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Energy and Economic Efficiency of the Thermomodernization of an Educational Building and Reduction of Pollutant Emissions—A Case Study

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Abstract: The study presents an investigation of thermal energy consumption for heating in an educational building located in the north-eastern part of Poland in 2017–2020, after deep thermomodernization. An evaluation of the actual energy effects was made based on measurements carried out over a 4-year operational period. They were compared with the results of theoretical calculations included in the energy audit and an attempt was made to describe the reasons for the discrepancies. The planned and achieved economic efficiency indicators were assessed and the amount of reduction of pollutant emissions was determined. The performed analysis allowed for an assessment of the impact of deep thermomodernization in terms of reducing heat energy consumption for central heating purposes, as well as reducing greenhouse gas emissions such as CO_2, SO_x, NO_x and benzo(a)pyrene to the atmosphere. The implementation of thermomodernization in buildings led to savings of about 43% in terms of heat energy consumption for heating and a reduction in pollutant emissions. The theoretical savings based on the audit were 50.4%. The obtained results show that deep thermomodernization contributes to the improvement of energy and ecological efficiency in educational buildings, however, without the possibility of using subsidies, the investment is unprofitable. All the obtained results were discussed with the available literature sources and have been summarized with appropriate conclusions.

Keywords: thermomodernization; educational building; energy efficiency; emissions; economic efficiency indicators

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1. Introduction

As buildings are responsible for around 30% of energy consumption and 27% of total global energy-related CO_2 emissions, taking action to increase their efficiency is important worldwide. The largest share of greenhouse gas emissions from buildings is related to the use of energy for heating, cooling, lighting, and appliances [1]. According to the JRC report [2], the energy efficiency of three-quarters of existing buildings is significantly lower than required by current standards. It was estimated that 85% of today's European Union (*EU*) building stock was built before 2001 and a large part was built without any energy performance requirements—a third of it is over 50 years old and more than 40% was built before 1960 [2]. Despite the numerous measures that have been introduced to reduce heat consumption in buildings, implemented by individual countries in recent years, the *EU*'s annual rate of energy-related building renovations is still only at 1% [3]. In order to intensify renovation in the EU and to push the building sector to achieve emission neutrality by 2050 [4], in October 2020 the European Commission launched a "Strategy for a renovation wave" [3]. It aims to double the *EU's* annual rate of energy-related building renovation by upgrading 35 million buildings by 2030. It was emphasized that investing in buildings reduces energy bills and emissions but can also generate social benefits.

The main document in the EU, covering both new and existing buildings, is the Energy Performance of Buildings Directive (2010/31/EPBD), revised in 2018 [5] to accelerate the cost-effective renovation of existing buildings by 2050. The directive obliges individual EU member states to develop their own renovation strategies. In Poland, such a document, known as the Long-term Building Renovation Strategy (*LBRS*) [6], was adopted in February 2022. As part of the *LBRS*, all buildings in Poland, both public and private, were reviewed. It was found that there are 14.2 million buildings in Poland, of which almost 40% are residential buildings, 36% are production, utility and warehouse buildings; 3% are public buildings and 18% are other non-residential buildings. A significant part of the buildings is characterized by low energy efficiency and will require thermomodernization in the coming years. The data show that the energy efficiency of buildings varies and depends both on their purpose and the year of construction. Buildings commissioned for use in the 21st century are characterized by relatively high energy efficiency levels; however, older buildings have poor thermal quality of the building envelope (Table 1). The value of thermal transmittance coefficients (*U*-values) of partitions in buildings erected in Poland before 2002 are more than twice as high as currently required. Thus, the insulation of partitions in this group of buildings will significantly minimize heat loss, and thus reduce energy consumption. Studies available in the literature have proved that changing the required *U*-values from the level that was in force in 2014–2016 to the level applicable from 31 December 2020 (Table 1) reduces the energy demand for heating a single-family building with natural ventilation at its location in climate zone II in Poland by 17% [7], and with its location in climate zone IV in Poland by almost 27% [8].

According to the *LBRS* strategy [6], in the years 2020–2030 in Poland, thermomodernization is planned in 236 thousand buildings per year. In the years 2030–2040, these plans concern 271 thousand buildings, and in the years 2040–2050, 244 thousand buildings per year. In the period 2021–2050, 7.5 million thermomodernizations are planned, of which 4.7 million deep thermomodernizations are part of staged thermomodernization over time. The recommended action plan combines the rapid increase in the scale of low thermomodernization with the gradual dissemination of deep, more comprehensive thermomodernization by 2030.

Low thermomodernization [6] is the replacement of a high-emission heat source, such as, e.g., a coal-fired boiler with an ecological heat source, which enables the improvement of air quality [13] because solid fuel combustion in individual central heating furnaces and boilers is responsible for half of the smog in Poland [14]. In the Buildings Performance Institute Europe (BPIE) Report [9,15], such a procedure has been called light thermomodernization.

Deep thermomodernization as defined in the *DSRB* strategy [6] is associated with the necessity to take additional measures, such as the insulation of the building envelope [16], replacement of windows, door joinery and installations [17] or the total or partial replacement of energy sources [13]. According to the *BPIE* Report [15], thermomodernization, as it is understood in this, way may be additionally divided into medium and complex thermomodernization, depending on the scope of activities. As part of the medium of thermomodernization, the replacement of window and door joinery or thermal insulation of a façade is additionally performed. As part of complex thermomodernization, other activities that improve the energy performance of buildings are additionally carried out [18]. In recent years, efforts to modernize to a nearly zero-energy building standard [19] and an increase in the use of renewable energy have also been noticeable.

Table 1. Standard values of the maximum thermal transmittance coefficient of the building envelope of newly constructed and modernized buildings in Poland in various periods of time, at room temperature $t_i \geq 16\ ^\circ C$ $t_i \geq 16\ ^\circ C$ [9–12].

<table>
<tr><th rowspan="3">Period of Validity</th><th colspan="5">Type of Building Envelope</th></tr>
<tr><th>External Walls</th><th>Roofs</th><th>Windows and Balcony Doors</th><th>Roof Windows</th><th>Doors</th></tr>
<tr><th colspan="5">$U_{C(max)}$ (W/(m^2 K))</th></tr>
<tr><td colspan="6">**In Newly Constructed Buildings**</td></tr>
<tr><td>1957–1964</td><td rowspan="3">1.16 or 1.42 (depending on the type of climate zone)</td><td>0.87</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1964–1974</td><td>0.87</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1974–1982</td><td>0.70</td><td colspan="2">2.0–5.8 (depending on the type of climate zone)</td><td>1.60–5.80</td></tr>
<tr><td>1982–1991</td><td>0.75</td><td>0.45</td><td rowspan="3">2.0–2.6 (depending on the climate zone)</td><td>-</td><td>1.10–5.60</td></tr>
<tr><td>1991–2002</td><td>0.55–0.70</td><td>0.30</td><td>-</td><td>3.0</td></tr>
<tr><td>2002–2008</td><td>0.30–0.50</td><td>0.30</td><td>2.00</td><td>2.60</td></tr>
<tr><td>2009–2013</td><td>0.30</td><td>0.25</td><td>1.70–1.80</td><td>1.80</td><td>2.60</td></tr>
<tr><td>2014–2016</td><td>0.25</td><td>0.20</td><td>1.30</td><td>1.50</td><td>1.70</td></tr>
<tr><td>2017–2019</td><td>0.23</td><td>0.18</td><td>1.10</td><td>1.30</td><td>1.50</td></tr>
<tr><td>since 31 December 2020</td><td>0.20</td><td>0.15</td><td>0.90</td><td>1.10</td><td>1.30</td></tr>
<tr><td colspan="6">**In Modernized Buildings**</td></tr>
<tr><td>2008-X.2015</td><td>0.25</td><td>0.22</td><td>1.70–1.90 (depending on the climate zone)</td><td>1.80</td><td>-</td></tr>
<tr><td>Od X.2015</td><td colspan="5">as in newly constructed buildings</td></tr>
</table>

In each of the cases, the performance of deep thermomodernization is associated with higher investment costs, especially when there is a need to perform additional work. This may include, for example, drying walls, securing the thermal insulation layer against the harmful effects of moisture or other repair works, such as reconstruction or the modernization of balconies, allowing for the minimization of thermal bridges [20,21]. According to the report provided in [22], investments not related to energy savings exceed investments in energy renovation. It is estimated that in the period spanning 2012–2016, the average investment costs of energy renovation per year with regard to the square meter of the heated usable area of non-residential buildings in *EU* countries amounted to 111 EUR/m^2 (from 49 EUR/m^2 in Latvia to 183 EUR/m^2 in Sweden), while the average investment costs of non-energy renovation were 82 EUR/m^2 (from 64 EUR/m^2 in Bulgaria to 349 EUR/m^2 in the Netherlands). In Poland, these costs amounted to 64 EUR/m^2 and 105 EUR/m^2, respectively [22].

For individual renovation groups, according to the *BPIE* Report [9,15], the average cost of thermomodernization works carried out in 2013 in Poland in the group of non-residential buildings, in relation to a square meter of heated usable area, was:

- 40 EUR/m^2 for light renovation;
- 80 EUR/m^2 for medium renovation;
- 170 EUR/m^2 for complex renovation.

Investors often lack the sufficient financial resources to carry out deep thermomodernization or are unable to benefit from financial support. This was the reason for the insignificant share of comprehensive thermomodernization in all thermomodernization carried out in Poland in the years 2006–2013. In the group of residential buildings, this share was only 7%, and in the group of non-residential buildings, the share was 15%, which is a result of the greater availability of support mechanisms for non-residential buildings [9].

A prerequisite for using financial support is the preparation of an energy audit of the building, which will determine the optimal scope of works, their cost and can help to estimate the planned energy and environmental effect. By performing an energy audit the impact of different weather conditions in different climatic zones can be taken into account. In individual regions of the world, there is considerable variation in terms of meteorological conditions, which affects the selection of the optimal solution, and therefore it is advisable that investment decisions are made on the basis of the audit [23]. For example, in Poland, the differences in heat demand for an identical building structure, depending on its location, can reach up to 20% [6,8].

The differentiation of climatic conditions, apart from other factors (such as the type of building, its age, previous modernizations, etc.) also influences the differentiation of the effectiveness of individual modernization measures. Hummel et al. [24] concluded that the largest and cheapest savings can be achieved in buildings that are not yet renovated based on an analysis of refurbishment actions for representative buildings from six European countries. They also confirmed that the cost of achieving savings of 40–60% is much cheaper than achieving higher savings. Liu et al. [25] analyzed the cost efficiency of retrofit measures in a cold climate, showing that the cost efficiency of envelope retrofits increases when supported by the upgrade of technical installations. Chen et al. [26] obtained similar results and highlighted that insulation measures are profitable only when coupled with new and efficient technical installations. Mauro et al. [27] analyzed cost-optimal retrofit measures in a Mediterranean climate and stated that cost-optimal levels do not usually include envelope retrofit. Zangheri et al. [28] observed that envelope thermomodernization may be profitable in warm climates where there is no need for a cooling systems.

The results of the research on the investments implemented in Poland [29] indicate that in the conditions of a temperate continental climate, in the north-eastern part of the country, as a result of the deep thermomodernization of utility buildings located in rural areas, final energy savings of 46–65% and a reduction in CO_2 emissions by 45–86% were achieved. In the case of small churches located in the same region of Poland, the energy effects were at the level of 32–66% [30]. Research on buildings from other regions of Poland has shown similar possibilities of reducing energy demands by up to 64% [31,32]. Blazy et al. [33] also analyzed the potential ecological effects.

