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Economic and Energy Analysis of the Operation of Windows in Residential Buildings in Poland

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Abstract: This article presents the results of the economic and energy analysis of the operation of five types of windows in residential buildings. The aim of this study was to determine (a) to what extent the construction and various insulation parameters of windows affect the operating costs of buildings, when using different heating systems, (b) to what extent the significant cost of purchasing windows with better insulation is compensated by lower building operation costs (heating and the lifecycle of windows), (c) how the temperature difference inside the building affects heat loss through windows and, as a result, heating costs when using different heating systems. Five types of windows were selected for detailed analysis: a double- and a triple-glazed PVC window, double- and triple-glazed wooden window, and triple-glazed aluminum window. When wooden double-glazed windows are replaced with aluminum windows, the return on investment occurs in just 2 to 4.4 years. It was also found that of the five types of windows tested, the total economic balance of the operation period is the most favorable for PVC windows, regardless of the type of glazing and the heating system. The operating costs of PVC windows in a model residential building are over 30% lower than in the case of wooden windows and almost 20% lower compared to aluminum windows.

Keywords: residential building; thermal insulation; windows; heat; costs; operation of windows; heating system; fuel

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1. Introduction

The gradual depletion of readily available energy sources and the need to protect the natural environment and ensure energy security make global reduction of energy consumption one of the basic goals of the broadly understood energy policy. Among the many possibilities to improve the primary energy use ratio, the most important is to increase the share of renewable energy sources in the energy balance and improve energy efficiency. This applies also to housing [1]. Residential buildings are very energy-intensive [2–4] and the construction sector as a whole is responsible for a significant proportion of the global environmental footprint [5], including CO_2 production [6,7]. It is estimated that up to 30 to 40% of the world's primary energy is used in buildings for heating, cooling, lighting, and ventilation [8]. In Europe, the construction sector has been identified as a major contributor to the reduction of greenhouse gas emissions, since it accounts for around 40% of total energy consumption [9]. One of the goals of the Paris Agreement is to limit global warming to 1.5 °C, and improving the energy efficiency of buildings is the key to achieving it [10]. Also, in the USA, the construction sector is one of the largest energy consumers, with buildings accounting for 40.4% of the country's total energy consumption. This indicates a huge potential for energy saving and emission reduction [10]. In recent years, optimizing energy use through efficient design has become an evolving research area [11]. The energy rating system for houses is now one of the world's leading initiatives for sustainable development and energy savings [12–14].

Windows are a very important structural element that affects the operation of a building. They must ensure resistance to wind load and provide air ventilation, sound insulation, lighting comfort, and resistance to fire. In addition, windows are a structural element that affects the energy efficiency and heat consumption associated with heating buildings [15]. However, windows are often considered to be one of the weakest structural elements due to high heat losses. Therefore, significant amounts of energy are required to maintain comfortable indoor conditions [16]. The surface of the windows takes up approximately 20% of the total area of the external partitions, and the total heat loss through the windows is even more than four times higher than that of insulated building walls [17]. Currently, windows are selected largely based on their thermal insulation properties [18], which are very important for building users due to heating costs. A completely different problem is the increase in heat consumption in the case of poor window insulation. In addition to increasing the operating costs of buildings, it causes an increased demand for heat carriers and can have a negative impact on the natural environment. Therefore, poor insulation contributes to the emission of harmful substances and increases the consumption of natural resources. The process of manufacturing modern windows is complex. It requires a large amount of raw materials, energy, water, and labor, including the use of machinery and appliances. Hence the significant cost of the finished product, reflected in market prices and price discrepancies. An important parameter of windows, which depends on the type of construction material, is the heat transfer coefficient. It is expressed by the heat transfer coefficient U, which is the basic parameter that allows determining the amount of heat that penetrates the windows of the building. This coefficient is an important parameter for the user of the building, right next to the price. The influence of the window structure on heat transfer to the outside of buildings, which has been the subject of many studies [19–22], is also important. The lower the heat transfer coefficient, the lesser the heat loss through the partition. According to [18], the value of the heat transfer coefficient has a large impact on smaller windows in warmer climates and larger windows in colder climates. In addition to the window material, the choice of optimal dimensions and location of windows plays an important role in the energy efficiency of the building. This is because different weather conditions and insolation angles affect the determination of the optimal dimensions and location of windows [16]. A very important problem is also the design of window systems in accordance with local climatic conditions. Not taking this factor into account when selecting windows for residential buildings can result in energy losses of up to 60% [23,24].

The worse the thermal insulation parameters of windows, the higher the consumption of heat, whose production has an impact on the natural environment. This is particularly important in the case of single-family buildings outside the municipal heating network. Their heating system is often based on conventional fuel: coal, heating oil, or gas, the choice of which is sometimes dictated by economic factors, with complete disregard for environmental issues. In Poland, 33% of households still use hard coal as the basic heating fuel [25]. Due to Poland's significant coal resources and the current geopolitical situation, which brings difficulties in access to cheap gas, hard coal-fired furnaces are likely not to disappear in the coming years. Therefore, it is even more important to reduce the heat consumption in residential buildings, e.g., by the use of appropriate windows. Therefore, it can be concluded that the types of windows and their characteristics have a great impact on the environmental and cost performance of buildings [26].

The selection and operation of windows, including the use of modern technologies to reduce heat consumption, is addressed in many studies. Some researchers have studied the use of different insulating materials and different types of glazing to reduce heat loss [27–30]. Others studied the impact of blinds and shutters on preventing heat loss [31–33]. There is also research on the modeling of many parameters affecting energy consumption and financial savings [34,35]. Nevertheless, as mentioned before, the selection and effects of window operation depend on many factors, including local conditions. These include climatic factors, the location of the building in relation to the cardinal directions, the closest surroundings of the building, etc. Differences in temperature outside or inside the building or a different intensity of solar radiation in a given climatic zone completely change the amount of heat exchange through the windows. Therefore, the research results presented in the literature regarding the use of windows in a given region of the world cannot always be completely related to a building located in a different zone. The thermal performance of the same window systems can vary depending on many factors, including air infiltration and the dimensions and geometry of the windows. Therefore, there is still a need for in-depth research on heat transfer through windows and other glazed building partitions [36]. The thermal insulation parameters of the window remain unchanged, regardless of external or internal conditions. Therefore, the following questions emerge:

- To what extent does the structure of the windows affect the heat loss in the building and, as a result, the costs of heating the building?
- How much does the type of heating system, and thus the fuel used to generate heat and heat buildings, affect the costs of heating the building?
- Is it worth investing in windows that are more expensive but have a longer lifespan and better insulation parameters?

2. Purpose and Scope

There are many types of windows worldwide, varying both in terms of construction materials and the structure itself, as well as production technology. In addition, these windows are operated in different climatic zones, where factors that affect the operation of windows, such as temperature, sunlight, wind, etc., are sometimes extremely different. The purpose of this work is to analyze heat losses through windows and the economic operation of windows in a residential building, using the following:

- Different types of windows;
- Different heating systems, including different fuel;
- Different temperatures inside the building.

The scope of work covered five types of windows from two leading Polish manufacturers: PVC, wooden, and aluminum windows with different glazing.

