heat source: the gas boiler room.

Energy analyses of the demand for non-renewable primary energy in the case of supplying the building with heat from the natural gas condensing boiler house are presented in Scheme 3. The total demand for primary energy within the respective energy classes of the building ranges from 101.96 kWh/(m^2·year) to 125.67 kWh/(m^2·year). It should be noted that in no case does the building meet the minimum PE according to the technical conditions [13].



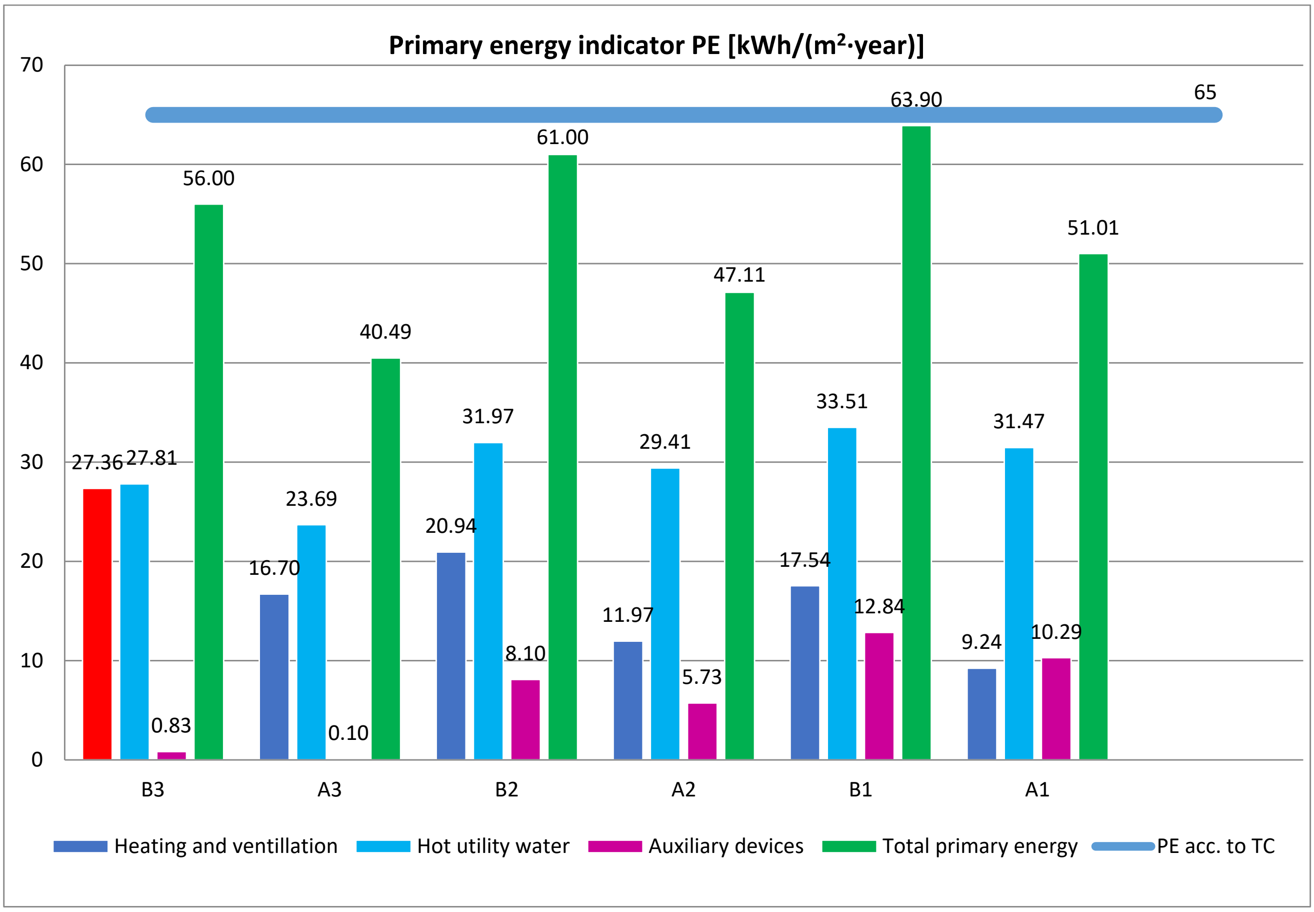
Scheme 3. Comparison of primary energy indicators PE for a building of a different energy class for the heat source: the gas boiler room.

Additionally, computational analyses were performed for a building of a different energy class. The glycol–water heat pump was assumed as the source here: supplied from a 20.4 kWp photovoltaic PV installation and the power grid. The results are presented in Scheme 4. The highest demand for final energy for heating and ventilation occurs in the case of a building with natural ventilation and with typically designed, external partitions; for this, the annual final energy demand FE_H is 31.43 kWh/(m^2·year). The lowest indicator of demand for final energy for heating occurs in the case of a building with mechanical supply and exhaust ventilation with heat recovery, with designed external partitions, meeting the requirements of buildings with passive energy characteristics; the indicator of annual demand for final energy FE_H is 9.34 kWh/(m^2·year). The indicator of the demand for final energy for the preparation of domestic hot water FE_W for all variants is 41.71 kWh/(m^2·year). The lowest indicator of the demand for final energy consumed by the auxiliary devices of FE_{meas} occurs in the case of natural ventilation and is 1.90 kWh/(m^2·year). The highest rate of demand for consumed energy occurs in the case of mechanical supply and exhaust ventilation with heat recovery, for which FE_{meas} is 13.19 kWh/(m^2·year).