Other studies [34–41] have highlighted the differences in the theoretical and real effects of thermomodernization. In the group of educational buildings located in the city of Bialystok, a 33% reduction in energy consumption was achieved, while the planned reduction in energy consumption was approximately 59–71% [34]. The main reason for the difference was the increase in temperature in the rooms (before modernization, some of the rooms were underheated). De Wilde [35] provides an extensive review of the possible reasons for the gap between predicted and measured energy efficiency of buildings and indicated that this difference is a function of time and external conditions. According to Sun and Hong [36], relative energy savings can vary by up to 20% due to occupant behavior. This aspect was also dealt with by Brom et al. [37] and they found that about 50% of the differences in heat consumption between the same buildings can be explained by the characteristics of the building itself and other physical parameters and the remaining 50% of differences may result from the behavior of occupants. Many studies [38–41] also emphasize the influence of solar radiation on the building's energy demand for heating, and thus on the effects of thermomodernization.

As shown above, in the available literature examples of assessing the effects of thermomodernization of buildings can be found, both theoretical and real, in terms of energy, energy and economy or energy and ecology, but there are no articles covering all these aspects together. In addition, the difference between theoretical and real energy efficiency can be significant and depends on the location of the building; therefore, the authors believe that more information, results, and successful case studies are needed.

As a result, the aim of this article is to present a comprehensive analysis of the effectiveness of the process of the deep thermomodernization of an educational building located in north-eastern Poland. Planned and actual energy effects were compared, as well as the associated reductions in pollutant emissions. The investment costs and economic efficiency indicators were assessed.

2. Materials and Methods

2.1. Considered Building and Retrofit Measures

An educational building, shown in Figure 1, located in the north-eastern part of Poland in Bialystok on the campus of the Bialystok University of Technology, was selected for the research. The analyzed building A is the one of the three parts of the object (A, B, IE). The geographic coordinates of the case study are, respectively: longitude 23°15′23″ E and latitude 53°11′83″ N. The building development area is 2125 m^2. It is a three-storey building with a full basement, put into use in 1988. The heated area of part A is 7536.5 m^2, while the volume is 31,142 m^3. The building houses lecture and training rooms, laboratories, an auditorium, and employees' rooms. The building was erected in a reinforced concrete framed structure with a modular grid with dimensions of 6.0 × 6.0 m and an auditorium span of 12.0 m.

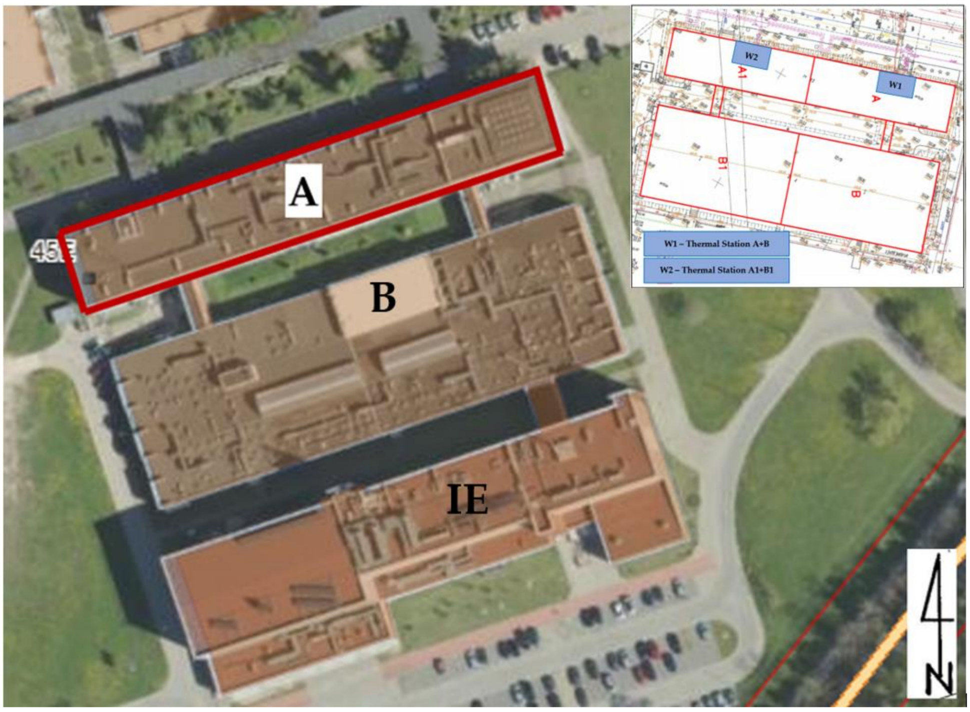


Figure 1. View of the location of the tested building (part A) with the layout of the W1 and W2 thermal substations in the state before modernization [42].

The basic technical parameters of the analyzed building (part A) are presented in Table 2.

A view of the tested building (part A) before thermomodernization is shown in Figure 2.

The analyzed building, shown in Figure 2, was constructed in the system of a reinforced concrete framed structure. The longitudinal external walls are made of aerated concrete 36 cm thick, ceramic brick 6.5 cm thick and ceramic façade tiles (from the outside). The external gable walls are made of 36 cm thick aerated concrete and ceramic façade tiles (from the outside). The external walls of the basement, 30 cm thick, are made of concrete and additionally (longitudinal walls) made of 12 cm thick perforated bricks. The ceilings in the building are made of hollow-core slabs and reinforced concrete slabs. The roofs are flat, covered with tar paper and insulated with mineral wool and is 4 cm thick above the auditorium, while 8 cm thick in the other rooms [43]. In part A of the building, the entire window and door joinery was replaced before 2011. New windows, which are made of PVC, are not equipped with air inlets. Fresh air is supplied into the building through the gaps obtained by thinning the rubber gaskets on the fragments of rebates of the window sashes to the frames. There were skylights above the auditorium and staircases.

Table 2. Basic technical parameters of the building A [43].

No.	Specification	Units	Data
1	construction year of a building	(year)	1982
2	building technology	-	framed technology
3	heated volume	(m^3)	21,668.6
4	volume	(m^3)	31,142.0
5	usable heated area	(m^2)	7.536.5
6	basement area	(m^2)	1881.9
7	building development area	(m^2)	2125.0
8	shape factor of buildings (the ratio surface to volume) A/V	(m^2/m^3)	0.35
9	windows area	(m^2)	1463.14
10	calculated heating consumed power (before thermomodernization)	(kW)	349.31
11	calculated heating consumed power(after thermomodernization)	(kW)	267.17
12	number of storeys	(pc.)	4
13	design mean internal temperature	(°C)	+17.7

Figure 2. View of tested building (part A) before thermomodernization, with characteristic stripes of clinker brick under the windows [photo authors].

The thermal transmittance coefficients of the building envelope generally met the requirements applicable at the time of their design (1980s). Table 3 presents the calculated *U*-values [43] determined based on archival documentation and the requirements in accordance with the technical conditions in force in Poland during the construction and modernization of the building.

Modernization measures were selected based on an analysis of the existing condition and archival documentation as well as after a thermovision inspection of all external partitions of the building. Selected thermal images showing the thermal condition of the building envelope before thermomodernization are shown in Figures 3 and 4.

Table 3. Thermal characteristics of the partitions of the analyzed building along with the applicable requirements in Poland during the construction and modernization of the building [9,43].

No.	Type of Building Envelope	Thermal Transmittance Coefficient U [W/m^2 K]		
		$U_{calc.}$. [43,44]	U_{max}	
			Construction Stage (Year: 1982)	Modernization Stage (Year: 2012)
1	External walls	0.76; 0.84	0.75	0.30
2	External walls of staircases	1.14		
3	External walls of basement	0.97; 1.43		
4	Roof	0.31	0.45	0.25
5	Roof over the staircases	0.45		
6	Roof over the auditorium	0.50		
7	Ceilings in loggias and recesses (above the basement)	0.41		
8	Ceiling under the outer ceiling of the auditorium and over the recesses at the entrances	0.90		
9	Windows	1.70	1.80	1.80
10	External doors	2.00; 2.50	5.60	2.60

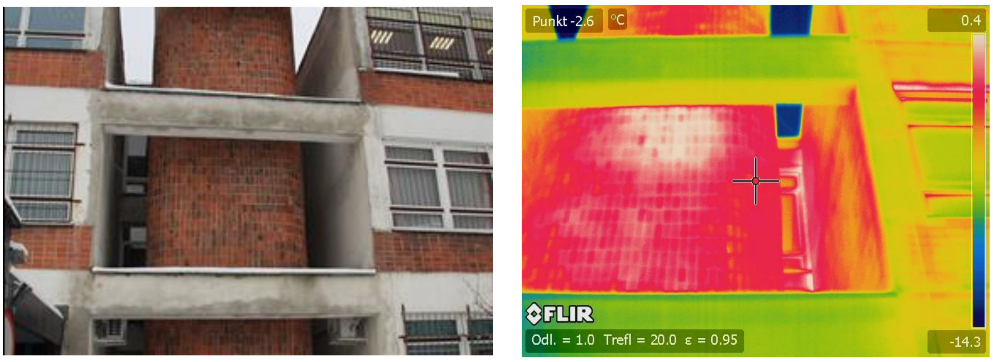


Figure 3. View of the staircase, to be insulated and a thermal image [photo authors].

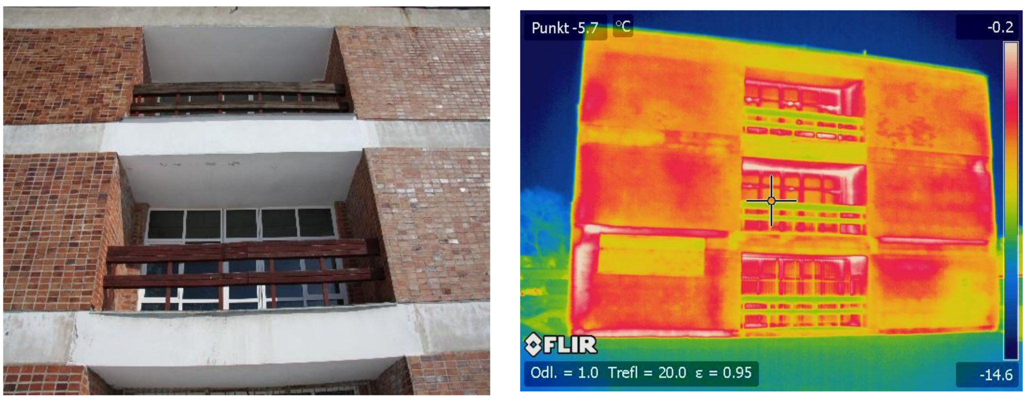


Figure 4. View of the gable wall, to be insulated and a thermal image [photo authors].

An increased temperature is observable (Figure 3), which highlights significant heat loss caused by structural elements (horizontal reinforced concrete beams), even though these are elements that are not part of the building envelope. A similar situation is visible in Figure 4 and concerns the horizontal elements of the loggias.

The thermomodernization measures, selected for analysis in part A of the building, relating to both the building envelope and the heating system, are shown in Figure 5.

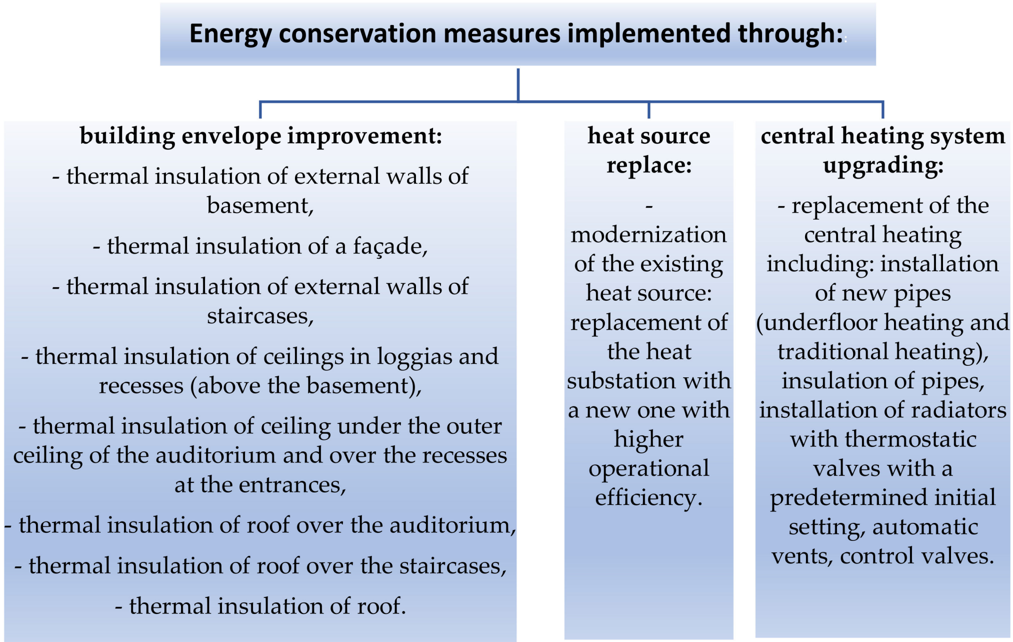


Figure 5. Energy conservation measures implemented in the analyzed building.