The scope of work also includes three types of heating systems (three types of fuel):

(a) Hard coal;
(b) Natural gas;
(c) Heating oil.

An analysis of heating costs was also made for two different temperatures inside the building, namely 22 °C and 20 °C.

This research was conducted to determine what the balance of economic benefits is from the installation of windows with better thermal insulation parameters. It was also to determine the dependencies between heating costs in the case of using individual windows with different heating systems. Will the investment in more expensive windows with better thermal insulation pay off? If so, how long would it take?

The analysis was made for 1 m^2 windows and a model residential building.

The choice of windows is important even at the early design stage to minimize the environmental impact of buildings [37] and their operating costs. The results of this research can therefore support early decisions of designers regarding the material and components of windows from the point of view of the final economic and environmental benefits related to the operation of buildings in given climatic conditions. The results of this research will also allow the prediction of differences in the energy consumption needed to heat buildings, depending on the types of windows used.

3. Materials and Methods

The subject of this research is five types of windows produced by the leading Polish manufacturers of windows, namely:

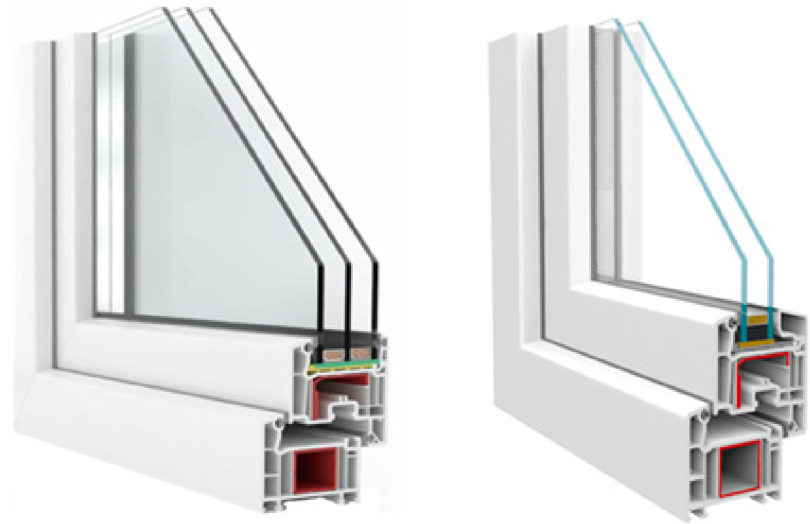
- Double-glazed PVC windows (PVC-2);
- Triple-glazed PVC windows (PVC-3);
- Double-glazed wooden windows (W-2);
- Triple-glazed wooden windows (W-3);

- Triple-glazed aluminum windows (ALU).

Figures 1–3 show the cross-sections of the windows covered by the tests.

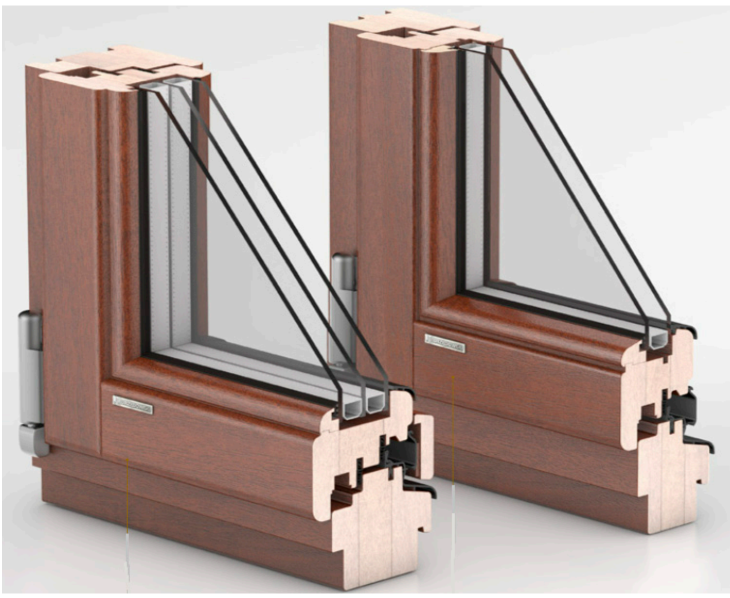
The first window, the cross-section of which is shown in Figure 1a, has a PVC frame. Its heat transfer coefficient is $U_w = 0.89\ W \cdot m^{-2} \cdot K^{-1}$. The glazing consists of two 4 mm thick panes separated by a 14 mm wide aluminum frame, which form one chamber, additionally filled with argon. The frame has five insulating chambers with reinforcements made of steel profiles and gaskets.

A PVC window with single-chamber insulated glazing (double-pane), the cross-section of which is shown in Figure 1b, has a frame made of PVC profiles with five insulating chambers. They are reinforced with steel profiles and gaskets. The glazing consists of two panes, 4 mm thick, separated by a 14 mm wide aluminum frame, which form a chamber, additionally supplemented with argon. The window's heat transfer coefficient is $U_w = 1.10\ W \cdot m^{-2} \cdot K^{-1}$.



(**a**) (**b**)

Figure 1. Cross-section of PVC windows: (**a**) triple-glazed, (**b**) double-glazed.



(**a**) (**b**)

Figure 2. Cross-section of a window with a wooden structure: (**a**) triple-glazed (**b**) double-glazed.

Figure 2a shows the construction of a wooden triple-glazed window. The window frame is made of a natural material with high thermal insulation parameters—a multi-layer glued wood profile 78 mm thick. Its glazing consists of three panes 4 mm thick, separated by 14 mm and 12 mm wide frames. The window's heat transfer coefficient is $U_w = 1.05\ W{\cdot}m^{-2}{\cdot}K^{-1}$. Figure 2b shows a double-glazed window with a wooden frame, also made of multi-layer glued wood—a 68 mm profile. The glazing of the window consists of two 4 mm thick panes separated by a 16 mm frame. The heat transfer coefficient of the window is $U_w = 1.4\ W{\cdot}m^{-2}{\cdot}K^{-1}$.

Among the tested windows, the model with lowest heat transfer coefficient, $U_w = 0.82\ W{\cdot}m^{-2}{\cdot}K^{-1}$, was the aluminum window whose cross-section is shown in Figure 3. It is made of aluminum profiles with three insulating chambers and gaskets, additional thermal insulating pads, as well as insulation foam in the sash frame and in the casing. It has glazing made of three 4 mm thick panes separated by an 18 mm wide aluminum frame, which form two chambers additionally supplemented with argon gas.

Figure 3. Cross-section of a triple-glazed aluminum window.

The analysis covered three types of heating systems, the most common in Poland, based on three types of fuel:

(a) Hard coal;
(b) Natural gas;
(c) Heating oil.

A small single-family, detached house, model Domino, offered by the company WACE-TOP, was adopted as a model residential building. The building is a two-story (ground floor and usable attic) house, with a total area of 100.2 m^2 and is made of brick, in traditional technology. The window area of the building is 15.2 m^2. The adopted location of the house was in the climatic zone characteristic of southern Poland, where the heating season lasts approximately 212 days, and the average temperature is 3.2 °C. The window penetration coefficient U_w was adopted based on the manufacturer's declaration and takes into account the entire window partition, i.e., panes, frame, door frame, seals, etc.