Scheme 4. Comparison of final energy indicators FE for a building of a different energy class for the heat source: the glycol–water heat pump combined with the PV installation.

Scheme 5 shows the total demand for primary energy for the respective energy classes of the building when supplied with heat energy from the heat pump. The primary energy indicator ranges from 40.49 kWh/(m^2·year) to 63.90 kWh/(m^2·year). For the respective energy classes, when a heat pump and a PV installation are used as a heat source, the requirements of the maximum FE indicator according to the technical conditions are met [6]. The analysis shows that the lowest demand for primary energy occurs in the case of a building with natural ventilation and partitions with increased thermal insulation. The downside of natural ventilation is the lack of sufficient impact on the efficiency and purity of the ventilated air.

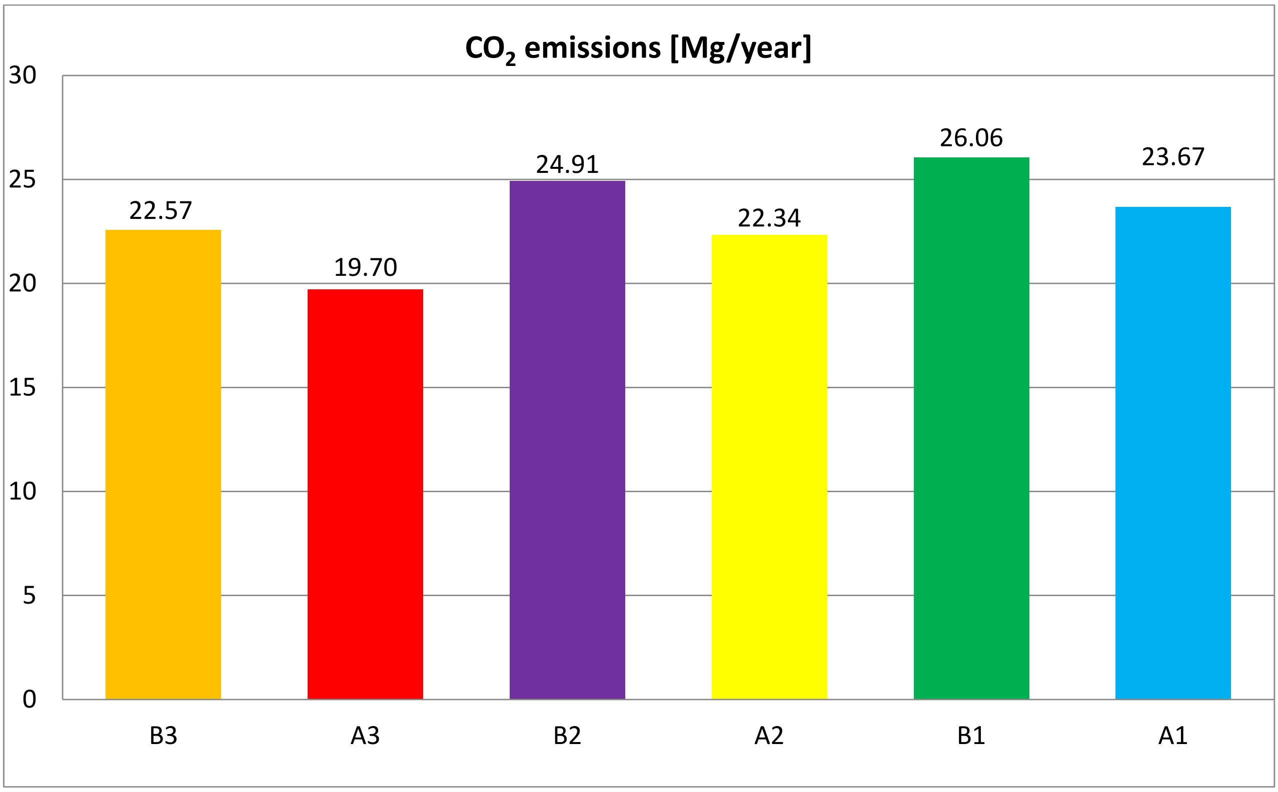


Scheme 5. Comparison of PE for a building of a different energy class for the heat source: the glycol–water heat pump combined with the PV installation.