In order to refer to the other buildings located on the campus of the university and to care for the homogeneous character of the entire complex, the layout and size of the red stripes under the windows characteristic of the building were repeated in the newly designed building facades (Figure 2). Additionally, the finishing of external staircases was made (Figure 3) with colored thin-layer plaster.

The building is supplied with heat from the municipal heat network. Before its modernization, heat for central heating and ventilation was prepared in two group heat substations W1 and W2. The single-function W1 node heated half of building A and half of building B, while the second, W2, heated the remaining parts of the A and B buildings. The division of buildings A and B into two parts together with the location of group heat substations W1 and W2 is shown in Figure 1.

In building A, the central heating installation in 1979 was designed as a two-pipe pumping installation with lower separation with the parameters of 95/70 °C. The pipelines were made of black steel pipes joined by welding. In the basement, they were led under the ceilings of the room and covered with glass wool in a gypsum-adhesive coat. Before modernization, most of the rooms had cast iron radiators, covered with wooden housings, except for the ground floor and a few rooms on the second floor, where the cast iron radiators were replaced with new steel plate radiators. Most of the radiators were equipped with thermostatic valves. Despite previous modernization work, the pipes in the central heating system were in poor technical condition. The radiators were contaminated with internal corrosion products, which adversely affected the operation of thermostatic valves and control valves. Planned modernization projects [43] for central heating installations and heat sources are shown in Figure 5.

The modernization works concerning two heat sources (Figure 1) consisted of replacing the two over-exploited heat sub-stations with individual heat sources for each building. In building A, a new single-stage, compact heat substation with a plate heat exchanger was designed, which after modernization only works for heating purposes, supplying heat to building A. The maximum design parameters of network water were 120/55 °C and the average parameters of network water in the heating period were 83.8/45.2 °C. The amount of heat energy consumed for heating purposes in building A from the substation was determined using an ultrasonic heat meter. On the other hand, in building B, a second individual source was designed. A single-function heat substation was foreseen, cooperating with brine-water heat pumps and vertical ground heat exchangers [45,46].

Modernization works related to central heating installation in building A included the replacement of old, contaminated cast iron radiators with steel panel radiators, the installation of new thermostatic valves, and dismantling of wooden radiator covers. Central heating installation parameters were 70/50 °C. All horizontal central heating installation pipes were replaced with new ones and thermally insulated with thermal insulation of a thickness compliant with applicable regulations.

The work covers an analysis of thermal energy consumption in the period 2017–2020 for heating and ventilation purposes after thermomodernization only for building A.

2.2. Method of Determining the Cost-Optimal Variant for Individual Modernization Measures

For each external partition of the building, the cost-optimal variant was selected in the energy audit [43], according to the methodology in force in Poland [12]. For all partitions, the optimal thickness was determined, at which the simple payback time *SPBT* [years], determined according to the Formula (1), assumes the minimum value.

$$SPBT = \frac{N_u}{\Delta O_{rU}} \tag{1}$$

where:

N_u—the inputs needed to carry out the investment, [EUR],

ΔO_{rU}—annual savings in energy costs resulting from the application of the thermomodernization improvement [EUR/year], calculated using the Formula (2):

$$\Delta O_{rU} = \left(8.64 \cdot 10^{-5} \cdot HDD(t_i)_j \cdot \frac{A_i}{\Delta R}\right) \cdot O_z + 12 \cdot \left(10^{-6} \cdot A_i \cdot \frac{t_{in} - t_e}{\Delta R}\right) \cdot O_{\mathrm{m}}, \tag{2}$$

$HDD(t_i)_j$ —number of degree days of the heating season, [days·K/year],

A_i—the area of the partition, [m^2],

ΔR—the difference of the total thermal resistance of the assessed partitions, [(m^2·K)/W],

O_{z}—the variable fee connected with distribution and transmission of the energy unit, [EUR/GJ],

t_{in}—average indoor air temperature in the heating zone, [°C],

t_e—design outside air temperature for a given climatic zone, [°C],

O_{m} —monthly fixed fee related to energy distribution and transmission, [EUR/MW].

2.3. Theoretical Model for Calculating Thermal Energy Consumption and Total Efficiency of a Heating System

The annual consumption of useful thermal energy using the calculation method before and after thermomodernization was determined based on the PN-EN ISO 13790: 2009 standard [47] and the Regulation of the Minister of Infrastructure [48]. The calculations were made for each month of the heating season, from January to May and September to December included, assuming the number of days of the heating season in accordance with the standard for the Bialystok weather station. The calculated number of days of the heating season is 232 days, and the number of heating degree days (*HDDs*) in the standard heating season based on the multi-year outdoor temperatures from 1991–2020 is $HDD(t_{in})_0 = 3550.4$ day·K/year [49].

The monthly calculated useful heat demand for heating and ventilation before and after thermomodernization was determined based on the relationship (3):

$$Q_{H,nd,n\ (Th)} = (Q_{tr,n} + Q_{ve,n}) - \delta_{H,gh} \cdot (Q_{sol,gt} + Q_{int,gt}), \tag{3}$$

where:

$Q_{H,nd,n\ (Th)}$—monthly useful heat demand for heating and ventilation before and after thermomodernization, [GJ/month];

$Q_{tr,n}$—monthly heat losses by transmission, before and after thermomodernization, [GJ/month];

$Q_{ve,n}$—monthly heat losses through ventilation, before and after thermomodernization, [GJ/month];

$\delta_{H,gh}$—efficiency coefficient of the use of heat gains in heating mode, before and after thermomodernization, [-];

$Q_{sol,gt}$—heat gains from radiation using glazed partitions in a monthly period, before and after thermomodernization, [GJ/month];

$Q_{int,gt}$—internal heat gains in the monthly period, before and after thermomodernization, [GJ/month].

After calculating the annual useful heat energy consumption in the building, the annual final energy demand of the building before and after thermomodernization was determined based on the following relationship (4):

$$Q_{K,H(Th)} = \frac{\sum_{I-IV,IX-XII}^{month} Q_{H,nd,n(Th)}}{\eta_{h,g} \cdot \eta_{hs} \cdot \eta_{h,d} \cdot \eta_{h,e}}, \tag{4}$$

where:

$Q_{K,H\ (Th)}$—computational annual final heat energy demand for heating and ventilation in the building before and after thermomodernization, [GJ/year],

$\sum_{I-IV,\ IX-XII}^{month} Q_{H,nd,n\ (Th)}$—annual computational consumption of useful thermal energy in the building before and after thermomodernization, [GJ/year],

$\eta_{h,g}$—average seasonal, operational efficiency of the heat substation generation, before and after modernization, [-],

$\eta_{h,s}$—average seasonal, operational efficiency of the heat accumulation system in the heating system, before and after modernization, [-],

$\eta_{h,d}$—average seasonal, operational efficiency of heat transmission in the heating system, before and after modernization, [-],

$\eta_{h,e}$—average seasonal, operational efficiency of regulation and heat use, before and after modernization, [-].

The total computational efficiency of the heating system before thermomodernization was 63.94%, while after modernization it was 83.93% [43]. Calculations of the total efficiency of the heating system together with the values of partial efficiencies of heat generation, heat accumulation, heat transmission as well as the regulation and use of heat before and after modernization and with the mentioned works improving the efficiency of the heating system after modernization are presented in Table 4.

In Poland, the partial efficiencies presented in relation (4) should be determined on the basis of the Regulation [48], the technical documentation of the building, installation and heat sources, technical knowledge and a site visit, as well as the available catalog data of devices with installation elements.

Figure 6 shows the view of the W1 heat substation with an average operational production efficiency of 0.89 before modernization, while Figure 7 shows the modernized heat substation, working only for heating purposes of the building in part A, with an average operational efficiency of 0.95 [43,48].

Table 4. Summary of the efficiency of the heating system before and after modernization, together with works improving the efficiency of the heating system after modernization [43,48].

No.	Efficiency, Symbol	The Value of the Efficiency Coefficient [-]		Type of Modernization Improvement
		Existing State	Modernization	
1	Generation of heat, $\eta_{h,g}$	0.89	0.95	installation of a new heat substation operating solely for heating purposes in building A
2	Heat transmission, $\eta_{h,d}$	0.82	0.95	45% new heating installation, thermal insulation of pipes, rinsing the heating installation, hydraulic adjustment of the heating installation
3	Regulation and use of the heating system, $\eta_{h,e}$	0.88	0.93	assembly of plate heaters, thermostatic radiator valves, vertical control valves, automatic air vents
4	Heat accumulation, $\eta_{h,s}$	1.00	1.00	no change, no accumulation tank
5	Total system efficiency, $\eta_{h,tot}$	0.6394	0.8393	

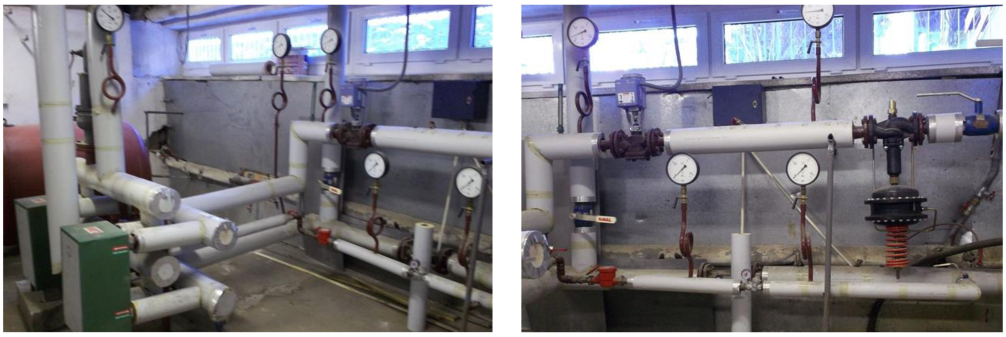


Figure 6. Technical condition of the W1 thermal substation and technological devices before modernization [photo authors].

Figure 7. View of the new heat substation and technological devices for building A after modernization [photo authors].

2.4. Methodology of Estimating the Actual Consumption of Thermal Energy

The monitoring of thermal energy consumption after the thermomodernization of building A covered the years 2017–2020. Measurement of the actual final thermal energy consumption $Q_{K,H\ (A)}$ was carried out using an ultrasonic heat meter installed in the modernized heat substation. In order to exclude seasonal fluctuations in external temperature changes that occurred before and after thermomodernization in 2017–2020, the values of the measured annual final thermal energy for central heating purposes were converted to standard seasonal conditions, taking into account the average external temperatures across many years (1991–2020) provided by the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) for the city of Bialystok [49].