The operation period of the windows was adopted based on the manufacturers' declarations as follows: 25 years for PVC windows, 40 years for wooden windows, and 50 years for aluminum windows. The adopted functional unit for the calculation of the investment payback period (calculation period) was 25 years, which was the operation period of the model with the lowest durability, i.e., the PVC window. The following types of fuels were used to calculate the demand for heating fuel: hard coal with a calorific value of 28.9 MJ·kg^{-1}, natural gas with a calorific value of 35.5 MJ·kg^{-1}, and fuel oil with a calorific value of 42.6 MJ·kg^{-1}. The efficiency of heating boilers was adopted as follows: for a coal-fired furnace 0.88, for a gas-fired furnace 0.97, and for a fuel-oil furnace 0.94.

Heat losses through window partitions were calculated based on the following dependence:

$$Q = U_w \cdot F \cdot \Delta t \tag{1}$$

where:

Q—heat loss (W).

U_w = heat transfer coefficient (W·m^{-2}·K^{-1}).

F·—window area (m^2).

Δt—temperature difference outside and inside the building (K).

The amount of fuel necessary to compensate for heat that is lost as a result of window penetration was calculated based on the relationship:

$$Mw = \frac{Q}{Wo \cdot e} \tag{2}$$

where:

Q—as above.

M_w—mass of fuel (kg, m^3).

W_o—calorific value of the fuel (MJ·kg^{-1}).

e—boiler efficiency (-).

Investment costs (EUR·m^{-2}·year^{-1}) were calculated according to the formula:

$$Ki = \frac{C \cdot Z}{T} \tag{3}$$

where:

K_i—investment costs (EUR·m^{-2}·year^{-1}).

C—cost of purchase and installation of the window (EUR).

Z—window durability period (years).

T—calculation period = 25 (years).

The adopted heating cost was the cost of generating heat to compensate for heat losses through window partitions. It was calculated as the quotient of the amount of fuel burned and its unit price. The operating costs of the windows was calculated as the sum of investment costs and heating costs.

Savings from investment (EUR·year^{-1}) were calculated as the difference in the cost of purchasing and installing different window variants for the model house compared to one year of operation. Savings on heating (EUR·year^{-1}) were calculated as the difference in the cost of consuming energy carriers when heating the model house with different window variants installed compared to one year of operation. The total savings (EUR·year^{-1}) are derived from the operating costs, that is, both the investment costs for the different window variants and the heating costs for the model house compared to one year of operation.

4. Results and Discussion

Table 1 presents the general characteristics of the tested windows. As observed, the costs of purchasing windows, including the purchase price and the cost of installation in the building, vary greatly. As building components, windows are typically high-value products that are more highly engineered and manufactured than other building materials [38]. In the case of windows made of the same material, the difference in costs between a double-and triple-glazed window is obvious. It results from their thermal insulation properties, i.e., the value of the U_w coefficient. Differences between PVC and aluminum triple-glazed windows result primarily from their different durability, while the relatively high cost of wooden windows is caused by the purchasing preferences of buyers, i.e., aesthetic finish and the use of wood as a natural construction material.

Table 1. General characteristics of windows.

Window Type	Purchase and Installation Cost (EUR)	Operation Lifecycle (Years)	Heat Transfer Coefficient U_w ($W \cdot m^{-2} \cdot K^{-1}$)
Double-glazed PVC window	223	25	1.10
Triple-glazed PVC window	244	25	0.89
Double-glazed wooden window	542	40	1.40
Triple-glazed wooden window	626	40	1.05
Triple-glazed aluminum window	690	50	0.82

Heat losses through the window partitions per 1 m^2 of the window, as well as in the entire model building, are listed in Table 2. These losses are closely related to the thermal insulation parameters of the windows, because it is the only variable factor. Lowering the temperature inside the building by 2 °C reduces heat losses by 10.6%, which will undoubtedly reduce the cost of heating the building.

Table 2. Heat loss through windows.

Window Type	Heat Loss (W)		Heat Losses during 1 Year of Operation ($MJ \cdot Year^{-1}$)	
	per 1 m^2 of Window	House	per 1 m^2 of Window	House
Double-glazed PVC window	20.6	313.4	378	5740
Triple-glazed PVC window	16.7	253.6	306	4644
Double-glazed wooden window	26.2	398.8	481	7306
Triple-glazed wooden window	19.7	299.1	360	5479
Triple-glazed aluminum window	15.4	233.6	282	4279

The annual heat loss of the model house through the window partitions, in terms of $kWh \cdot m^{-2} \cdot year^{-1}$, is the lowest (11.8 $kWh \cdot m^{-2} \cdot year^{-1}$) for windows of aluminum construction. These windows have the lowest heat transfer coefficient of 0.82 ($W \cdot m^{-2} \cdot K^{-1}$) and are triple-glazed. They are constructed of aluminum profiles with three insulating chambers and gaskets, additional thermal insulating pads, as well as insulation foam in the sash frame and in the casing. On the other hand, the highest heat loss over the year, approximately 20.2 $kWh \cdot m^{-2} \cdot year^{-1}$, occurs in a house with double-glazed wooden windows installed. These windows, despite the natural and environmentally friendly construction material of wood, are unfortunately characterized by a very high heat transfer coefficient, at approximately 1.40 ($W \cdot m^{-2} \cdot K^{-1}$). Such low insulation parameters of a wooden window are due, among other things, to the lack of insulating chambers inside the frame structure. Szul [39] shows that the average heat consumption for heating single-family residential buildings located in the same climatic zone as the model building is approximately 182.3 $kWh \cdot m^{-2} \cdot year^{-1}$. The losses for a model house presented in Table 2 are on average approximately 10% of the above-mentioned consumption, which is a low value, because as published studies show, heat losses through window partitions can reach up to 30% [40,41].

Figure 4 presents the costs of energy carriers necessary to generate 1 GJ of heat in a model building. These costs depend primarily on the prices of fuel, i.e., hard coal, natural gas, and heating oil. The adopted fuel prices are as of June 2023 and are much higher than two years before, which is caused by the geopolitical situation and the general increase in the prices of goods and services in late 2022 and 2023. In addition, the cost of generating heat depends on the calorific value of fuels and the efficiency of the heating boiler. By far the lowest unit cost of heat is that of coal, for which the production of 1 GJ costs EUR 15.94. This is over two times lower than in the case of heating oil. It is the costs that are often the decisive factor taken into account by the owners of single-family residential buildings when choosing a heating system. The positive aspect is that the most environmentally friendly heating system among those covered by this research, i.e., natural gas-powered, is not the one with the highest heat generation costs.