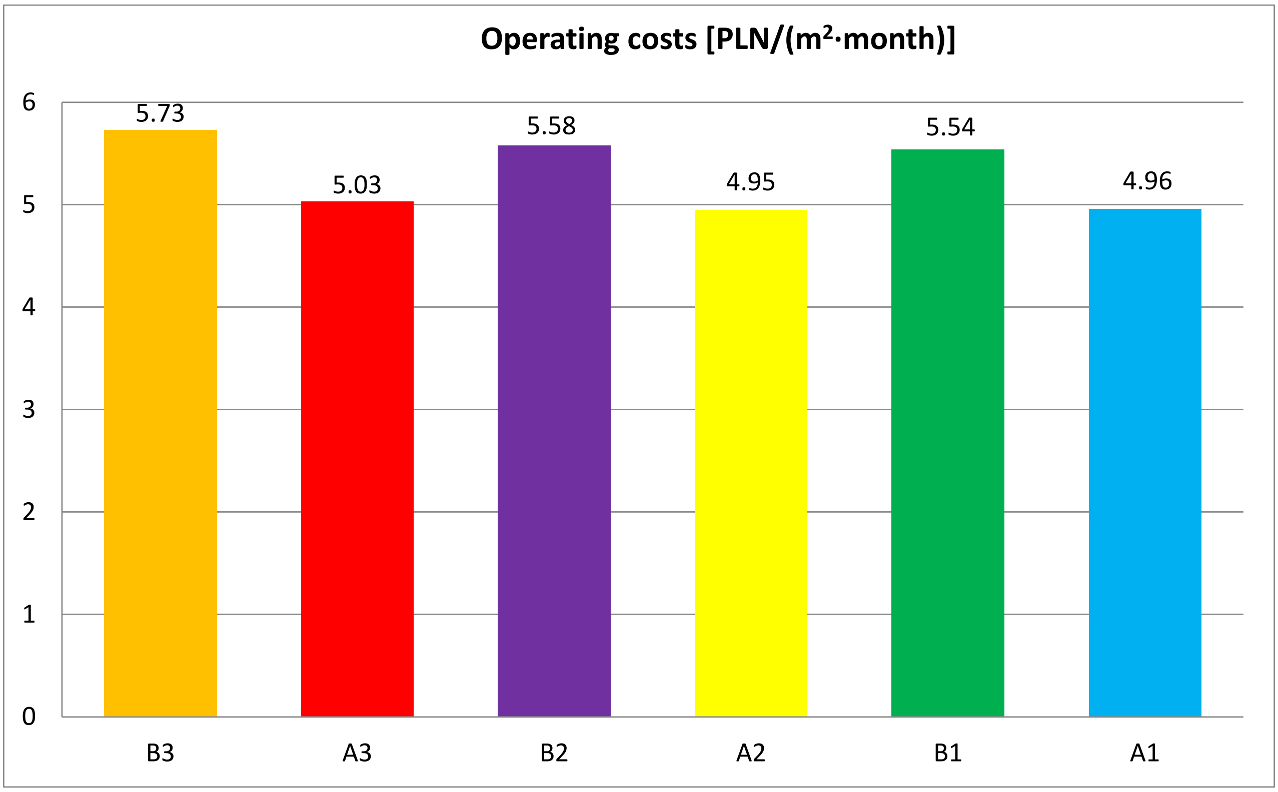
For a building of a different energy class supplied with heat from the glycol–water heat pump, the environmental analysis was carried out, taking into account CO_2 emissions. The results of the calculations are shown in Scheme 6. Lower CO_2 emissions occur for a building with designed partitions meeting the requirements of buildings with passive energy characteristics compared to a building with standard partitions with a heat transfer coefficient U, in accordance with the technical conditions [13]. In the case of buildings equipped with mechanical ventilation, there is an increased demand for energy for auxiliary purposes. This then results in higher emissions compared to buildings with natural ventilation.

An economic analysis comparing operating costs related to heating, preparation of domestic hot water and the operation of auxiliary devices was also performed. Scheme 7 presents the results of the economic analysis. It shows that significantly lower operating costs are incurred in the case of designing partitions with increased thermal insulation that meet the requirements for buildings with passive energy characteristics. It was noted that the lowest operating costs are generated for a building with mechanical exhaust ventilation and with designed external partitions, meeting the requirements of buildings with passive energy characteristics.

In order to obtain the energy performance of a building with almost zero demand for primary energy, it was decided to perform additional analyses involving the comparison of various heat sources and energy carriers. The calculations for a building with designed external partitions, meeting the requirements of buildings with passive energy characteristics and with mechanical supply and exhaust ventilation with heat recovery, were made.



Scheme 6. CO_2 emissions for buildings in different energy classes for the heat source: the glycol–water heat pump combined with the PV installation.