For this purpose, the number of degree days ($HDDs$) of the heating season was determined for each year from dependence (5), and then the energy index of degree days ∂ was determined using dependence (6).

$$HDD(t_i)_j = \begin{cases} \sum_{j=0}^{n} \left[t_j(17.7\ ^\circ\mathrm{C}) - t_e\ (m)\right] \cdot L_d(m) & for\ t_e(m) < 15\ ^\circ\mathrm{C}, \\ 0 & for \quad t_e\ (m) > 15\ ^\circ\mathrm{C}. \end{cases} \tag{5}$$

where:

$HDD(t_i)_j$—number of degree days calculated for a base space heating temperature of 17.7 °C of each "j"-th month of the year and a limit temperature of 15 °C, [day·K/year],

t_j—average indoor air temperature in the heating zone, accepted for calculations +17.7 °C, [°C],

$t_e\ (m)$—monthly average outside air temperature in the given month of the "j"-th year, adopted on the basis of data provided by the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) for the city of Białystok, [°C],

$L_d\ (m)$—number of heating days in a given month during the heating season, [days].

The degree-days energy index was calculated as the ratio of the number of degree days of the standard heating season based on the data of external temperatures from the multi-year period (1991–2020) and the number of degree days of the heating season for the analyzed year based on the measured external temperatures in the "j"-th year.

$$\partial = \frac{HDD(t_{in})_0}{HDD(t_{in})_j}, \tag{6}$$

where:

$HDD(t_{in})_0$—number of degree-days calculated in standard year, [day/K·year], $HDD(t_{in})_0 = 3550.4$ dayK/year [12],

$HDD(t_{in})_j$—the number of degree days in a given "j"-th year, [day·K/year].

Table 5 presents the number of $HDDs$, which were calculated in accordance with Formula (5), which characterizes the heating season in a given year and the calculated degree-day energy index ∂, which was used to convert the actual final energy consumption to the standard heating season.

Table 5. Characteristics of "j"-th heating season based on the number of degree days and the energy index of degree days ∂ before and after thermomodernization.

Year	The Number of Degree-Days $HDD(t_{in})_0$ [day·K/year]	Degree Days Energy Index ∂ [-]	The Number of Degree-Days (1991–2020) $HDD(t_{in})_0$ [day·K/year]	Number of Days in the Standard Heating Season [days]
Before thermomodernization	3267.0	1.09	3550.4	232
2017	3291.9	1.08		
2018	3290.3	1.08		
2019	2966.0	1.20		
2020	2923.9	1.21		
Average 2017–2020	3118.0	1.14		

The measured final thermal energy consumption for heating $Q_{K,H\ (A)}$ was corrected for the standard heating season, in accordance with formula (7):

$$Q_{K\ (A)} = \frac{HDD(t_{in})_0}{HDD(t_{in})_j} \cdot Q_{K,H\ (A)}, \quad (7)$$

where:

$Q_{K\ (A)}$—annual heat energy (final energy) consumption, adjusted to standard conditions, [GJ/year] or [kWh/year], using a simple conversion, 1 GJ = 277.778 kWh.

$Q_{K,H\ (A)}$—measured actual annual thermal energy consumption (final energy) for heating purposes, [GJ/year].

The indicator of the annual final energy demand [kWh/(m^2·year)] for heating building A, including the state before and after thermomodernization, was calculated in accordance with Formula (8):

$$FE_{H(A)} = \frac{Q_{K\ (A)}}{A_F}, \quad (8)$$

where:

$FE_{H(A)}$ —annual final energy demand index for heating adjusted to standard conditions, [kWh/(m^2·year)],

$Q_{K\ (A)}$—annual final energy consumption for heating adjusted to standard conditions, [kWh/year],

A_F—heated area of the usable part of the building, [m^2]; $A_F = 7536.5$ m^2.

In addition to the annual final energy demand indicator, the article specifies a second indicator allowing for the energy assessment of the building after thermomodernization, namely the annual non-renewable primary energy demand indicator, which was calculated on the basis of Formula (9) and compared with the value before thermomodernization.

$$EP_{H(A)} = w_H \cdot FE_{H(A)}, \quad (9)$$

where:

$EP_{H(A)}$ —indicator of the annual demand for non-renewable primary energy for heating purposes, [kWh/(m^2·year)],

w_H—coefficient of expenditure of non-renewable primary energy for the production and delivery of the final energy carrier to building A in accordance with Polish regulations, [GJ/year], $w_H = 0.56$—calculated for the Enea Bialystok *CHP* plant [48].

(Enea is one of the producers and suppliers of electricity and system heat in Poland).

The energy effects obtained after the thermomodernization of building A were determined based on the following dependency (10):

$$Q_{K(A)}\% = \left(1 - \frac{Q_{K(A),1(avg)}}{Q_{K\ (A),0(avg)}}\right) \cdot 100\,, \quad (10)$$

where:

$Q_{K(A)}$%—percentage of final thermal energy saving after thermomodernization, [%],

$Q_{K(A),1(avg)}$—annual final thermal energy consumption for heating purposes after thermomodernization, [GJ/year],

$Q_{K\ (A),0(avg)}$—annual final thermal energy consumption for heating purposes before thermomodernization, [GJ/year].

2.5. Methodology of Estimating the Ecological Effects of Thermomodernizatiom

The article determines, on the basis of measured and theoretical values of final energy, the ecological effects that can be achieved by carrying out thermomodernization projects in a building along with the modernization of a heat source. The ecological analysis was limited to the savings that result from a reduction in energy consumption without the production stage of insulation materials as well as demolition and their disposal after use. Because the intention of the authors of this article was to present the effects for a specific investment (case study) in conditions which are directly influenced by the investor (he decides about the material used to insulate the building envelope, practically always on the basis of the price—ecology in the “scope of LCC” in Polish practice, unfortunately, there is no significance) no further extensive ecological analysis was carried out. The authors assumed that the CO_2 reduction effect, on which the investor deciding on a specific thermo-modernization element has a direct impact (its scope and materials and devices used) will be illustrated, which will improve the energy performance of the building (such indicators are used when selecting a specific investment, for example, for financing under various programs in the EU).

In order to determine the reduction of pollutant emissions to the atmosphere resulting from the combustion of fuels in the Enea Bialystok *CHP* Plant, the amount of pollutant emissions was calculated before its modernization according to Formula (11) and after the thermo-modernization, depending on relation (12).

$$EMp_{0\ (A)} = Q_{K\ (A),0(avg)} \cdot w_{i\ (e)}, \tag{11}$$

where:

$EMp_{0\ (A)}$—the amount of pollutant emissions in the existing state, [Mg/year],

$Q_{K\ (A),0(avg)}$—average annual final energy consumption before thermomodernization works, [GJ/year],

$w_{i\ (e)}$—the emission factor of the *i*-th pollutant during fuel combustion in the Enea Bialystok *CHP* Plant, [kg/GJ].

$$EMp_{1\ (A)} = Q_{K,HD,1\ (avg)} \cdot w_{i\ (e)}, \tag{12}$$

where:

$EMp_{1\ (A)}$—the amount of pollutant emissions after thermomodernization, [Mg/year],

$Q_{K,HD,1\ (avg)}$—average annual final energy consumption after the completion of thermomodernization works, [GJ/year].

When calculating the amount of emissions of pollutants CO_2, SO_x, NO_x and benzo(a)pyrene into the atmosphere in accordance with Formulas (11) and (12), the values of the emission factor of the *i*-th pollutant $w_{i\ (e)}$ were as follows: for the emission of sulfur dioxide $w_{SO_2} = 0.40$ kg/GJ; for nitrogen dioxide emissions $w_{NO_x} = 0.16$ kg/GJ; for carbon dioxide emissions $w_{CO_2} = 46.12$ kg/GJ and for benzo(a)pyrene emissions $w_{b(a)p} = 3 \cdot 10^{-5}$ kg/GJ, which are in line with the benchmark values given for CO_2 emissions by The National Center for Emissions Management in Poland (*KOBIZE*) for 2020 [50], and for SO_x, NO_x, and benzo(a)pyrene emissions in accordance with the National Center for Emissions Management [51]. The given values of the emission indicators were calculated as weighted average indicators based on the structure, percentage share, and technology of the fuels burned at the Enea Bialystok *CHP* plant.

The ecological effects obtained as a result of thermomodernization in the building were determined from Formula (13):

$$\Delta EM\%_{(A)} = \left(1 - \frac{EMp_{1\ (A)}}{EMp_{0\ (A)}}\right) \times 100 \tag{13}$$

where:

$\Delta EM\%_{(A)}$obtained ecological effects after thermomodernization, [%].

2.6. Methodology for Assessment of the Theoretical and Real Cost Effectiveness of Investments

In the article, two indicators for assessing the effectiveness of energy-saving projects, such as the cost of savings (*CS*) and the cost of energy savings (*CSE*) were used.

The CS index, calculated using Formula (14), expresses the ratio of the discounted expenditure, the costs of renovation and repair incurred as part of the implementation of a given modernization improvement to the discounted financial effects resulting from energy cost savings. For the project to be profitable, the value of the cost of the savings should meet the following condition: $0 < CS < 1$. Lower CS-values indicate a higher profitability of the investment.

$$CS = 1 - \frac{NPV}{\Delta O_{rH} \cdot UPW}, \tag{14}$$

where:

CS —cost of saving, [EUR/EUR],
ΔO_{rH}—annual savings in energy costs, [EUR/year],
UPW—the sum of the discount rate for the period in question,
NPV—Net Present Value, [EUR], calculated using Formula (15).

$$NPV = \sum_{t=1}^{25} \frac{1}{(1+i)^t} \cdot \Delta O_{rH} - N_o, \tag{15}$$

gdzie:

t—years of operation, [-]
i—discount rate, [%]
N_o—planned costs of works, [EUR].

The indicator CSE considers the investment cost required to save a unit of energy and is calculated using Formula (16). It expresses the ratio of costs incurred for a thermo-modernization investment to the amount of energy generated by savings resulting from the investment. The value of CSE should be compared to the unit costs of thermal energy supplied to the building. For the investment to be profitable, the value of CSE should be within the limits of $0 < CSE <$ unit variable fee connected with the distribution and transmission of the energy unit.

$$CSE = \frac{N_0}{\Delta Q_k}, \tag{16}$$

where:

CSE —cost of energy saving, [EUR/GJ],
ΔQ_k—annual saving of energy, [GJ/year].

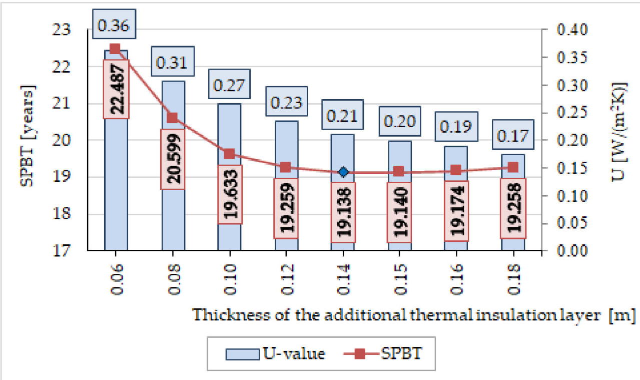
In the analyzed case study, CSE was determined by assuming the implementation of the investment within a year and failure-free operation for $t = 25$ years of calculating energy effects. The discount rate $i = 4.4\%$ was adopted. The unit variable fee connected with the distribution and transmission of the energy unit was EUR 9.25 EUR/GJ [42].

3. Results and Discussion

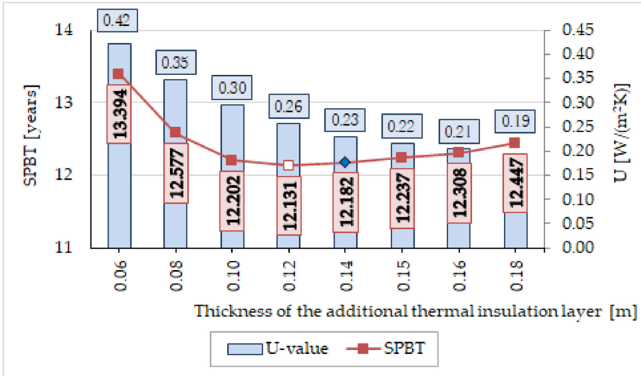
3.1. The Cost-Optimal Variant for Individual Modernization Measures

The performed thermomodernization of building A covers both the upgrade of the heating system and the building envelope improvement (Figure 5). The scope of thermo-modernization works and the technical and economic parameters were determined based on an energy audit of the building [42].