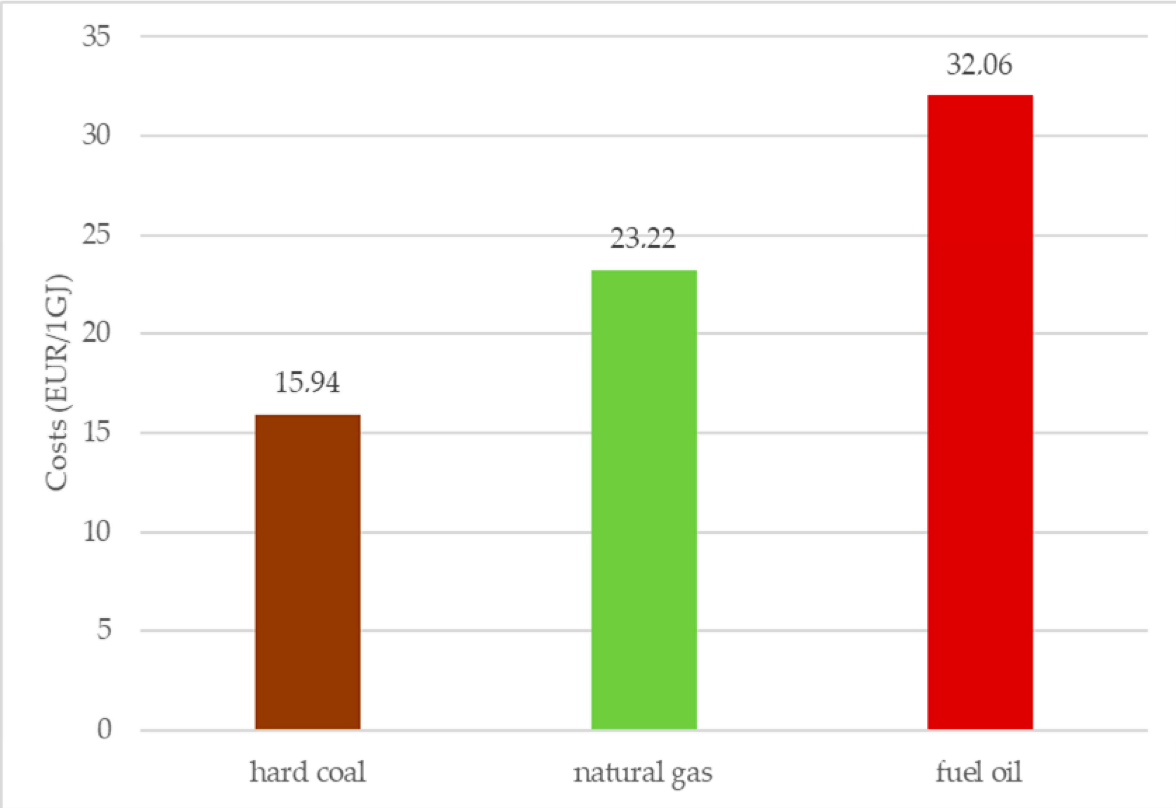


Figure 4. Cost of fuel to produce 1 GJ of heat.

The investment costs related to the purchase and installation of windows and the costs of heating that would cover heat losses through windows are presented in Table 3. The unit cost of the purchase and assembly of windows, known as investment costs, depended, among others, on the window durability period expressed in years (Table 1). Upon analyzing Table 3, it can be seen that aluminum windows, although the most expensive among all the studied models (Table 1), are not characterized by the highest investment costs. For example, the cost of purchasing and installing aluminum windows was almost three times higher than triple-glazed PVC windows, while the difference in investment costs is less than 30%. Heating costs (Table 3) are strictly dependent on the cost of generating 1 GJ of heat and the thermal insulation parameters of the windows. They range from EUR 4.5 $m^{-2} \cdot year^{-1}$ in the case of an aluminum window and the use of a coal-fired heating system up to EUR 15.4 $m^{-2} \cdot year^{-1}$ for wooden, double-glazed windows and a heating system based on fuel oil. It can therefore be concluded that selecting windows with high thermal insulation parameters and using the heating system that is cheapest in operation allows reducing costs more than three times. Research by [42] shows that the selection of appropriate windows can reduce heating costs by up to 21%. Of course, the above analysis does not include the environmental costs associated with the use of solid fuels.

Table 3. Operating costs of windows per 1m^2 of window (EUR·m^{-2}·year^{-1}).

Window Type	Investment Costs (EUR·m^{-2}·Year^{-1})	Heating Costs (EUR·m^{-2}·Year^{-1})		
		Hard Coal	Natural Gas	Fuel Oil
Double-glazed PVC window	8.9	6.0	8.8	12.1
Triple-glazed PVC window	9.8	4.9	7.1	9.8
Double-glazed wooden window	13.5	7.7	11.2	15.4
Triple-glazed wooden window	15.7	5.7	8.4	11.6
Triple-glazed aluminum window	13.8	4.5	6.5	9.0

Table 4 presents a comparison of the profits from the installation of individual window models relative to each other in a model residential building with a window area of 15.2 m^2. Investment savings are the highest (102.2 EUR·year^{-1}) in the case of installing a double-glazed PVC window instead of a wooden triple-glazed window. The huge disproportion in the cost of purchase and installation of both windows is not mitigated even by a significant difference in the durability period: 25 years for a PVC window and 40 years for a wooden window.

Table 4. Comparison of investment savings for different windows for a model house (EUR·year^{-1}).

	PVC-2	PVC-3	DR-2	DR-3	ALU
PVC-2	-	−12.5	−70.0	−102.2	−73.8
PVC-3	12.5	-	−57.5	−89.7	−61.3
W-2	70.0	57.5	-	−32.2	−3.8
W-3	102.2	89.7	32.2	-	−61.3
ALU	73.8	61.3	3.8	61.3	-

Of course, the savings presented in Table 4 are only apparent and could be significant, for example, when a house is built or renovated for sale. In the case of longer operation, the most important costs are those related to heating the building, which depend not on the price of the window, but on its thermal insulation properties. Optimal window design and selection of window glazing is a key energy saving strategy in buildings [43]. Profits brought from the difference between heating costs (EUR·year^{-1}), also referred to a model residential building, are presented in Table 5. Upon analyzing Table 5, it can be seen that the replacement of double-glazed wooden windows with aluminum windows brings annual savings from EUR 48.2 for a coal-fired heating system to EUR 97.0 when the fuel is oil. Of course, the reduction of heating costs is also associated not only with the type of construction material, but also with the number of window panes. Hart [28] proves that the energy saving potential of thin triple glazing instead of typical low-emission windows in residential buildings can be up to 16% in climates that require building heating. Table 5 shows that even the installation of a window made of the same material but with three rather than two panes increases the savings on heating costs. For PVC windows, they range from 17.5 to 35.1 (EUR·year^{-1}), depending on the type of heating system, and for wooden windows—from 29.1 to 58.6 (EUR·year^{-1}).

A summary of the total annual savings related to the operation of windows in a model building, which includes both investment and heating costs, is presented in Table 6. Upon analyzing the data offered, it can be seen that from the point of view of operating costs, it is most advantageous to replace wooden windows with PVC and aluminum windows; however, the amount of savings also depends on the heating system used. In the case of the most expensive fuel, i.e., heating oil, replacing double-glazed wooden windows with triple-glazed PVC windows brings savings of EUR 142.9·year^{-1}, which over 25 years amounts to EUR 3.572. The above profit results not only from lower heating costs, but also from lower costs of purchase and installation of PVC windows. Gorantla [44] indicates that appropriate glazing can lead to savings on heating reaching more than USD 16 per 1 m^2 of window. However, taking into account not only heating costs but also investment costs, replacing double-glazed PVC windows in a single-family building with triple-glazed brings a saving of only 5.0–22.7 EUR·year^{-1} (depending on the heating system used).