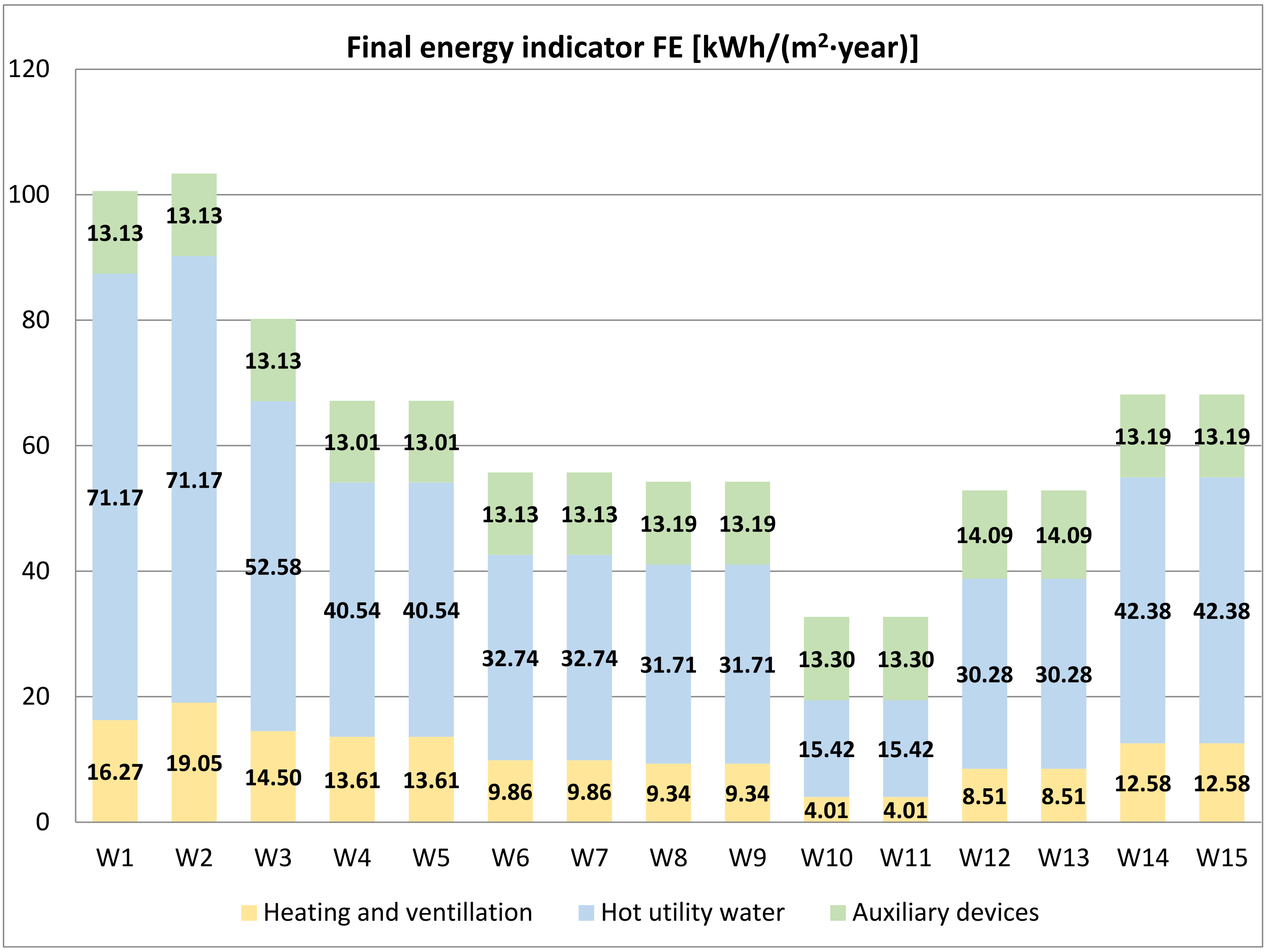
Scheme 7. Operating costs for buildings of a different energy class for the heat source: the glycol–water heat pump combined with the PV installation.

Energy, economic and environmental analyses were performed for the following variants of heat sources:

Variant W1—eco-pea coal boiler house;
Variant W2—biomass boiler house–pellets;
Variant W3—natural gas condensing boiler;
Variant W4—a heating substation supplied from the heating network from a coal-fired heating plant;
Variant W5—a heating substation supplied from the heating network from a coal-fired heating plant;
Variant W6—an air-to-water heat pump and, as a peak source of heat, a heating center supplied from a heating network from coal-fired cogeneration;
Variant W7—an air-to-water heat pump supplied by a 21.6 kWp PV photovoltaic installation and a thermal center supplied by a coal-fired cogeneration heating network as the peak heat source;
Variant W8—air-to-water heat pump and natural gas condensing boiler house as the peak heat source;
Variant W9—air-to-water heat pump supplied by a 28 kWp PV photovoltaic installation and a natural gas condensing boiler house as the peak heat source;
Variant W10—glycol–water heat pump;
Variant W11—glycol–water heat pump supplied by a 20.4 kWp photovoltaic PV installation;
Variant W12—a glycol–water heat pump and a natural gas condensing boiler house as the peak heat source;
Variant W13—glycol–water heat pump supplied by a 25.2 kWp PV photovoltaic installation and a natural gas condensing boiler house as the peak heat source;
Variant W14—an air-to-water heat pump supplied by natural gas and a natural gas condensing boiler house as the peak heat source;
Variant W15—an air-to-water heat pump supplied by natural gas and a natural gas condensing boiler house as the peak heat source, and an additional 18 kWp photovoltaic PV installation.