For each of the thermomodernized partitions of the building, the thickness of the insulation was optimized in accordance with Formula (1) and the thicknesses of insulation materials commonly available on the market were adopted. The results of optimization are shown in Figure 8.



(**a**)



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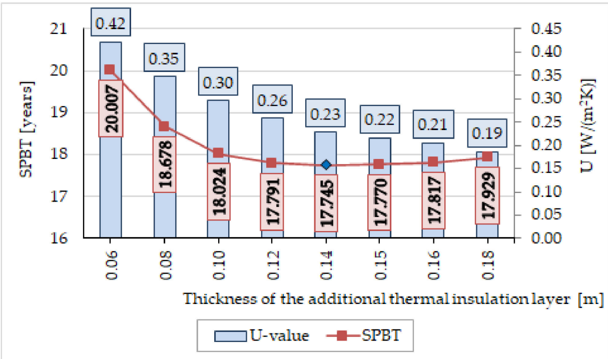

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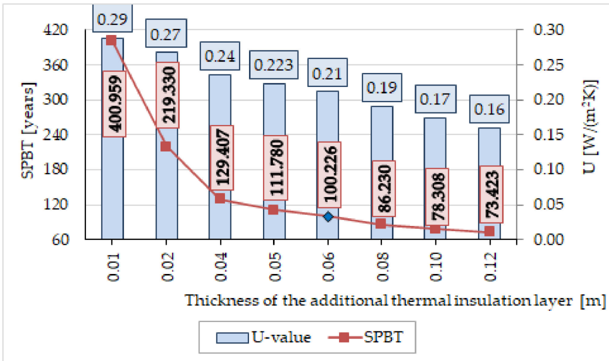

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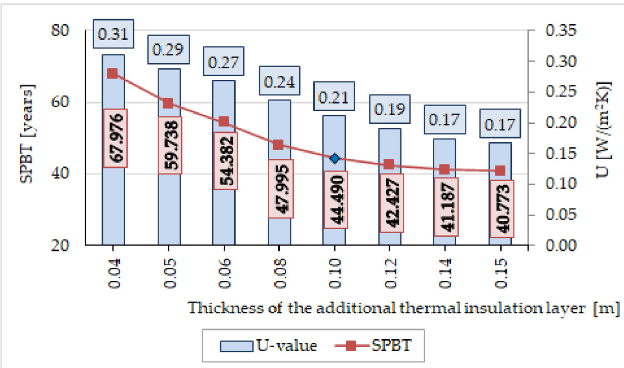

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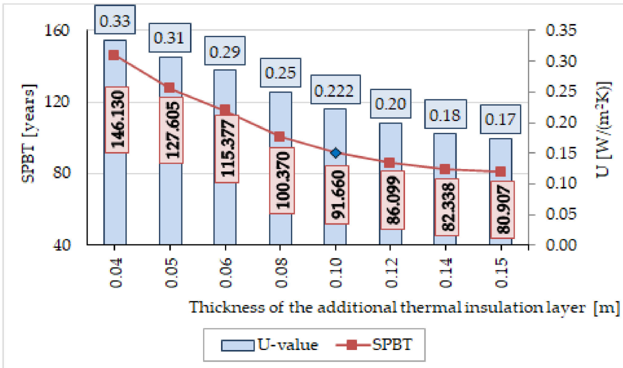

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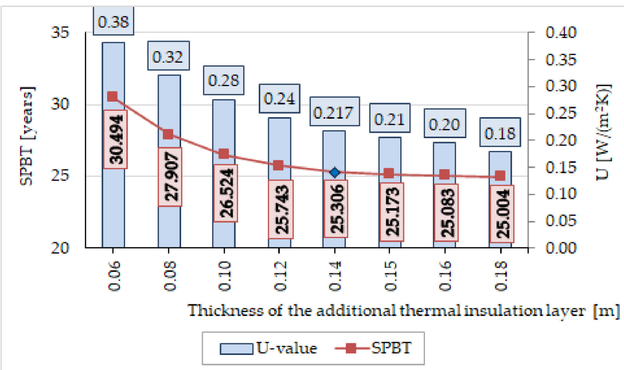

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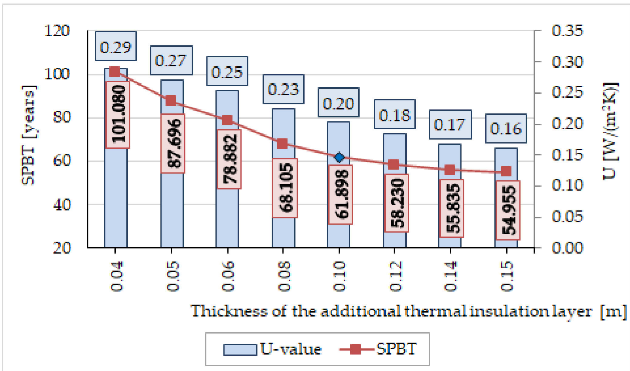

(**h**)

Figure 8. Results of optimization of the insulation thickness of building partitions along with an indication of the optimal, economical thickness of the thermal insulation of individual parts of the

building envelope: (**a**) external walls; (**b**) external walls of staircases; (**c**) external walls of basement; (**d**) roof; (**e**) roof over the staircases; (**f**) roof over the auditorium; (**g**) ceilings in loggias and recesses (above the basement); (**h**) ceiling under the outer ceiling of the auditorium and over the recesses at the entrances [own elaboration with using *U*-value data from [43].

The economically optimal insulation thickness should meet two, and in principle three conditions. The first (economic) condition relates to the Simple Payback Period (*SPBT*). The optimal insulation thickness is the one with the lowest *SPBT*-value. The second and third conditions concern an appropriate level of thermal insulation of partitions after thermomodernization, regulated by national regulations. At the stage of planning, the modernization investment in the analyzed building in Poland, the requirements for partitions in buildings undergoing thermomodernization (condition 2), were stricter than for partitions in newly designed buildings (condition 3), as presented in Table 1. For all of the analyzed external walls, except for external walls of staircases, the insulation thickness for which the *SPBT* was the shortest (condition 1), at the same time ensured condition 2 for the minimum value of the total thermal resistance of the partition after thermomodernization, specified in the Regulation [12] (condition 2). In the case of external walls of staircases, 14 cm was assumed as the thickness to be implemented, which meets condition 2, instead of 12 cm with a minimum *SPBT* (condition 1). At the same time, all the analyzed walls met the requirements of the minimum *U*-value of partitions, in line with the technical conditions applicable in Poland at that time [9] (condition 3). In the case of roofs and external ceilings, due to technical limitations, the criterion determining the optimal thickness was not the *SPBT* index (condition 1), but the required minimum value of the thermal resistance of the partition (condition 2) and, at the same time, the *U*-value of the partition (condition 3).

Table 6 summarizes the *U*-values of building partitions after thermomodernization in the building of part A, the type of insulation material, the thermal conductivity, and the determined optimal insulation thickness, in accordance with Figure 8 [43].

Table 6. List of the calculated values of thermal transmittance coefficients of building partitions after thermomodernization, along with the type of insulation material and the adopted optimal thickness [43,44].

No.	Part of the Building Envelope	Thermal Transmittance Coefficient after Thermomodernization *U*-Value [W/m^2 K]	Type of Insulating Material, Thermal Conductivity λ [W/m·K], the Optimal Thickness of the Thermal Insulation [cm]
1	External walls	0.21	Expanded polystyrene (EPS), λ = 0.04 W/m·K, 14 cm
2	External walls of staircases	0.23	Expanded polystyrene (EPS), λ = 0.04 W/m·K, 14 cm
3	External walls of basement	0.22; 0.24	Extruded polystyrene (XPS), λ = 0.04 W/m·K, 14 cm
4	Roof	0.21	roof panels made of mineral wool, λ = 0.04 W/m·K, 6 cm
5	Roof over the staircases	0.21	roof panels made of mineral wool, λ = 0.04 W/m·K, 10 cm
6	Roof over the auditorium	0.22	roof panels made of mineral wool, λ = 0.04 W/m·K, 10 cm
7	Ceilings in loggias and recesses (above the basement)	0.22	Expanded polystyrene (EPS), λ = 0.04 W/m·K, 14 cm
8	Ceiling under the outer ceiling of the auditorium and over the recesses at the entrances	0.20	Expanded polystyrene (EPS), λ = 0.04 W/m·K, 10 cm

A summary of the thermal transmittance coefficients of building envelope before and after thermomodernization is presented in Figure 9. The *U*-values have been significantly reduced. The smallest reduction (1.5 times) was achieved in the case of the roof, and the largest (more than 5 times) in the case of the external walls of the basement.

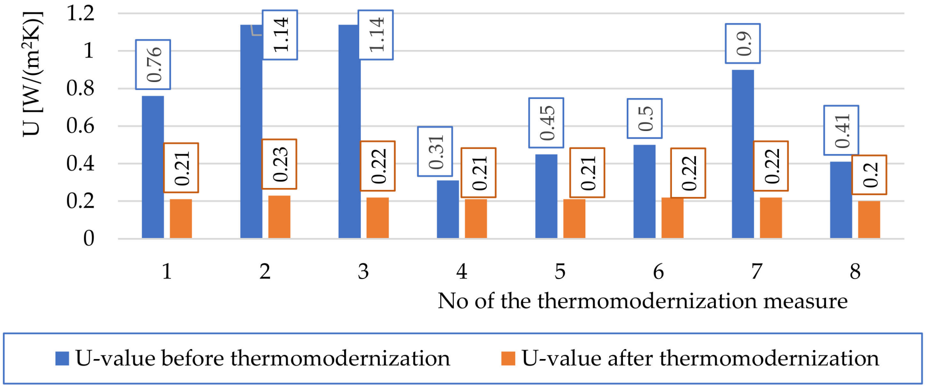

Figure 9. Calculated values of thermal transmittance coefficients before and after thermomodernization of the tested object for individual parts of the building envelope: 1—façade, 2—external walls of staircases, 3—external walls of basement, 4—roof, 5—roof over the staircases, 6—roof over the auditorium, 7—ceilings in loggias and recesses (above the basement), 8—ceiling under the outer ceiling of the auditorium and over the recesses at the entrances.

A view of building A after thermomodernization is shown in Figure 10. The reconstructed area, characteristic for the building red stripes along the building, under the windows, are visible.

Figure 10. The view of building A after thermomodernization with visible reconstruction, characteristic for the red stripes along the building, under the windows [photo authors].

3.2. Thermal Energy Consumption

A revealed by the theoretical model and the calculation method based on dependence (3), the annual usable energy consumption in the analyzed educational building was 1696.2 GJ/year before thermomodernization, and 1103.1 GJ/year after thermomodernization.

After taking into account the efficiency (Table 4), the final thermal energy consumption calculated in accordance with Formula (4) was 2651.9 GJ/year before thermomodernization, and after it was 1314.3 GJ/year (Table 7).

Table 7. The results of the theoretical calculations of the monthly consumption of useful thermal energy and final thermal energy in the tested building before and after thermomodernization.

