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Analysis of the Influence of Selected Factors on Heating Costs and Pollutant Emissions in a Cold Climate Based on the Example of a Service Building Located in Bialystok

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Abstract: In recent years, due to the rapidly growing global energy crisis and the ever-increasing prices of energy carriers, more attention has been paid to the energy efficiency of existing buildings, especially in the context of reducing harmful emissions and lowering heating costs. The purpose of this study was to analyse the influence of selected factors on heating costs and air pollution in a cold climate based on the example of a service building located in Bialystok, Poland. The following scenarios were assumed: the implementation of a heating schedule, improvement of the thermal insulation of the building envelope, lowering of the indoor temperature in all rooms, and moving away from a traditional heat source (gas boiler) to renewable energy (heat pump). The results showed that improvements in heat transfer coefficients had the greatest impact on reducing heating costs and that emissions from renewable energy sources depend largely on the national energy mix.

Keywords: heating costs; environmental pollution; renewable energy; heat pumps; operating schedule; operating temperatures

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1. Introduction

Recently, in light of the rapidly growing global energy crisis and ever-increasing prices of energy carriers, more attention has been paid to the energy performance of buildings—both newly designed as well as existing, as evidenced by the analyses in [1–4]. Taking into account that more than half of buildings were built before 1960 [5], improving the energy efficiency of the latter appears to be justified and could make a real contribution to reducing the heating energy needs in the building sector and limiting carbon dioxide (CO_2) emissions into the atmosphere.

Responding to the need to align existing regulations with the goals and objectives of the "Fit for 55 Package", on 15 December 2021 the European Commission published the new proposal for the Energy Performance of Building Directive (EPBD) [6]. With regard to existing buildings, a new definition has been introduced for the term "deep renovation", which is to be understood as the transformation of a building into a "nearly-zero-emission building" (by 2030) or a "zero-emission building" (after 2030). Furthermore, reviewing national building renovation plans to include a roadmap and national targets by 2030, 2040, and 2050 becomes mandatory, and Member States are required to ensure that public and non-residential buildings are at least class F by 2027 and class E by 2030, while all residential buildings will be class F by 2030 and class E by 2033 [7].

Achieving this means renovating 15% of the current building stock, estimated at around 40 million buildings across the EU [7], and represents the only way to reduce a building's energy needs and thus lower the (currently very high) heating costs. Unfortunately, many techno-economic analyses [8–11] prove that although the renovation of existing buildings significantly reduces operating costs, it is an extremely expensive solution in terms of investment cost. Therefore, the need to find the most economically efficient and optimal solutions leading to a low final energy rate is becoming the motivation for much scientific research and numerous analyses.

Heide et al. [5] compared eight different heat pump-based HVAC combinations using two buildings with different levels of envelope performance. The simulations showed that a low final energy demand can be achieved through a balance between investments in increasing the energy efficiency of the building envelope and in HVAC systems. In addition, it was proven that heat pumps can make a significant contribution to reducing a building's energy consumption.

Firląg, as part of his research [12], proposed the possible requirements for a cost-optimal energy building in a cold climate dominated by heating and based on investment and operating cost calculations. He verified which is more cost-effective—reduction in energy demand or increase in production from renewable energy sources. The results of the study showed that, economically, the most advantageous was the NF40 low-energy building variant with an air-source heat pump.

Hałacz et al. [13] analysed and compared different variants of heating and ventilation systems and determined pollutant emissions for selected variants. They found that energy consumption was an important factor in the selection of heating and ventilation systems, and its value was affected by the thermal insulation of the building envelope, the presence of thermal bridges, and the tightness of the building. However, they stated that measures to improve the energy efficiency of single-family homes should not only increase the insulation of the building envelope, but also include the modernization of heating systems and the installation of mechanical ventilation systems with heat recovery.