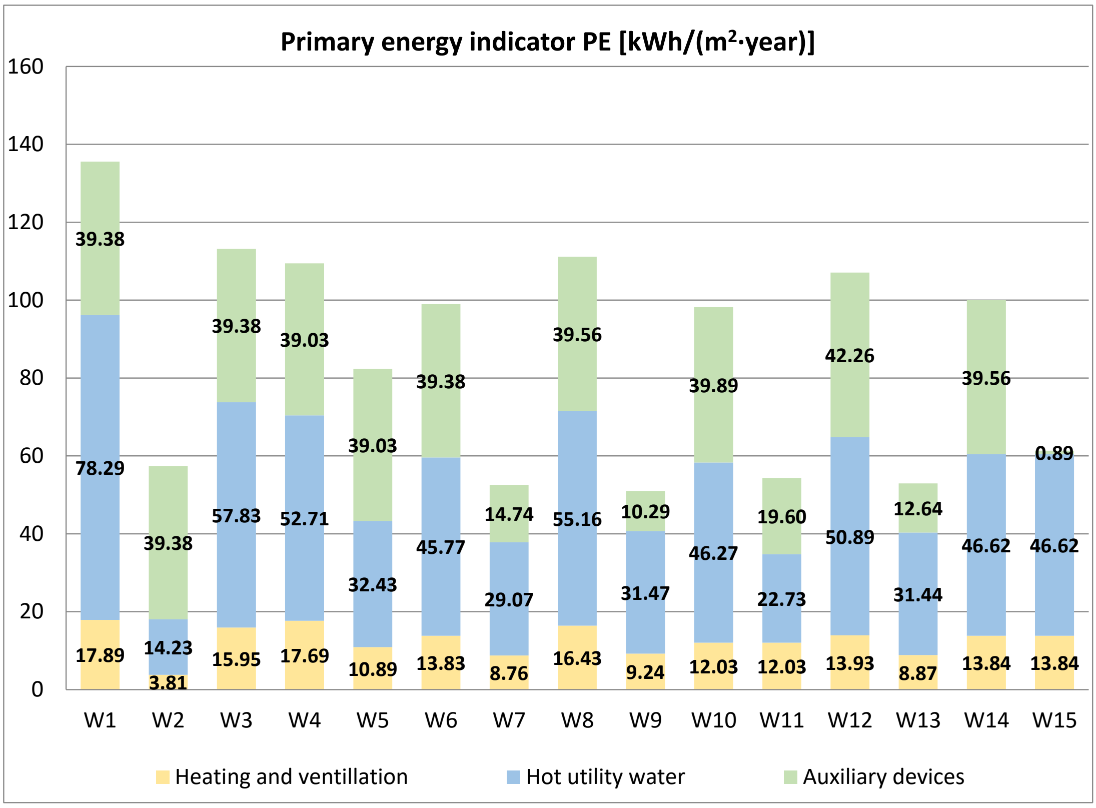
For the analyzed sources of heat and energy as well as energy carriers, indicators of demand for final energy were determined, taking into account the efficiency of heating systems and the demand for energy consumed by auxiliary devices. Scheme 8 presents the results of the analyses which reveal that the lowest final energy indicator FE occurs when a highly efficient glycol–water heat pump is used (variant W10 and variant W11). Systems based on solid fuel sources—hard coal and biomass—pellets (variant W1 and variant W2) are characterized by the lowest efficiency.

In the case of demand for non-renewable primary energy PE (Scheme 9), the lowest indicators are in the case of using high-efficiency heat pumps as a source of heat, additionally supplied by a photovoltaic PV installation (variants W6, W7, W8, W9, W10, W11, W12, W13) and in the case of using a biomass boiler (variant W2) as a source of heat for heating purposes and preparation of domestic hot water. For the above-mentioned variants based on renewable, alternative heat sources, the requirements for primary energy demand indicators are met according to the technical conditions [13]. For heat sources based on fossil fuels such as hard coal or natural gas, the maximum indicators of primary energy PE are exceeded, which excludes them from use in Poland in view of the legal considerations.