No.	Month	Useful Thermal Energy [GJ]		Final Thermal Energy [GJ]	
		Before	After	Before	After
1	January	411.3	287.9	643.0	343.0
2	February	307.1	209.3	480.1	249.4
3	March	195.4	109.9	305.5	131.0
4	April	53.0	17.7	82.9	21.1
5	May	2.0	0.2	3.1	0.2
6	June	0.0	0.0	0.0	0.0
7	July	0.0	0.0	0.0	0.0
8	August	0.0	0.0	0.0	0.0
9	September	8.9	1.7	13.9	2.0
10	October	110.7	57.2	173.1	68.2
11	November	263.1	178.3	411.4	212.4
12	December	344.8	240.9	539.1	287.1
13	Annually	1696.2	1103.1	2651.9	1314.3

The measured actual amount of heat energy before thermomodernization was 2336.3 GJ/year, while after correcting for the energy factor of degree days ∂ (Table 5) it was 2539.0 GJ/year. Comparing the amount of measured, real energy before thermomodernization to the value calculated before thermomodernization, the difference amounts to only 4.3%. It can be concluded that the theoretical calculations included in the energy audit were made correctly, and the assumed calculation conditions, i.e., internal temperatures, multiple air changes in rooms, heat transfer coefficients, after an assessment of the technical condition of the central heating installation and heat sources (assumed efficiencies) were found to be close to real conditions.

A summary of the calculation results of theoretical usable thermal energy consumption for heating purposes and the building's final thermal energy demand before and after thermomodernization each month is presented in Table 7. The total efficiency of the heating system before thermomodernization was 0.6394, and after thermomodernization it was 0.8393 (Table 4).

After carrying out the thermomodernization improvements provided in the energy audit and presented in Figure 5, the theoretical calculated final energy consumption in the building decreased by 1337.6 GJ/year, which is a reduction of 50.4%.

An evaluation of the actual energy effects after thermomodernization was carried out on the basis of measurements obtained during the 4-year operation period. They were compared with the results of theoretical calculations after thermomodernization included in the energy audit and an attempt was made to describe the reasons for the discrepancies.

The actual heat demand of a building for central-heating purposes changes during the heating seasons, as each season may be different, as shown in Table 7. It is caused by changes in outdoor air parameters, such as outside temperature, insolation, amount of rainfall or direction, and the strength of the wind. During the transitional periods in Poland (in September–October, and April–May), i.e., in early autumn and spring, these changes cause large differences between the real and calculated heat demand. Hence, the measured final thermal energy consumption before and after thermomodernization was adjusted for the energy index of degree days ∂ in order to eliminate fluctuations in seasonal temperature changes and to standardize the parameters of the outside air.

Table 8 presents the measured annual values of final energy consumption in building A before and after thermomodernization in 2017–2020, together with the values corrected for the energy index of degree days ∂ (Table 5).

Table 8. Annual final thermal energy consumption in the tested building, measured before and after thermomodernization in 2017–2020 and converted to standard seasonal conditions.

No.	Year	The Measured Final Thermal Energy $Q_{K,H\,(A)}$ [GJ/year]	The Measured Final Heat Energy Corrected for the Factor ∂ $Q_{K\,(A)}$ [GJ/year]
1	Before thermomodernization	2336.3	2539.0
2	2017	1466.4	1581.8
3	2018	1277.1	1378.0
4	2019	1205.5	1443.1
5	2020	1151.7	1398.5

An assessment of the measured monthly final energy consumption after retrofit in 2017–2020 for each month (blue) compared to the value calculated after thermomodernization (green) is presented in a graphical form in Figures 11–14. In addition, the graphs show the computational final energy consumption before thermomodernization (gray) in each month of the heating season. The final energy consumption in each month presented in the graphs, measured with an ultrasonic heat meter, was corrected for the energy factor of degree days ∂ (Formulas (5) and (6)) and calculated according to the relationship (7). Figures 11–14 show the outdoor air temperatures for the multi-year period 1991–2020 (black curve) and the actual, measured average outdoor air temperatures in the studied year (red curve, Institute of Meteorology and Water Management), in order to show temperature differences in each heating season, which have an impact on the amount of heat energy consumed in the building. The graphs highlight the outdoor temperatures of the three coldest months of the heating season in Poland, which are December, January, and February.

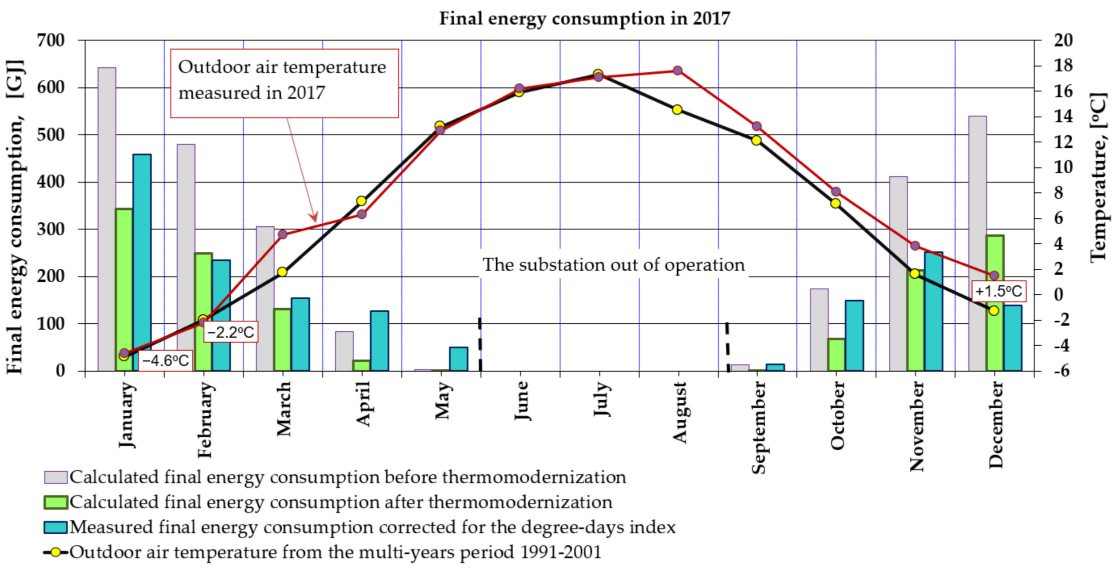

Figure 11. Final heat energy consumed for heating and ventilation needs of building A in 2017 and final energy corrected by the energy index of degree days ∂ together with the monthly outdoor air temperatures recorded in 2017 and the average outdoor air temperature for the multi-year period for the Bialystok weather station.

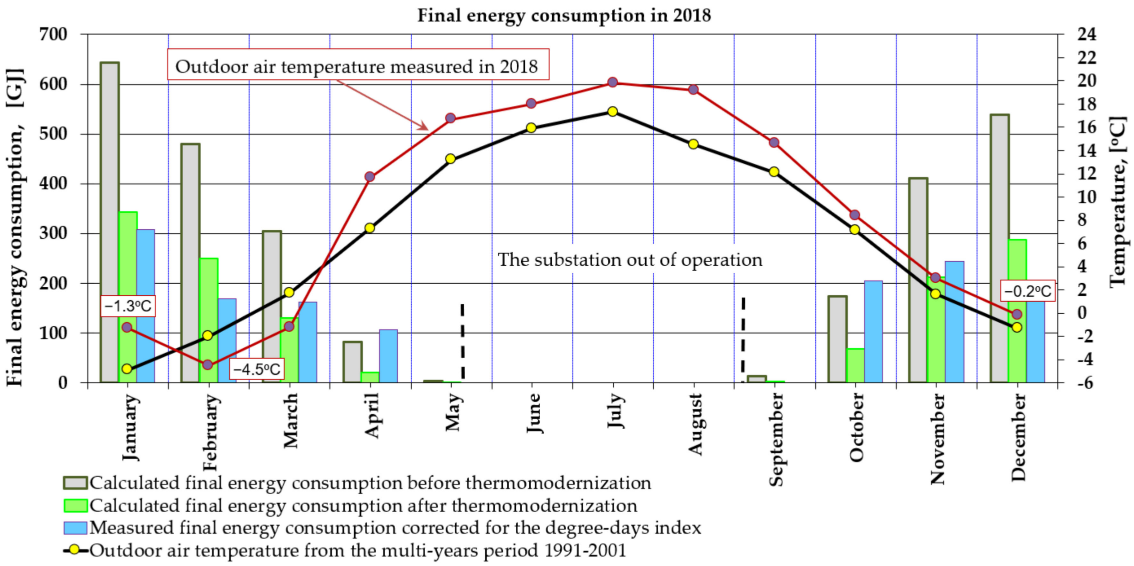

Figure 12. Final heat energy consumed for heating and ventilation needs of building A in 2018 and final energy corrected by the energy index of degree days ∂ together with the monthly outdoor air temperatures recorded in 2018 and the average outdoor air temperature for the multi-year period for the Bialystok weather station.

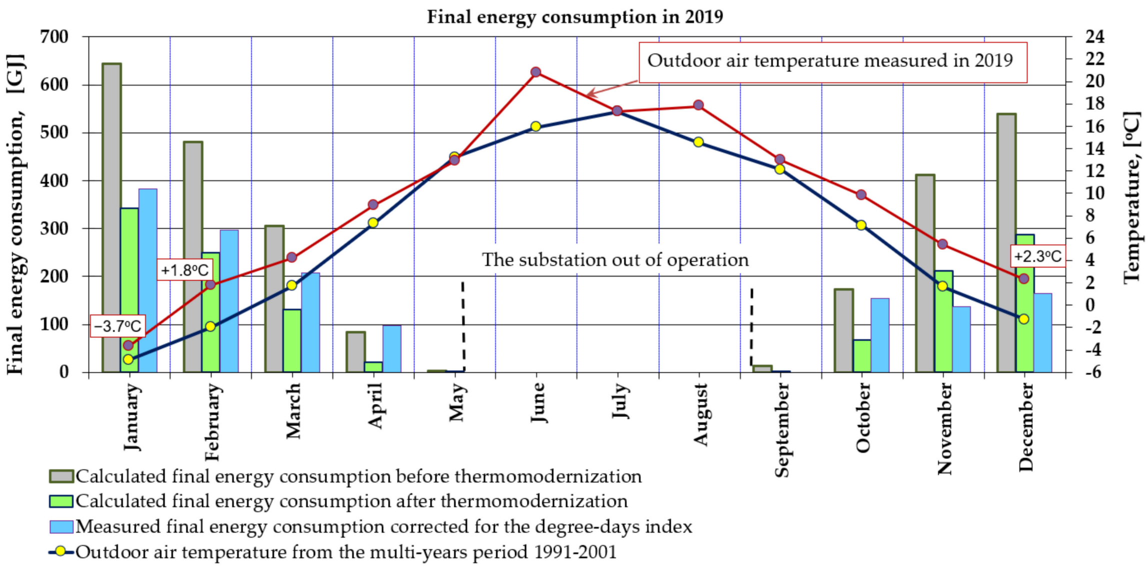

Figure 13. Final heat energy consumed for heating and ventilation needs of building A in 2019 and final energy corrected by the energy index of degree days ∂ together with the monthly outdoor air temperatures recorded in 2019 and the average outdoor air temperature for the multi-year period for the Bialystok weather station.

The typical heating season in this region of Poland lasts 232 days. The number of *HDDs* of the standard heating season based on the long-term external temperatures (1991–2020) is 3550.4 day·K/year (for the average calculated internal temperature in the building of +17.7 °C) [42], the average temperature of the standard heating season (for the months IX-XII and IV) is +3.8 °C, and for the three coldest months of the heating season in Poland (XII, I and II) it is −2.7 °C.