Rivoire et al. [14] analysed the use of a ground source heat pump (GSHP) in different buildings (residential, office, hotel) and climates. They verified how climate, thermal insulation, and building use affect system performance, annual energy consumption, cost-effectiveness, and environmental benefits compared to traditional systems. They proved that proper (compliant with current regulations) thermal insulation is capable of reducing a building's heating demand by up to 70–90% compared to standard 1950s insulation levels.

Franco et al. [15] in their study evaluated the prospect of achievable energy savings in a non-residential (academic) building in Pisa. They estimated that energy savings of 44% could be reached, and that a significant part (33%) thereof is guaranteed by the use of demand-controlled ventilation.

Roccatello et al. [16] found that heating and DHW in existing building stock, which consists mainly of uninsulated or poorly insulated buildings, was the major contributor to energy consumption in the residential sector, and that hybrid heat pump systems could be a viable solution to increased energy efficiency, especially for this type of building.

Vijay and Hawkes [17] have shown that heat pumps—the most efficient heating technology—are closely related to the electricity price system. How the price is shaped for the consumer will have a significant impact on heating technology.

Siudek et al. [8] analysed several home construction and heating source scenarios, comparing investment and operating costs, and potential emission reduction. They proved that with an increase in thermal insulation and the use of renewable energy sources, construction costs increase, but the energy costs of operating the house definitely decrease. Based on the results, they also found that, in addition to bringing newly built structures up to current standards, even greater benefits can arise from retrofitting existing rural homes, extending environmental benefits and generating savings in household energy bills.

According to the studies discussed above, as well as an additional literature review [18–26], it can be seen that the improvement of the energy efficiency of buildings is achieved by increasing the insulation of the building envelope and the tightness of the window frames, rational energy consumption, and moving away from traditional heat sources, such as a coal-fired or gas boiler, to renewable energy. Moreover, as mentioned in [15], among the most important elements in improving the energy performance of large non-residential buildings is the proper management and control of the heating, ventilation, and air conditioning (HVAC) system.

The purpose of this research was to analyse the impact of selected factors on heating costs and environmental pollution in a cold (heating-dominated) climate based on the example of a service building located in Bialystok, Poland. The scenarios assumed were: (1) the implementation of a heating schedule, (2) improvement of the thermal insulation of the building envelope, (3) lowering of the indoor temperature in all rooms by 1 °C, and (4) moving away from a traditional heat source (gas boiler) to renewable energy (heat pump).

Compared to the previously discussed research, the analyses provided in this study allow verifying the impact of a wider range of factors (relating to the building envelope, type of heat source, lowering the internal temperature, and rationalization of energy consumption) on heating costs and environmental pollution, based on the model of an existing service building. This means that, in contrast to the studies mentioned above, this analysis focuses on the overall impact of a larger number of factors, rather than an in-depth analysis of the impact of one or two factors in different variants. Furthermore, the energy-economic and environmental assessments were performed simultaneously within a single study. Although this article provides relative basic information, its added value is certainly the multi-criteria nature of the analysis provided. The results of the study could be a source of preliminary information when selecting a solution to increase the energy efficiency of a building and reduce heating costs, as well as a starting point for further, deeper analysis. The conclusions of the ecological analysis also raise awareness of the importance of a national energy mix in the context of the environmental effect of individual solutions.