Table 5. Comparison of heating savings for a model house (EUR·year^{-1}).

	Window Type	PVC-2	PVC-3	W-2	W-3	ALU
Hard coal	PVC-2	-	17.5	−25.0	4.2	23.3
	PVC-3	−17.5	-	−42.4	−13.3	5.8
	W-2	25.0	42.4	-	29.1	48.2
	W-3	−4.2	13.3	−29.1	-	19.1
	ALU	−23.3	−5.8	−48.2	−19.1	-
Natural gas	PVC-2	-	25.4	−36.3	6.1	33.9
	PVC-3	−25.4	-	−61.8	−19.4	8.5
	W-2	36.3	61.8	-	42.4	70.3
	W-3	−6.1	19.4	−42.4	-	27.9
	ALU	−33.9	−8.5	−70.3	−27.9	-
Fuel oil	PVC-2	-	35.1	−50.2	8.4	46.8
	PVC-3	−35.1	-	−85.3	−26.8	11.7
	W-2	50.2	85.3	-	58.6	97.0
	W-3	−8.4	26.8	−58.6	-	38.5
	ALU	−46.8	−11.7	−97.0	−38.5	-

Table 6. Comparison of total savings for a model house (EUR·year^{-1}).

	Window Type	PVC-2	PVC-3	W-2	W-3	ALU
Hard coal	PVC-2	-	5.0	−94.9	−98.0	−50.5
	PVC-3	−5.0	-	−100.0	−103.0	−55.5
	W-2	94.9	100.0	-	−3.1	44.4
	W-3	98.0	103.0	3.1	-	47.5
	ALU	50.5	55.5	−44.4	−47.5	-
Natural gas	PVC-2	-	13.0	−106.3	−96.1	−39.9
	PVC-3	−13.0	-	−119.3	−109.1	−52.9
	W-2	106.3	119.3	-	10.2	66.5
	W-3	96.1	109.1	−10.2	-	56.2
	ALU	39.9	52.9	−66.5	−56.2	-
Fuel oil	PVC-2	-	22.7	−120.2	−93.8	−27.0
	PVC-3	−22.7	-	−142.9	−116.5	−49.6
	W-2	120.2	142.9	-	26.4	93.2
	W-3	93.8	116.5	−26.4	-	66.8
	ALU	27.0	49.6	−93.2	−66.8	-

Figure 5 shows the total costs, i.e., the costs of investment and heating compensating for heat losses through windows in a model building, over a period of 25 years of operation. The proportions between both components of total costs depend mainly on fuel prices. The total costs range significantly, from EUR 5.558 to EUR 11,001, using different types of windows and different heating systems. Even when using the same heating system, the type of installed windows affects the difference in costs by almost 30%, which is consistent with the results of published studies. According to [45], the appropriate configuration of windows can reduce the energy intensity of a building by about 20%. Of course, the costs of heating the building will be much higher when heat losses through other partitions in the building, i.e., walls, or roof are taken into account, as well as losses through leaks, etc. In addition, other factors that can further reduce heating costs are also important, e.g., optimal dimensions and arrangement of windows. The results presented in the literature show that choosing the optimal window dimensions and locations can reduce a building's total energy consumption by 2% and 15%, respectively, in cold and hot climates [16].

From an environmental point of view, the production of wooden windows is more favorable because wood is a renewable material, and the manufacturing process of wooden windows itself does not cause as many harmful emissions as the production of aluminum or PVC windows. Unfortunately, the research presented in this paper proves the opposite environmental impact of their operation. The low insulation parameters of wooden windows result in greater heat loss. This, in turn, contributes to increased consumption of energy. This is particularly unfavorable when energy is produced from fossil fuels, as the combustion process carries environmental damage. The problem could be solved by improving the insulating properties of wooden windows. This could be done by, for example, introducing heat-insulating material into chambers inside the window frames, especially in the casing, as it is done with aluminum windows. Unfortunately, from a technological point of view, this would be more difficult and generate additional costs, which would result in increasing the already relatively high price of wooden windows. As it stands, wooden windows are approximately 2.5 times more expensive than PVC windows with better insulation parameters (Table 1). From a technological point of view, it would be simpler to use special low-emission glazing in wooden windows. In addition to improving thermo-isolation parameters, it would also improve the window's sound insulation.

Generally speaking, upon analyzing the very small price difference between double-glazed and triple-glazed windows, one can also come to the conclusion that double-glazed windows should no longer be produced. The windows that are the subject of this study are designed for single-family buildings, which significantly limits the possibility of modernizing them to, for example, store solar energy or even convert it, as is the case in the windows of large format commercial buildings, where glazing accounts for most of the wall surface.