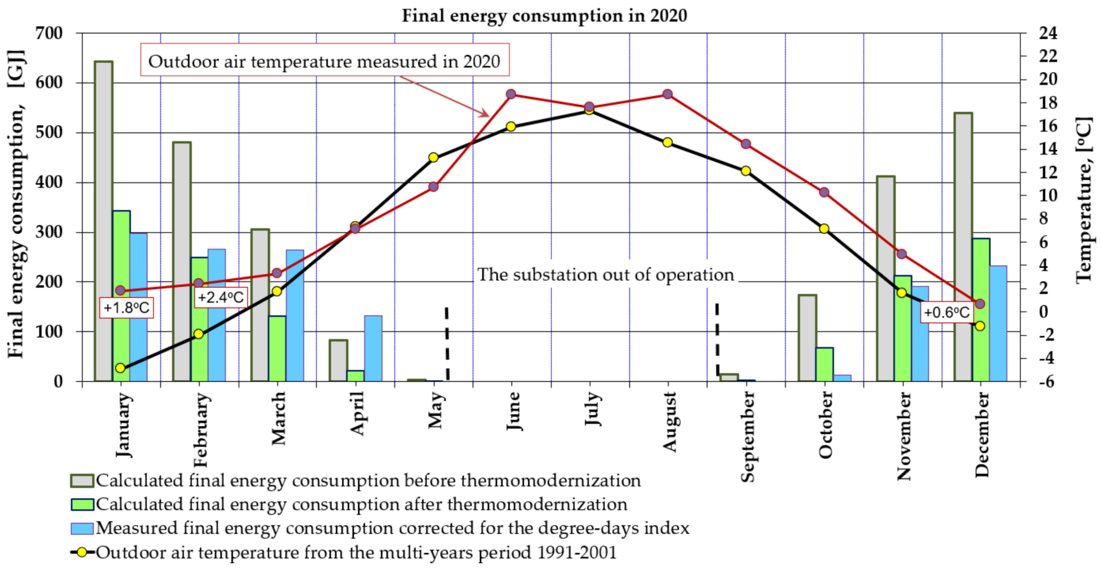

Figure 14. Final heat energy consumed for heating and ventilation needs of building A in 2020 and final energy corrected by the energy index of degree days ∂ together with the monthly outdoor air temperatures recorded in 2020 and the average outdoor air temperature for the multi-year period for the Bialystok weather station.

In 2017–2020, the average number of degree days was 3118.0 day·K/year, while the average energy index of degree days for the studied 4-year period was 1.14 (Table 5).

The longest heating season was recorded in 2017, the number of *HDDs* of the heating season was 3291.9 day·K/year, and the average seasonal outdoor temperature (for the months IX-XII and IV) was +4.9 °C while taking into account the months of XII, I and II the average temperature was −1.8 °C as shown in Figure 11. The measured thermal energy consumption in 2017 was 1581.8 GJ/year.

Very low outdoor temperatures were also recorded in 2018, where the average temperature was −2.0 °C (for the months of XII, I, II). The measured consumption of thermal energy in 2018 was 12.9% lower than that measured in 2017 and amounted to 1378.0 GJ/year. Thermal energy consumption in individual months is shown in Figure 12. This could probably be influenced by the gains from insolation in the building, which from the SE side it has a high number of glazed areas, as well as warranty repairs lasting one year after the completion of thermomodernization works. In 2018, the number of *HDDs* in the heating season was 3290.3 day·K/year, and the average seasonal outdoor temperature (for the months IX–XII and I–V) was +5.2 °C (Figure 12).

In the heating season (for the months IX-XII and IV), the sum of the total solar radiation intensity on the surface with SE orientation and inclination to the level of 90 °, based on the multi-year data was 988.6 kWh/(m^2·season). This value was adopted when calculating the theoretical gains from insolation in the building. In the case of the measured values, the intensity of solar radiation differed depending on the heating season. In 2017 it was 826.0 kWh/(m^2·season), in 2018 it was 1252.3 kWh/(m^2·season), in 2019 it was 1104.3 kWh/(m^2·season), and in 2020 it was 1081.7 kWh/(m^2·season) [48]. This fact meant that in 2017 the gains of thermal energy from solar radiation amounted to approx. 84%, and in 2018 to as much as 127% compared to the calculated ones. In 2019 and 2020, they were at 112% and 109% of computing gains, respectively.

In 2019, an increase in final energy consumption was recorded in the building by 4.5% compared to 2018. The measured thermal energy consumption in 2019 was 1443.1 GJ/year, consumption for specific months is shown in Figure 13. The likely increase in heat consumption in the building after thermomodernization in 2019 could be associated with lower gains, by 148 kWh/(m^2·season), from insolation compared to 2018, and to some extent, it could also be influenced by the way of use, e.g., no lowering of temperatures in classrooms by means of thermostatic valves when airing the rooms. In 2019, the number of degrees days in the heating season was 2966.0 day·K/year, and the average seasonal outdoor temperature (for months IX-XII and IV) was +6.1 °C but while taking into account only the months of XII, I, and II, the average temperature was +0.1 °C as shown in Figure 13.

The shortest heating season was registered in 2020, the number of $HDDs$ of the heating season was 2923.9 day·K/year, and the average seasonal outdoor temperature (for the months IX-XII and IV) was +6.2 °C, while taking into account only the months of XII, I and II the average temperature was +1.6 °C as shown in Figure 14. The measured thermal energy consumption in 2020 was 1398.5 GJ/year.

Based on the theoretical data of the annual final energy demand before and after thermomodernization (Table 7) and the measured thermal energy before and after the thermomodernization was corrected by the degree-day index (Table 8), after taking into account the heated area (with regulated temperature) of building A, the annual demand index was calculated at a final energy of $FE_{H(A)}$[kWh·m^{-2} ·year^{-1}] according to Formula (8). The calculation results of the theoretical and real seasonal energy demand index before and after thermomodernization are presented in Table 9.

Table 9. The theoretical and real indicator of seasonal final energy demand $FE_{H(A)0,1}$ before and after thermomodernization in 2017–2020 in the tested building A.

Final Heating Energy Indicator [kWh·m^{-2} ·year^{-1}]						
State before Thermomodernization $FE_{H(A),0}$		**State after Thermomodernization $FE_{H(A),1}$**				
Theoretical	**Real**	**Theoretical**	**Real**			
			2017	2018	2019	2020
97.74	93.58	48.44	58.30	50.79	53.19	51.55

The theoretical indicator of the seasonal demand for final energy before thermomodernization was 97.74 kWh·m^{-2}·year^{-1}, and after thermomodernization, it was 48.44 kWh·m^{-2}·year^{-1}. The measured amount of thermal energy after thermomodernization on the basis of which the final heating energy index was determined changed in the years 2017–2020 in the range from 58.30 kWh·m^{-2} ·year^{-1} to 50.79 kWh·m^{-2} ·year^{-1}.

Based on Table 9, it can be seen that there is a significant difference between the indicators in the first year of operation after thermomodernization (2017) and the following years (2018–2020). There is also a visible difference between the theoretical indicator amounting to 48.44 kWh·m^{-2} ·year^{-1} and the values of real indicators which are within the range of 50.79–58.30 kWh·m^{-2} ·year^{-1}.

3.3. The Reduction of Thermal Energy Consumptions

The reduced final energy ratios determined on the basis of energy consumption in 2018, 2019 and 2020 compared to 2017 are the result of the overlapping effects of warranty repairs and supplementary works performed during this period after the thermal insulation of the building, the modernization of central heating installations and heat sources by contractors, and the difference in profits from solar radiation. These profits ranged from approx. 811 GJ in 2017 to 1267 GJ in 2018; in 2019 and 2020, they amounted to approximately 1082 GJ and 1053 GJ, respectively.

Examples of photos from the stage of thermal insulation works, with errors that required improvement, are presented in Figure 15. After removing the existing facade layer of ceramic tiles, a very uneven wall surface was obtained (Figure 15a). Its equalization was not always possible in such a way that the thermal insulation adhered closely to the wall surface. This resulted in a significant gap (2–4 cm) of the polystyrene layer from the existing face of the wall (Figure 15b). This was the reason for the local reduction in the thermal insulation of the wall after thermomodernization. The fastening of polystyrene boards causing point thermal bridges (the heads of the anchors are not secured with polystyrene, but with adhesive mortar), is shown in Figure 15c. Point bridges are small (plastic anchors are used, not metal ones) and their removal is practically impossible after the façade has been made. On the other hand, the problems resulting from the fragmentary lack of adhesion of the thermal insulation to the face of the wall were eliminated by sealing the places of the base strip and the places where windowsills are installed. These treatments have resulted in marked effects in the form of lowering the energy consumption for heating.

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

Figure 15. Examples of photos from the thermomodernization stage of the building: (**a**) uneven wall; (**b**) the gap between the polystyrene and the wall; (**c**) point thermal bridges [photo authors].

In accordance with relationship (9), the theoretical indicator and real indicator of demand for non-renewable primary energy $EP_{H(A)0,1}$ [kWh·m^{-2} ·year^{-1}] before and after thermomodernization were calculated, the values of which are presented in Table 10.

Table 10. Theoretical and real indicator of non-renewable primary heating energy $EP_{H(A)0,1}$ before and after thermomodernization in 2017–2020 in building A.

Non-Renewable Primary Heating Energy Indicator [kWh·m^{-2} ·year^{-1}]						
State before Thermomodernization $EP_{H(A),0}$		**State after Thermomodernization $EP_{H(A),1}$**				
Theoretical	**Real**	**Theoretical**	**Real**			
			2017	2018	2019	2020
54.74	52.41	27.13	32.65	28.44	29.79	28.87

The highest value of the non-renewable primary energy indicator determined on the basis of actual heat consumption was recorded in 2017 and it was 32.65 kWh·m^{-2} ·year^{-1}, while the lowest was in 2020 and was 28.87 kWh·m^{-2} ·year^{-1}. The value of the indicator is closely related to the final heating energy index and depends on the coefficient of non-renewable primary energy expenditure for the production and delivery of the final energy carrier to the building. For the calculations, the calculated coefficient was adopted based on the structure of the fuel burned, percentage shares, and technologies of the fuels burned in the Enea Bialystok *CHP* plant, amounting to $w_H = 0.56$.

The calculated theoretical (in line with the energy audit) indicator of primary non-renewable energy before thermomodernization was 54.74 kWh·m^{-2} ·year^{-1}, and after thermal modernization, it was 27.13 kWh·m^{-2} ·year^{-1}.

The energy effects obtained after thermomodernization of building A were determined based on dependency (10). In the case of the calculation method, the annual final energy saving was 50.4%, while in the case of the assessment of the actual energy effects, it was from 37.7% (2017) to 44.9% (2020). The annual final theoretical, calculated and measured energy savings are included in Table 11.

Table 11. Annual final energy savings in the tested building A in 2017–2020.

Year	Annual Final Energy Savings $Q_{K(A)}\%$ [%]	
	Real	Theoretical
2017	37.7	50.4
2018	45.7	
2019	43.2	
2020	44.9	
average	42.9	

3.4. Ecological Effects of Thermomodernizatiom

In order to determine the reduction in the emission of pollutants into the atmosphere resulting from the combustion of fuels in the Enea Bialystok *CHP* Plant, the amount of pollutant emissions was calculated before modernization according to Formula (11) and after the thermomodernization according to relationship (12).

The calculation results of theoretical and measured pollutant emissions are presented in Table 12.

Table 12. The amount of pollutant emissions before and after thermomodernization, both the theoretical and real values [Mg/year].

Type of Contamination	The Amount of Pollutant Emissions [Mg/year]						
	State before Thermomodernization		State after Thermomodernization				
	Theoretical	Real	Theoretical	Real			
				2017	2018	2019	2020
CO_2	122.31	117.1	60.62	72.95	63.56	66.56	64.5
SO_x	1.06	1.02	0.53	0.63	0.55	0.58	0.56
NO_x	0.42	0.39	0.21	0.25	0.21	0.22	0.22
b(a)p	8×10^{-5}	8×10^{-5}	4×10^{-5}	5×10^{-5}	4×10^{-5}	4×10^{-5}	4×10^{-5}

The emission of pollutants is strictly dependent on the combustion technology or type of fuel used, and the amount of final energy used for heating and ventilation purposes. After the thermomodernization of building A, along with the modernization of the heat source, the emission of pollutants into the atmosphere was reduced. As a result of deep thermomodernization in part A of the building, on the basis of theoretical calculations in accordance with the energy audit [42], a reduction in the emission of CO_2, NO_x, SO_x and b(a)p was achieved. The reduction of individual compounds was as follows: CO_2 -61.69 Mg/year, NO_x -0.54 Mg/year, SO_x -0.21 Mg/year, and in the case of benzo(a)pyrene, the emission reduction was $4{\cdot}10^{-5}$ Mg/year.