2. Materials and Methods

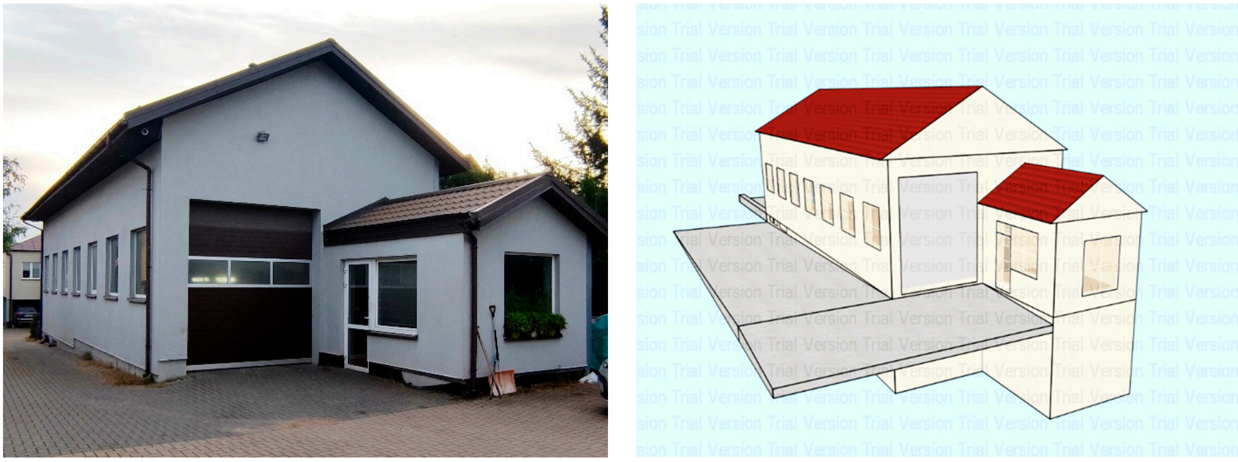
The object that was analysed is an existing service building, namely a vehicle-diagnostic station, constructed in 2004, made in traditional (brick) technology, and located in Bialystok in the northeastern region of Poland. This region is the climatic zone IV of Poland, where, based on [27], the outdoor temperature designed for is −22 °C, and the average annual outdoor temperature is −6.9 °C. According to the software data used, Bialystok corresponds to the 6A ASHRAE climate zone [28], for which the following parameters are assumed:

- outside temperature designed for: −19.3 °C;
- wind speed: 1.3 m/s;
- wind direction: 40°.

The facility consists of two floors—the basement, which includes a checkroom, toilet, and boiler room, and the ground floor, which includes the service area (workshop with diagnostic stations) and a waiting room with an office. It is characterized by its simple construction and meets all necessary technical requirements. The volume of the building is 935 m^3, while the usable area is160 m^2. The glazed surface of the building envelope (windows, glazed-door) was calculated at about 24 m^2. A photo of the analysed building and its visualization created in DesignBuilder are shown in Figure 1.

The model of the building was created in DesignBuilder software, where the heating demand calculations, as well as the simulations of all assumed scenarios were also performed.