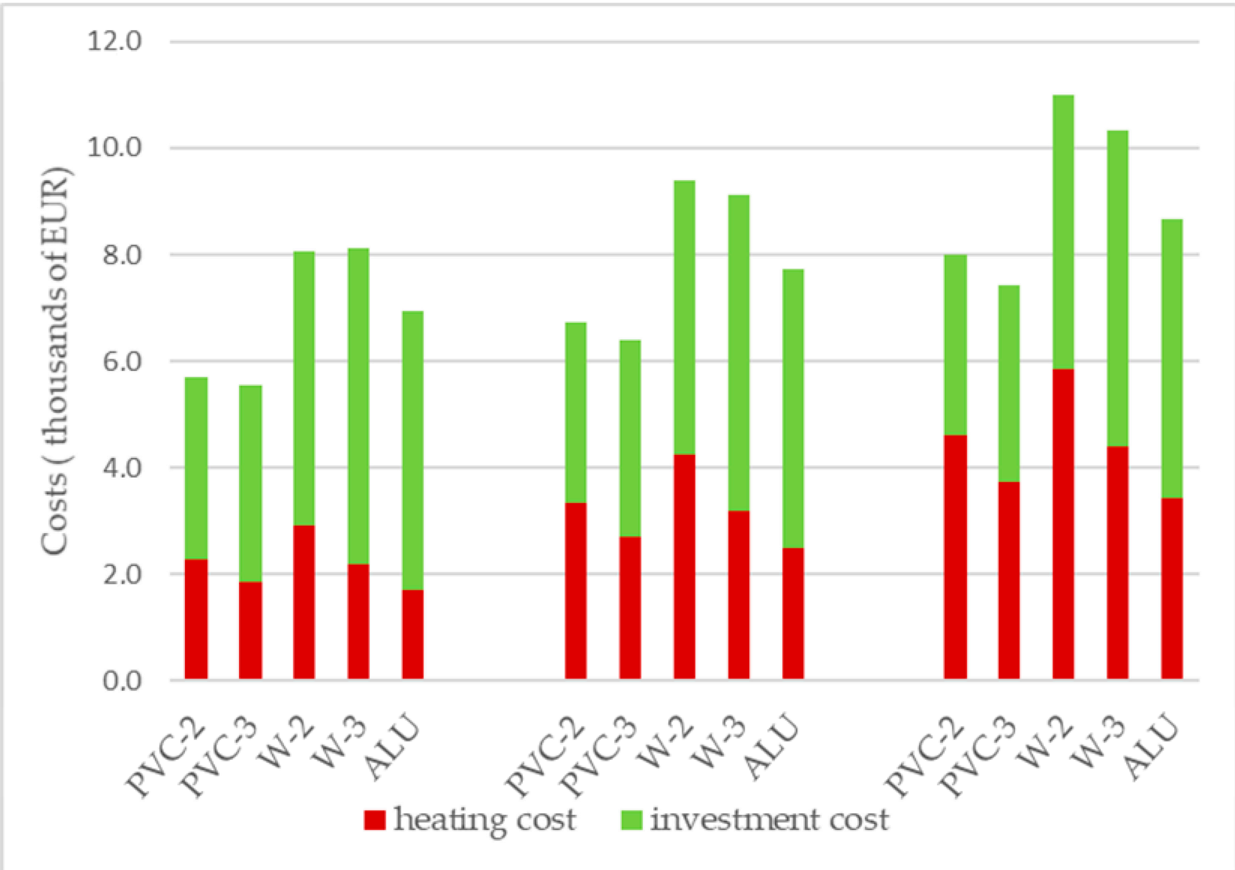


Figure 5. Operating costs of windows over 25 years in a model house for t_w = 22 °C.

Currently, in light of the current energy crisis, the concepts for saving energy are broadly discussed [46]. One of the proposals is to lower the temperature inside the buildings. In the case of a model building, lowering the temperature inside by 2 °C, i.e., to 20 °C, reduces energy consumption, and thus the costs related to the compensation of heat losses through windows, by more than 10%, as shown in Figure 6. Due to the significant heating costs, looking for various methods of reducing them is a worthwhile pursuit. Burns [29] indicates that the use of various types of window accessories, such as cellular shades, blinds, storm covers, etc., brings energy savings of 10% or more. From the economic point of view, it is also advantageous to support the heating system with an appropriate control system or the use of heat pumps [47,48].

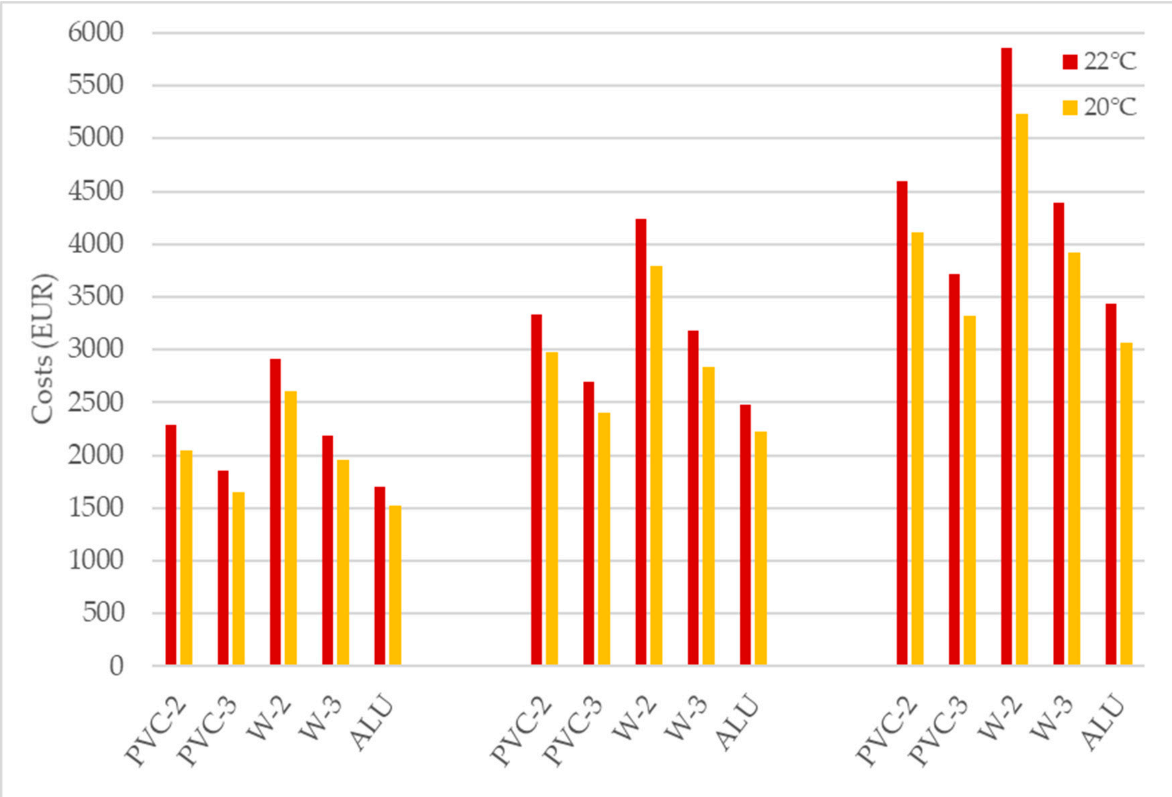


Figure 6. Heating costs over 25 years in a model house for t_w = 22 °C and t_w = 20 °C.

Table 7 offers data on the payback period of the investment, which includes replacing double-glazed PVC windows with triple-glazed PVC windows and wooden double-glazed windows with aluminum windows. In the selected options, the difference in heating costs resulting from the replacement of windows covers the difference in investment costs. As observed, the payback period expressed in years depends on the type of heating system and the temperature maintained inside the building. In the case of changing double-glazed wooden windows to aluminum ones, the investment pays back within 2 to 4.4 years. The decision regarding the choice between wooden and aluminum windows often depends not only on economic issues but also on aesthetics, environmental considerations, fashion, etc., which is why the data on replacing double-glazed PVC windows with triple-glazed is more interesting. Regardless of the type of heating system and the temperature inside the building during the operation of the windows, the return on investment takes no less than 9 years.

Table 7. Payback period resulting from savings on heating costs for different indoor temperatures.

Fuel Type	Inside Temperature (°C)	Payback Period (Years)	
		PVC-2–PVC-3	W-2–ALU
Hard coal	22	17.8	4.0
	20	20.0	4.4
Natural gas	22	12.2	2.7
	20	13.7	3.0
Fuel oil	22	8.9	2.0
	20	9.9	2.2

Of course, the use of fossil fuels for residential heating must be gradually reduced following the regulations of the European Green Deal. One of its goals is to reduce greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. As a country whose economy relies heavily on coal-based energy, Poland faces a major challenge of deep energy transition. Unfortunately, the transition is hampered by the current geopolitical situation and related problems in the energy markets. However, please note that the most significant task is first of all to reduce the share of hard coal in electricity production. This could be easier and more effective than a radical and sudden change in heating systems for single-family buildings. The change of heating systems in single-family buildings is also in progress and is facilitated by a number of government programs that allow the use of subsidies for the replacement of old heating furnaces for more environmentally friendly models.