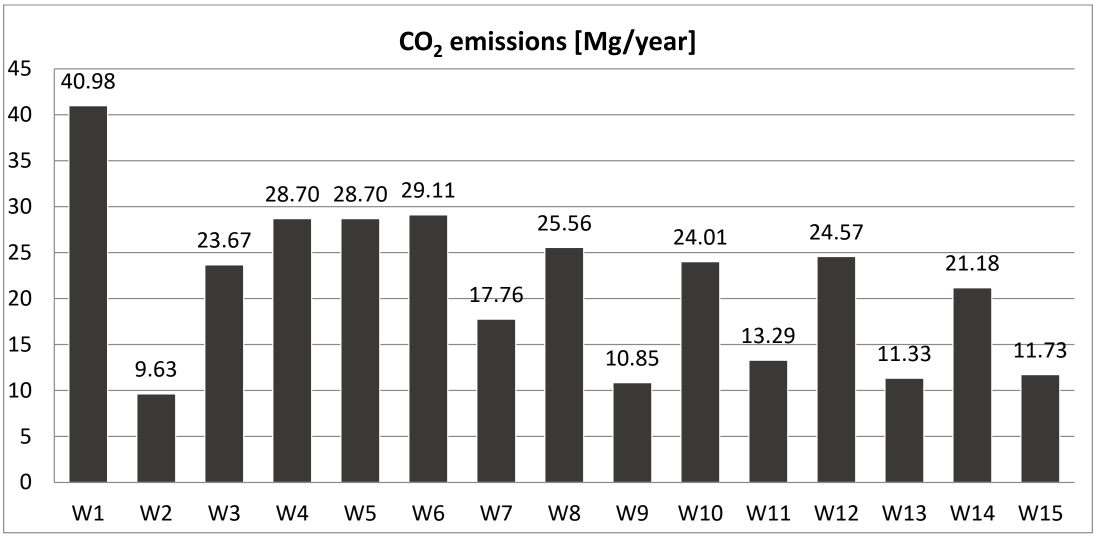


Scheme 8. Comparison of indicators of demand for final energy of FE for various heat sources and energy carriers.

The environmental analysis carried out for the purposes of this article consisted in the assessment of CO_2 emissions into the atmosphere for 15 analyzed heat sources applied for heating purposes and preparation of domestic hot water, including energy for the operation of auxiliary devices (Scheme 10). The lowest CO_2 emission occurs in the case of a building supplied with heat from a biomass–pellet boiler (variant W2) and a building using heat pumps as energy sources combined with photovoltaic PV installations. In the case of buildings equipped with biomass boilers, it must be borne in mind that there are legal restrictions on use of biomass in cities and health resorts. The most negative impact on the environment occurs in the case of heating buildings by means of solid fuel boilers running on hard coal. Heating systems based on heat substations supplied by centralized heat are also characterized by high emission rates. This is due to the fact that, in Poland, a large part of heating or cogeneration systems rely on hard coal. Heating systems supplied by electricity from the power grid are characterized by high emissions. The reason is that the Polish power industry, in which fossil fuels are still main energy carriers, is characterized by low energy efficiency.

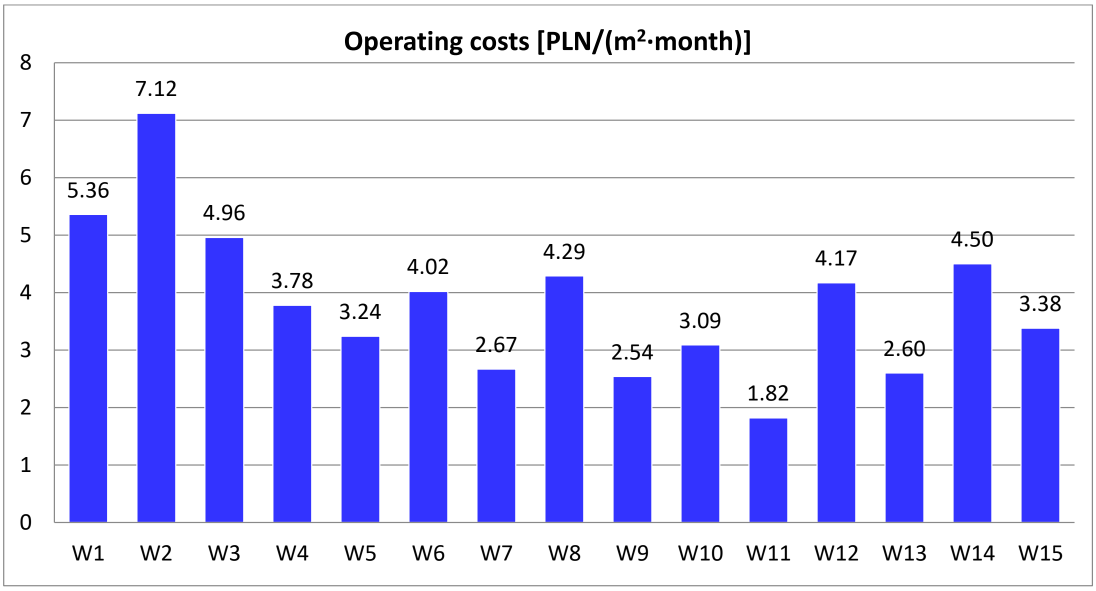


Scheme 9. Comparison of primary energy demand ratios indicators PE for various heat sources and energy carriers.