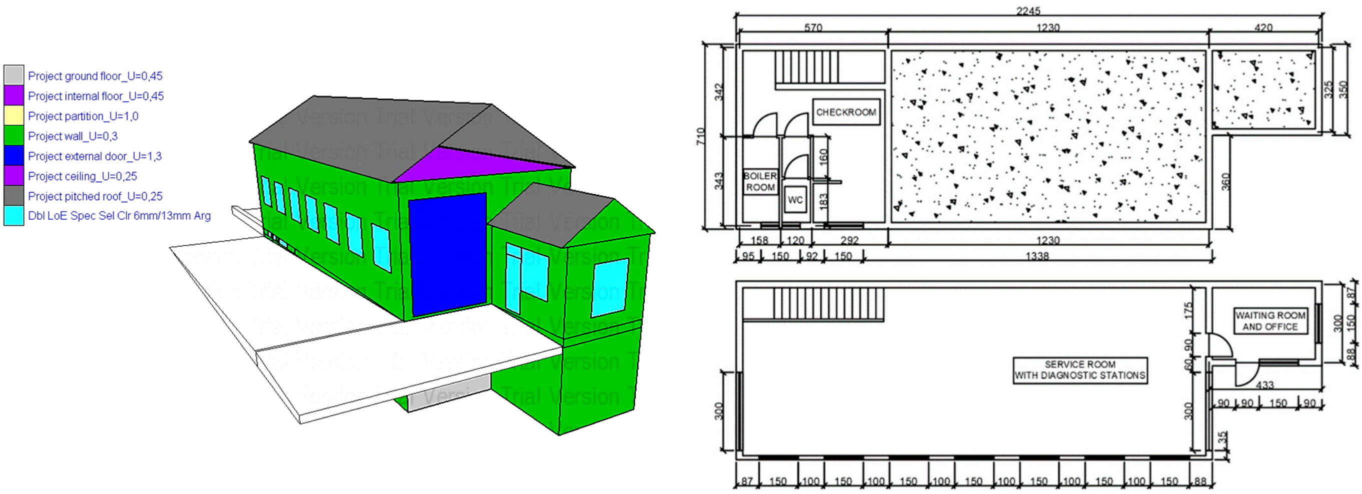
In the baseline (real conditions) scenario, the heating temperature was set at: 24 °C in the WC, 20 °C in the checkroom, and 18 °C in the service area, waiting room (with office), and boiler room. The ventilation of the rooms is carried out naturally by gravity. The assumed air exchange rate was 2 ac/h in all rooms except the checkroom and the waiting room (with office), where the value was 1 ac/h. According to PN-EN12831 [27] rules, the override wind exposure coefficient was set at 0.03 (medium sheltered site—towns or city periphery, heated zone with multiple façades exposed), while the override heigh coefficient was set at 1.0 (height of the building between 0–10 m).



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

Figure 1. Analysed service building: (**a**) Photo of the building from the northeast and east elevations; (**b**) Visualization of the building created in DesignBuilder v7 software.

Heat gains from people, light, and equipment were included in the calculations. Based on long-term observations, it was assumed that four people would be in the building at the same time. A model of the building, with data on the partitions and their color-distinction, is shown in Figure 2.



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

Figure 2. Analysed service building: (**a**) Model of the building with partitions data; (**b**) Plan of the basement and first floor of the building.

Currently, the heat source in the existing building is a De Dietrich gas-condensing boiler with a capacity of about 10 kW and an efficiency of 100%, while the heat receivers are convection panel radiators. Domestic hot water in the building is prepared using an electric instantaneous water heater. In order to learn the characteristics of the building's usage, the following measurements were taken:

- consumption of natural gas for heating the building, during the annual billing period;
- monthly electricity consumption for lighting, equipment operation, or hot water preparation.

Data were recorded and collected between 2020 and 2022. However, due to a mechanical defect of the meters and changes in an energy source, some periods had to be disregarded. Finally, we used the one year period from July 2021–July 2022 for verification of the model in the case of energy consumption for heating, and the two year period of 2020 and 2021 to estimate the average electricity consumption.

As the purpose of this study was to determine, among other things, the impact of selected factors on the heating costs of the considered service building located in Bialystok, in addition to the baseline scenario, the following alternatives were analysed:

1. Implementation of a scheduling of the building's use, closely adapted to its occupancy during a typical work day;
2. Lowering the heating in all rooms by 0.5 °C, 1 °C, and 2 °C;
3. Improving the heat transfer coefficients, "U", of the building envelope, consistent with the 2021 guidelines;
4. Implementation of a ground source heat pump with a COP of 3.5 (moving away from natural gas to electricity).

Detailed characteristics of the adopted scenarios are provided in Sections 2.1–2.4.

Unit prices for electricity and natural gas [29], as well as the euro exchange rate, were based on the current data as of 10 October 2022. Then, taking into account the values shown in the table below (Table 1), the efficiency of the gas boiler or heat pump, and the amount of energy (natural gas or electricity) required to heat the building, the heating costs were calculated for all scenarios.

Table 1. Gas and electricity price per kWh.

Location	Gas Price (€) [1]	Electricity Price (€) [1]
Białystok	0.07	0.19

[1] All fixed and variable costs are included.