5. Conclusions

There is a very large selection of windows available on the market. They differ in construction, thermal insulation parameters, durability, design, and price. In the current situation of the global energy crisis, however, economic and environmental factors should be decisive when choosing windows, both at the design stage of buildings and their subsequent operation.

The purpose of this article was to present the economic and energy analysis of the operation of five types of windows in residential buildings. The research results prove that despite the higher purchase and installation price, replacing windows with better thermal insulation parameters can bring measurable economic benefits and a return on investment in a very short time. When wooden double-glazed windows are replaced with aluminum windows, this return occurs already within 2 to 4.4 years. It was found also that out of the five window types tested, the total economic balance of the operation period is the most favorable for PVC windows, regardless of the type of glazing and the heating system. Operating costs of PVC windows in a model residential building are over 30% lower than in the case of wooden windows and almost 20% lower compared to aluminum windows. Reducing the internal temperature in the model building from 22 °C to 20 °C results in a reduction of costs related to the compensation of heat losses through windows with the poorest thermal insulation parameters (wooden double-glazed windows) by up to EUR 625 in the case of an oil-fired heating system over the assumed period of operation.

The above analysis does not include the environmental costs associated with the use of solid fuels. Unfortunately, the lower heating using fossil fuels could pose a social problem following the need to reduce emissions as part of the European Green Deal. Ana-logically, high operating costs of wooden windows, whose production is the most environmentally friendly, constitutes a certain investment barrier. The above factors prove that the energy transition process is an exceptionally complicated problem and poses a serious economic challenge for both the state and society.

The conducted economic and energy analysis can be useful for manufacturers, architects, and investors who are looking for solutions that increase the energy efficiency of buildings and reduce the operating costs of buildings. At a later stage of the research, comparative analyzes of the possibilities of reducing the operating costs of windows will be carried out, taking into consideration the use of renewable energy sources for heating residential buildings and the impact of additional factors, such as the arrangement and size of windows, the use of window accessories such as roller blinds, blinds, etc.

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References

1. Urbańska, K.; Dyjakon, A. Wpływ rodzaju stolarki okiennej na opłacalność inwestycji w budownictwie energooszczędnym. *Bud. o Zoptymalizowanym Potencjale Energetycznym* **2017**, *20*, 75–82. [CrossRef]
2. Casini, M. Active dynamic windows for buildings: A review. *Renew. Energy* **2018**, *119*, 923–934. [CrossRef]
3. Apostolopoulos, V.; Mamounakis, I.; Seitaridis, A.; Tagkoulis, N.; Kourkoumpas, D.-S.; Iliadis, P.; Angelakoglou, K.; Nikolopoulos, N. An integrated life cycle assessment and life cycle costing approach towards sustainable building renovation via a dynamic online tool. *Appl. Energy* **2023**, *334*, 120710. [CrossRef]
4. Martinopoulos, G.; Papakostas, K.T.; Papadopoulos, A.M. A comparative review of heating systems in EU countries, based on efficiency and fuel cost. *Renew. Sustain. Energy Rev.* **2018**, *90*, 687–699. [CrossRef]
5. Zhou, Y.; Ma, M.; Tam, V.W.; Le, K.N. Design variables affecting the environmental impacts of buildings: A critical review. *J. Clean. Prod.* **2023**, *387*, 135921. [CrossRef]
6. Hong, J.; Shen, G.Q.; Peng, Y.; Feng, Y.; Mao, C. Uncertainty analysis for measuring greenhouse gas emissions in the building construction phase: A case study in China. *J. Clean. Prod.* **2016**, *129*, 183–195. [CrossRef]
7. METRICS, International Energy Agency Building Energy Performance. *Supporting Energy Efficiency Progress in Major Economies*; International Energy Agency: Paris, France, 2015.
8. Granqvist, C.G. Electrochromics for smart windows: Oxide-based thin films and devices. *Thin Solid Films* **2014**, *564*, 1–38. [CrossRef]
9. Rodrigues, V.; Martins, A.A.; Nunes, M.I.; Quintas, A.; Mata, T.M.; Caetano, N.S. LCA of constructing an industrial building: Focus on embodied carbon and energy. *Energy Procedia* **2018**, *153*, 420–425. [CrossRef]
10. Zeng, Z.; Lu, D.; Hu, Y.; Augenbroe, G.; Chen, J. A comprehensive optimization framework for the design of high-performance building systems. *J. Build. Eng.* **2023**, *65*, 105709. [CrossRef]
11. Tushar, Q.; Bhuiyan, M.; Sandanayake, M.; Zhang, G. Optimizing the energy consumption in a residential building at different climate zones: Towards sustainable decision making. *J. Clean. Prod.* **2019**, *233*, 634–649. [CrossRef]
12. Kordjamshidi, M. Modelling Efficient Building Design: Efficiency for Low Energy or No Energy? In *House Rating Schemes: From Energy to Comfort Base*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 53–115. [CrossRef]
13. Su, Y.; Wang, L.; Feng, W.; Zhou, N.; Wang, L. Analysis of green building performance in cold coastal climates: An in-depth evaluation of green buildings in Dalian, China. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111149. [CrossRef]
14. Li, J.; Tian, Y.; Zhang, Y.; Xie, K. Spatializing environmental footprint by integrating geographic information system into life cycle assessment: A review and practice recommendations. *J. Clean. Prod.* **2021**, *323*, 129113. [CrossRef]
15. Ko, W.H.; Schiavon, S.; Zhang, H.; Graham, L.T.; Brager, G.; Mauss, I.; Lin, Y.-W. The impact of a view from a window on thermal comfort, emotion, and cognitive performance. *Build. Environ.* **2020**, *175*, 106779. [CrossRef]
16. Foroughi, R.; Asadi, S.; Khazaeli, S. On the optimization of energy efficient fenestration for small commercial buildings in the United States. *J. Clean. Prod.* **2021**, *283*, 124604. [CrossRef]
17. Intini, F.; Rospi, G.; Cardinale, N.; Kühtz, S.; Dassisti, M. Life Cycle Assessment of Italian Residential Windows: Sensitivity of Analysis. *Int. J. Heat Technol.* **2016**, *34*, S235–S241. [CrossRef]
18. Saadatian, S.; Rodrigues, C.; Freire, F.; Simões, N. Key drivers of life-cycle environmental and cost assessment of windows for different European climate zones. *J. Build. Eng.* **2022**, *50*, 104206. [CrossRef]