On the other hand, taking into account the reduction of pollutant emissions based on the measured values, the reduction in pollutants for 2017–2020 was as follows: CO_2 from 44.15 to 53.55 Mg/year; NO_x from 0.15 to 0.18 Mg/year; SO_x from 0.38 to 0.46 Mg/year, and in the case of benzo(a)pyrene, the emission reduction was 3×10^{-5} Mg/year.

The obtained ecological effects determined in accordance with Formula (13), both with the theoretical method and based on actual measurements of heat consumption in the building in 2017–2020, are presented in Table 13.

Table 13. Percentage reduction of pollutant emissions after thermomodernization in the building A on the basis of the theoretical model and measurement method of thermal energy consumption.

<table>
<tr><th rowspan="3">Type of Contamination</th><th colspan="5">Percentage Reduction of Pollutant Emissions[%]</th></tr>
<tr><th rowspan="2">Theoretical</th><th colspan="4">Real</th></tr>
<tr><th>2017</th><th>2018</th><th>2019</th><th>2020</th></tr>
<tr><td>CO_2</td><td>50.4</td><td>37.7</td><td>45.7</td><td>43.2</td><td>44.9</td></tr>
<tr><td>SO_x</td><td>50.4</td><td>37.7</td><td>45.7</td><td>43.2</td><td>44.9</td></tr>
<tr><td>NO_x</td><td>50.4</td><td>37.7</td><td>45.7</td><td>43.2</td><td>44.9</td></tr>
<tr><td>b(a)p</td><td>50.4</td><td>37.7</td><td>45.7</td><td>43.2</td><td>44.9</td></tr>
</table>

Based on the calculations of the theoretical method, a reduction in CO_2, NO_x, SO_x, and b(a)p pollutant emissions was achieved, of 50.4%, while the reductions obtained in 2017–2019 and based on actual measurements of thermal energy consumption ranged from 37.7% to 44.9%.

3.5. Cost Effectiveness of Investments

Table 14 summarizes the costs planned in the audit and real incurred costs for the thermomodernization of the analyzed building. Percentage underestimation and overestimation of the amount of investment costs were specified.

Table 14. Comparison of planned cost in the energy audit and the real costs of the thermomodernization investment in the analyzed building.

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">Activities to Achieve the Reducing Energy Consumption</th><th colspan="2">Investment Costs [EUR]</th><th rowspan="2">The Difference between Theoretical and Real Costs [%]</th></tr>
<tr><th>Theoretical [42]</th><th>Real</th></tr>
<tr><td>1</td><td>Thermal insulation of a façade</td><td>84,327</td><td rowspan="2">186,582</td><td rowspan="2">96.9</td></tr>
<tr><td>2</td><td>Thermal insulation of external walls of staircases</td><td>10,454</td></tr>
<tr><td>3</td><td>Thermal insulation of external walls of basement</td><td>29,382</td><td>146,046</td><td>397.1</td></tr>
<tr><td>4</td><td>Thermal insulation of roof</td><td>66,731</td><td rowspan="3">86,939</td><td rowspan="3">−6.4</td></tr>
<tr><td>5</td><td>Thermal insulation of roof over the staircases</td><td>1462</td></tr>
<tr><td>6</td><td>Thermal insulation of roof over the auditorium</td><td>24,678</td></tr>
<tr><td>7</td><td>Thermal insulation of ceilings in loggias and recesses (above the basement)</td><td>1445</td><td rowspan="2">11,434</td><td rowspan="2">127.6</td></tr>
<tr><td>8</td><td>Thermal insulation of ceiling under the outer ceiling of the auditorium and over the recesses at the entrances</td><td>3579</td></tr>
<tr><td>9</td><td>Replacement of roof skylights</td><td>-</td><td>3414</td><td>100</td></tr>
<tr><td>10</td><td>Replacement of lightning protection system</td><td>-</td><td>10,569</td><td>100</td></tr>
<tr><td>11</td><td>Replacement of the central heating</td><td rowspan="2">130,765</td><td>87,889</td><td rowspan="2">−7.32</td></tr>
<tr><td>12</td><td>Construction of the heat substation</td><td>33,309</td></tr>
<tr><td colspan="2">Total:</td><td>352,823</td><td>566,182</td><td>60.5</td></tr>
</table>

The theoretical total cost (estimated in 2012 in the energy audit) of thermomodernization work in the analyzed case study, in relation to a square meter of heated usable area, was 217 EUR/m^2. This value turned out to be 28% higher than the average for the deep modernization carried out in Poland in 2013, in the group of non-residential buildings [8].

The largest difference in the amount of the planned investment costs and the real costs was noticed in the case of the insulation of basement walls (by almost 400%). This was due to the need to perform additional work which often occurs in practice, and is usually unforeseen at the audit stage, which was mainly related to drying the existing walls and making damp-proof insulation to protect the new thermal insulation against the harmful effects of moisture. In the event of improvements consisting of thermal insulation of the roofs and modernization of the central heating system and heat sources, the actual costs were approximately 7% lower than planned. Overall, the total cost of the thermomodernization investment turned out to be 60.5% higher than that planned in the energy audit.

Assuming a discount rate of 4.4% and a 25-year savings period, the *CS* and *CSE* economic indicators were calculated using Formulas (14)–(16). The results are shown in Figures 16 and 17.

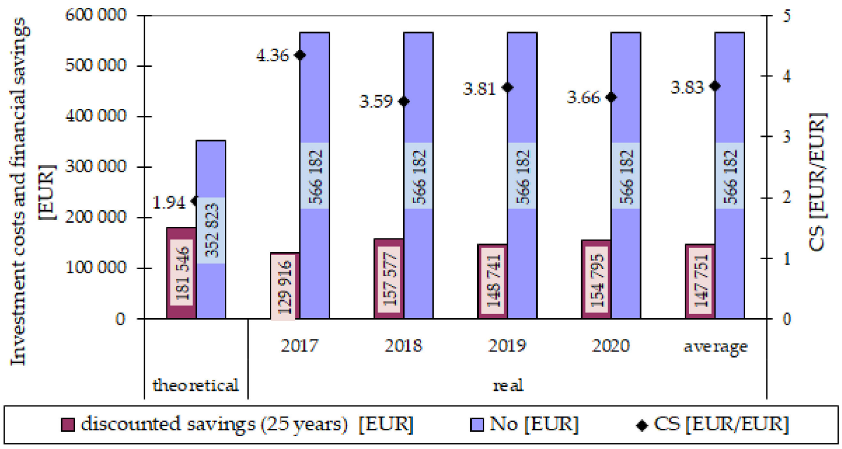

Figure 16. Financial outlays and savings as well as the *CS* index of deep thermomodernization carried out in the analyzed building.

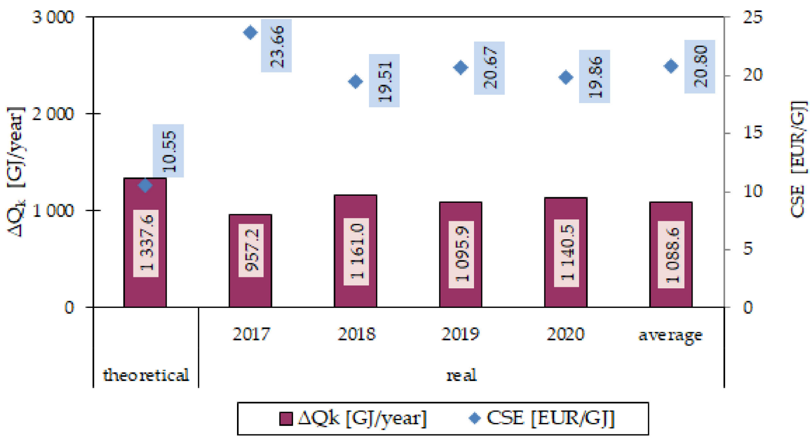

Figure 17. Annual energy savings and the *CSE* index of a thermomodernization investment in the analyzed building.

None of the *CS*-values presented in Figure 15 met the economic efficiency condition of $0 < C < 1$. The C value determined for investment outlays and savings based on the performed energy audit, i.e., at the planning stage of the thermomodernization investment, was 1.94 EUR/EUR and exceeded the upper value of the economic efficiency condition by 94%. The value of the *CS* index with real costs and savings was much higher and amounted to 3.59–4.26 EUR/EUR (the average value from the 4 years analyzed was 3.83 EUR/EUR). This clearly shows that for such investments, which are necessary for the energy policy and environmental reasons, to be undertaken by the investor, they should receive financial support.

The analysis of the obtained values of the CSE index (Figure 17) shows that the cost of saving a unit of energy was over two times higher than the unit cost of purchasing thermal energy (amounting to 9.25 EUR/GJ). The slightly more favorable value of the CSE index, which exceeded the upper limit of profitability by only 14.1%, resulted mainly from underestimating, by almost 40%, the amount of planned investment costs in the energy audit (Table 14).

4. Conclusions

The analysis carried out in this paper concerns a specific building, however, it provides information on the real energy and ecological savings that can be achieved after the deep thermomodernization of a large educational building, in the conditions of a temperate continental climate. It also provides information on the profitability of investing funds in improving the energy standard.

Correctly performed thermal calculations for planned investments improving energy performance, verified by comparison with the real consumption of energy, do not guarantee the achievement of the same effects that were predicted during theoretical calculations. In the analyzed case study, the real energy consumption reduction in 2017–2020 varied from 37.7% to 45.7% which gives an average of 43%, and the planned reduction in energy consumption based on the energy audit was approximately 50.4%. In our case, the real reduction in energy consumption was almost 7% lower than the theoretical value. The achieved real reduction of CO_2, NO_x, SO_x, and b(a)p pollutant emissions to the atmosphere was also lower by 7% than the theoretical reduction.

Significant disturbances of the energy and environmental effects achieved may result from the shortcomings or errors made at the construction stage, as well as non-standard operating and meteorological conditions.

Measurements of energy consumption and analyses made for the building in question also show the possibilities and effects of repairing errors made at the construction stage. Therefore, it seems important to introduce, in this type of investment, recommendations for obligatory thermal imaging measurements before and after construction works. Control thermovision inspections will allow for the identification and elimination of those places which, during the subsequent operation of the building, will increase the consumption of thermal energy, or may cause technical and operational problems.

The theoretical calculated final heating energy indicator before thermomodernization in building A was only 4.3% higher than the real one. It is 97.74 $kWh \cdot m^{-2} \cdot year^{-1}$, while the real one is 93.58 $kWh \cdot m^{-2} \cdot year^{-1}$.

After thermomodernization, the theoretical final heating energy indicator of heating was 48.44 $kWh \cdot m^{-2} \cdot year^{-1}$, and the average real final energy index for 2017–2020 was 53.46 $kWh \cdot m^{-2} \cdot year^{-1}$ and was higher by 9.4%.

Energy efficiency does not always go hand in hand with economic efficiency. In the analyzed building, the economic efficiency was not satisfactory. The cost of saving a unit of energy was more than 2 times higher than a paid fee per unit of thermal energy. Namely, the cost of energy saving was 20.80 EUR/GJ with the purchase cost of thermal energy amounting to 9.25 EUR/GJ. For this reason, it was necessary to use the financial support dedicated to projects aimed at improving the quality of the environment.

When planning the thermomodernization of a large educational building, possible changes in investment costs should be considered, especially when the investment process is stretched over time. In the analyzed case study, the difference between the real costs and the costs estimated in the energy audit (prepared 4 years before the investment implementation) amounted to as high as 60.5%. Therefore, it is recommended to assume higher investment costs at the planning stage if the work is to be carried out much later.

A properly prepared investment of deep thermomodernization, based on an energy audit and other methods of thermal diagnostics of the building, leads to significant energy and ecological effects. These effects can be significantly increased by changing the heat source to a more environmentally friendly one.

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