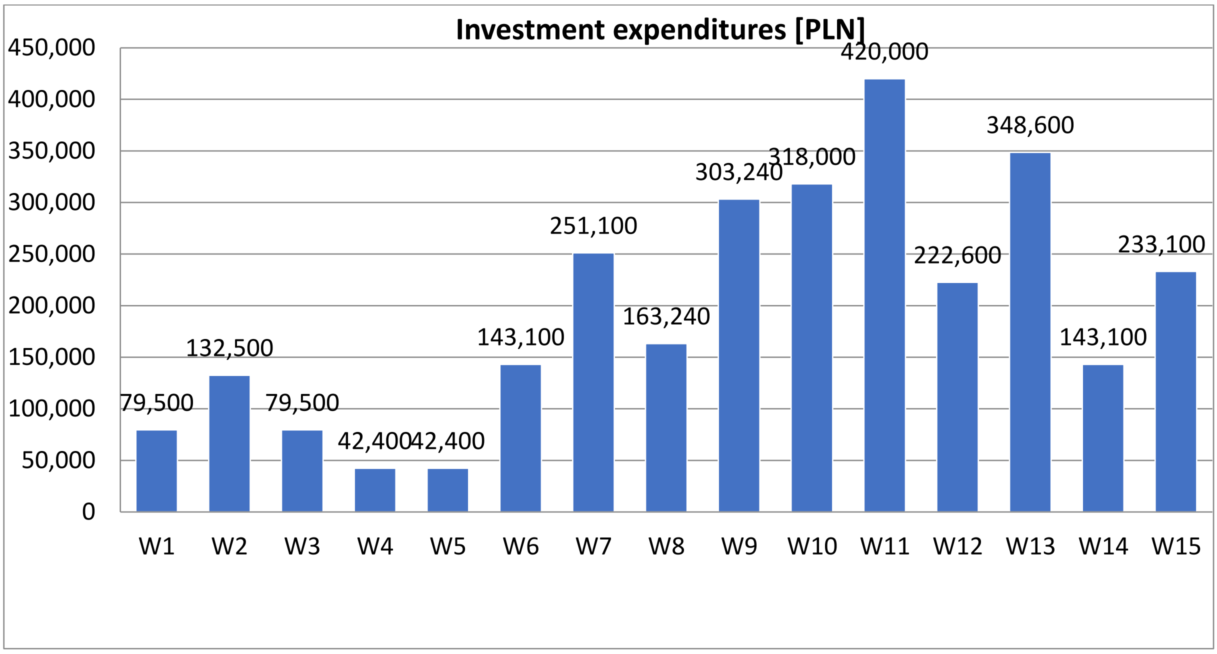


Scheme 10. Comparison of CO_2 emissions for buildings supplied from various energy sources and carriers.

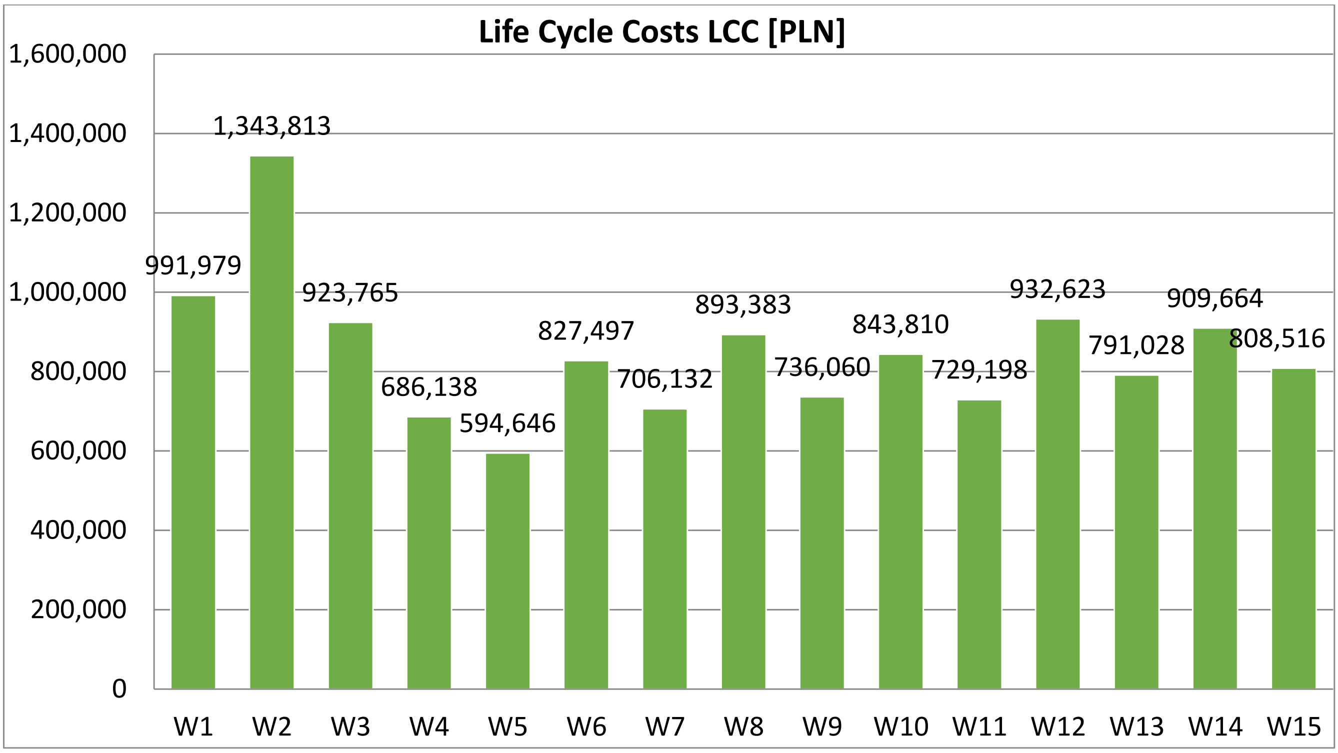
To assess the profitability of individual variants of the heating systems, economic analyses were performed based on the comparison of operating costs, costs of the heating system and LCC costs in the life cycle of the heat and energy source (Schemes 11–13). High operating costs are typical for a building supplied from a biomass boiler (variant W2), buildings supplied from a hard coal boiler (variant W1) and buildings supplied from a natural gas condensing boiler house (variant W3). The lowest operating costs are in the cases of buildings supplied from highly efficient heat pumps additionally combined with photovoltaic installations (variants W9, W11, W13). From the perspective of the investment costs incurred, the highest costs are generated by heating systems based on renewable, alternative energy sources. The lowest investment costs are, in turn, attributed to heat sources such as heat substations powered from municipal heating plants or cogeneration systems, as well as solid fuel or natural gas boilers. Taking into account the costs in the life cycle of the LCC for 10 years of operation, it follows that the most advantageous solution is the W5 variant based on a heating substation supplied from a heating network from coal-burning cogeneration. However, it does not meet the requirements for PE as stipulated in the technical conditions [13]. Solutions with heat pumps as heat sources combined with photovoltaic PV installations (variants W7, W9, W11) are also economically noteworthy.