19. Gorantla, K.; Shaik, S.; Setty, A.B.T.P. Effects of Single, Double, Triple and Quadruple Window Glazing of Various Glass Materials on Heat Gain in Green Energy Buildings. In *Materials, Energy and Environment Engineering: Select Proceedings of ICACE*; Springer: Singapore, 2017; pp. 45–50. [CrossRef]
20. Mohelnikova, J.I.T.K.A.; Altan, H.A.Ş.I.M. Evaluation of optical and thermal properties of window glazing. *Wseas Trans. Environ. Dev.* **2009**, *5*, 86–93.
21. Hee, W.J.; Alghoul, M.A.; Bakhtyar, B.; Elayeb, O.; Shameri, M.A.; Alrubaih, M.S.; Sopian, K. The role of window glazing on daylighting and energy saving in buildings. *Renew. Sustain. Energy Rev.* **2015**, *42*, 323–343. [CrossRef]
22. Wang, T.-P.; Wang, L.-B. A steady heat transfer model of hollow double glazing under entire wave length heat radiation. *Energy Build.* **2014**, *81*, 72–83. [CrossRef]
23. Ke, Y.; Zhou, C.; Zhou, Y.; Wang, S.; Chan, S.H.; Long, Y. Emerging Thermal-Responsive Materials and Integrated Techniques Targeting the Energy-Efficient Smart Window Application. *Adv. Funct. Mater.* **2018**, *28*, 1800113. [CrossRef]
24. Jelle, B.P.; Hynd, A.; Gustavsen, A.; Arasteh, D.; Goudey, H.; Hart, R. Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. *Sol. Energy Mater. Sol. Cells* **2012**, *96*, 1–28. [CrossRef]
25. Polish Statistical Office (GUS). Zużycie Energii w Gospodarstwach Domowych w 2019 r. Energy Consumption in Households in 2019. Zakład Wydawnictw Statystycznych, Warszawa, 2020. Available online: www.stat.gov.pl (accessed on 4 September 2023).
26. Souviron, J.; van Moeseke, G.; Khan, A.Z. Analysing the environmental impact of windows: A review. *Build. Environ.* **2019**, *161*, 106268. [CrossRef]
27. Heydari, A.; Sadati, S.E.; Gharib, M.R. Effects of different window configurations on energy consumption in building: Optimization and economic analysis. *J. Build. Eng.* **2021**, *35*, 102099. [CrossRef]
28. Hart, R.; Selkowitz, S.; Curcija, C. Thermal performance and potential annual energy impact of retrofit thin-glass triple-pane glazing in US residential buildings. *Build. Simul.* **2019**, *12*, 79–86. [CrossRef]
29. Kirankumar, G.; Saboor, S.; Vali, S.S.; Mahapatra, D.; Setty, A.B.T.P.; Kim, K.-H. Thermal and cost analysis of various air filled double glazed reflective windows for energy efficient buildings. *J. Build. Eng.* **2019**, *28*, 101055. [CrossRef]
30. Bernat, T. Evaluation of Thermal Insulation of the Gastronomic Refrigeration Furniture Prototype. *Agric. Eng.* **2021**, *25*, 83–98. [CrossRef]
31. Burns, E.; Phan-Gruber, E.; Rivett, B.; Hart, R.; Curcija, C. *New Rating Opening Windows to a World of Comfort, Opportunity, and Cost-Effective Savings*; Window Covering Manufacturers Assoc.: New York, NY, USA, 2019.
32. Peng, J.; Jonsson, J.; Hart, R.; Curcija, D.C.; Selkowitz, S.E. Parametric Study of Window Attachment Impacts on Building Heating/Cooling Energy Consumption. In Proceedings of the 15th IBPSA International Building Simulation Conference, San Francisco, CA, USA, 7–9 August 2017. [CrossRef]
33. Shree, V.; Goyal, N.; Saxena, A.; Bhattacharyya, S.; Dwivedi, A.; Goel, V. Assessment of thermal loading in energy-efficient buildings: Parametric review on the window design aspects. *J. Therm. Anal. Calorim.* **2023**, *148*, 2703–2718. [CrossRef]
34. Tushar, Q.; Zhang, G.; Bhuiyan, M.A.; Giustozzi, F.; Navaratnam, S.; Hou, L. An optimized solution for retrofitting building façades: Energy efficiency and cost-benefit analysis from a life cycle perspective. *J. Clean. Prod.* **2022**, *376*, 134257. [CrossRef]
35. Menzies, G.; Muneer, T. Life cycle assessment of multi-glazed windows. In *Academic Research*; NorDan UK Ltd.: London, UK, 2017; p. 15.
36. Sadko, K.; Piotrowski, J.Z. Numerical investigations of the thermal properties of window systems: A review przegląd numerycznych metod określania właściwości cieplnych okien. *Struct. Environ.* **2022**, *14*, 126–141. [CrossRef]
37. Basbagill, J.; Flager, F.; Lepech, M.; Fischer, M. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Build. Environ.* **2013**, *60*, 81–92. [CrossRef]
38. Salazar, J. Life cycle assessment (LCA) of windows and window materials. In *Eco-Efficient Construction and Building Materials*; Woodhead Publishing: New Delhi, India, 2014; pp. 502–527. ISBN 9780857097675. [CrossRef]
39. Szul, T. Application of a Thermal Performance-Based Model to Prediction Energy Consumption for Heating of Single-Family Residential Buildings. *Energies* **2022**, *15*, 362. [CrossRef]
40. Zhao, X.; Mofid, S.A.; Jelle, B.P.; Tan, G.; Yin, X.; Yang, R. Optically-switchable thermally-insulating VO_2-aerogel hybrid film for window retrofits. *Appl. Energy* **2020**, *278*, 115663. [CrossRef]
41. Djamel, Z.; Noureddine, Z. The Impact of Window Configuration on the Overall Building Energy Consumption under Specific Climate Conditions. *Energy Procedia* **2017**, *115*, 162–172. [CrossRef]
42. Elghamry, R.; Hassan, H. Impact of window parameters on the building envelope on the thermal comfort, energy consumption and cost and environment. *Int. J. Vent.* **2020**, *19*, 233–259. [CrossRef]
43. Shaik, S.; Gorantla, K.; Mishra, S.; Kulkarni, K.S. Thermal and cost assessment of various polymer-dispersed liquid crystal film smart windows for energy efficient buildings. *Constr. Build. Mater.* **2020**, *263*, 120155. [CrossRef]
44. Gorantla, K.; Shaik, S.; Kontoleon, K.J.; Mazzeo, D.; Maduru, V.R.; Shaik, S.V. Sustainable reflective triple glazing design strategies: Spectral characteristics, air-conditioning cost savings, daylight factors, and payback periods. *J. Build. Eng.* **2021**, *42*, 103089. [CrossRef]
45. Tafakkori, R.; Fattahi, A. Introducing novel configurations for double-glazed windows with lower energy loss. *Sustain. Energy Technol. Assessments* **2021**, *43*, 100919. [CrossRef]

46. Kowalczyk, Z.; Kwaśniewski, D. Environmental impact of the cultivation of energy willow in Poland. *Sci. Rep.* **2021**, *11*, 4571. [CrossRef]
47. Piotrowska-Woroniak, J.; Szul, T.; Cieśliński, K.; Krilek, J. The Impact of Weather-Forecast-Based Regulation on Energy Savings for Heating in Multi-Family Buildings. *Energies* **2022**, *15*, 7279. [CrossRef]
48. Piotrowska-Woroniak, J.; Szul, T. Application of a Model Based on Rough Set Theory (RST) to Estimate the Energy Efficiency of Public Buildings. *Energies* **2022**, *15*, 8793. [CrossRef]