Scheme 11. Comparison of operating costs for buildings supplied from various energy sources and carriers.



Scheme 12. Comparison of investment expenditures for buildings supplied from various energy sources and carriers.



Scheme 13. Comparison of life cycle costs for buildings supplied from various energy sources and carriers.

4. Conclusions

Prior to performing energy, economic and environmental analyses to select the optimal heat source for multi-family residential buildings, what energy class a given building will be should first be considered. If the goal is to obtain a building with almost zero energy performance, solutions leading to a higher standard of thermal insulation are recommended, meeting the requirements for buildings with passive energy performance. In order to maintain appropriate microclimate conditions in the rooms, it is recommended to use mechanical supply and exhaust ventilation with heat recovery. It is important that the designed building is characterized by the lowest indicator of demand for usable energy for heating and ventilation purposes.

After the implementation of various energy sources for such a building standard, it follows that, due to the need to fulfil legal requirements regarding the maximum non-renewable primary energy indicator, PE, according to the technical conditions [13], it is possible to use heat sources based on renewable, alternative heat sources such as heat pumps additionally supplied from photovoltaic PV installations and biomass boilers in Polish conditions. It is also possible to use hybrid solutions that are a combination of a conventional system and one based on highly efficient alternative heat and energy sources. The environmental analysis shows that the lowest indicator is attributed to a building supplied with heat from a biomass boiler–pellets (variant W2) and heat sources based on highly efficient heat pumps additionally supplied by photovoltaic PV installations. Taking into account the LCC (life cycle costing) for 10 years of operation, it follows that the most advantageous solution is the W5 variant, based on a heating substation supplied from a heating network from coal-fired cogeneration. Such a solution, however, does not meet the requirements for the maximum PER, as stipulated in the technical conditions [13]. From the economic perspective, the recommended solutions for the heating system for the assessed building are highly efficient heat pumps supplied by a PV photovoltaic installation (variants W7, W9, W11).

To summarize, from the energy, economic and environmental points of views, the most advantageous solution is the variant of the energy source based on a glycol–water heat pump supplied by a 20.4 kWp PV photovoltaic installation and the power grid. The recommended solution meets the requirements for the maximum PE indicator as stipulated in the legal regulations applicable [6]. Such a system is also characterized by satisfactory CO_2 emission rates contributing to the building's environmental impact and relatively low costs in the LCC.

5. Summary

Energy, economic and environmental analyses of the possibilities of using alternative high-efficiency sources of heat and energy for multi-family residential buildings in order to increase energy efficiency in Poland are aimed at determining the optimal sources of heat and energy for the building. When performing such calculations for a multi-family residential building, it should be noted that approximately 45–70% of usable energy is consumed to prepare utility hot water.

The following general conclusions and guidelines for designers of energy-efficient multi-family houses were drawn from the conducted research:

- as it is impossible to reduce water consumption for hygienic and sanitary purposes, it is necessary to use highly efficient heat and energy sources based on renewable energy;
- when designing an energy-saving building, the first step is to reduce the demand for usable energy for heating and ventilation purposes;
- the use of mechanical supply and exhaust ventilation with heat recovery in the building is a solution that improves energy efficiency and ensures the appropriate microclimate in the rooms;
- the reduction of heat loss by penetration through external partitions is a solution that improves energy efficiency: solutions that increase thermal insulation should be used;
- the recommended solution for the optimal source of heat and energy should be technically feasible and consider the plot size or the roof area for a PV installation;
- in order to increase the energy efficiency of a building, solutions based on high-efficiency heat sources should be applied;
- for environmental reasons, the most advantageous solution is the use of renewable energy sources (RES);
- solutions based on renewable energy sources are characterized by high investment costs, which, for financial reasons, limits the possibility of their use by potential investors. It is therefore recommended to perform economic analyses based on the LCC indicator at the design stage.

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