What is more, for each of the scenarios, an ecological analysis (a comparison of the volatile pollutant emissions into the atmosphere) was carried out. The emission factors for natural gas and electricity [30,31], converted to kg/kWh, used in the analysis, are shown in the following table (Table 2). The emissions of pollutants were estimated as the product of the unit emission factors and the heating demand of the building, and then the results were checked using Audytor EKO software. In the last step, investment costs were estimated for scenarios 3 and 4.

Table 2. Emission factors of selected pollutants.

Pollutant	Emission Factors	
	Gas Fuel [kg/kWh]	Electricity [kg/kWh]
Total dust	1.8	26
CO_2	207,540	698,000
CO	108	203
NO_x/NO_2	180	522

2.1. Scenario 1

In this scenario, heating schedules were set based on the occupancy of the building for particular days throughout the year. The schedules took into account the plant's operating hours, occupancy, and holidays. In real conditions, the highest occupancy was observed from 7:30–17:00. The implemented schedules are presented in Table 3.

2.2. Scenario 2

In this scenario, it was assumed that for each room the indoor temperature would be reduced by 0.5 °C, 1 °C, or 2 °C. As a result, the temperature:

- In the boiler room, service room, and waiting room (with office) was lowered from 18 °C to A. 17.5 °C, B. 17 °C, and C. 16 °C;

- In the checkroom, from 20 °C to A. 19.5 °C, B. 19 °C, and C. 18 °C;
- In the WC, from 24 °C to A. 23.5 °C, B. 23 °C, and C. 22 °C.

Table 3. Heating schedules.

Type	Time					Coverage
	A	B	C	D	E	
Weekdays	00^{00}–5^{00}	00^{00}–5^{30}	00^{00}–6^{00}	00^{00}–6^{30}	00^{00}–7^{00}	50%
	5^{00}–19^{00}	5^{30}–18^{30}	6^{00}–18^{00}	6^{30}–17^{30}	7^{00}–17^{00}	100%
	19^{00}–24^{00}	18^{30}–24^{00}	18^{00}–24^{00}	17^{30}–24^{00}	17^{00}–24^{00}	50%
Winter day	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	100%
Weekends, holidays	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	50%
All other days	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	00^{00}–24^{00}	0%

2.3. Scenario 3

In this scenario, where needed, the thickness of the thermal insulation of the building partitions was increased so that the heat transfer coefficients, "U", would meet the requirements for 2021, as contained in [32]. The replacement of windows, doors, and garage doors was also assumed. A comparison of the actual, required, and adopted values of the heat transfer coefficients, "U", for each partition is provided in Table 4.

Table 4. Comparison of heat transfer coefficient values.

Partition	Actual "U" W/(m^{2}K)	Required "U" W/(m^{2}K)	Adopted "U" W/(m^{2}K)
Roof	0.25	0.15	**0.15**
Ground floor	0.45	0.30	**0.30**
Internal floor	0.45	1.00	**0.45**
External wall	0.30	0.20	**0.20**
Internal wall	1.00	1.00	**1.00**
External door	1.30	1.30	**1.30**
External/internal glazing	1.30	0.90	**0.90**

2.4. Scenario 4

In this scenario, the condensing gas boiler was replaced by a ground source heat pump with a COP of 3.5. This change does not directly affect the amount of building's heating demand. However, due to the different type of energy carrier (electricity instead of gas) and the different value of the energy efficiency factor, it translates into a difference in the total cost of heating.

3. Results and Discussion

3.1. Model Verification

The first step was to verify the building model, based on real data. Measurements showed that to heat the building under real conditions, 510 m^3 of natural gas was needed during the annual billing period (from July 2021 to July 2022), which translates into a consumption of about 5600 kWh of thermal energy.

Furthermore, based on the monthly electricity consumption in 2020 and 2021 (Figure 3), the average annual electricity usage of the building was estimated at approximately 5500 kWh. This was also taken into account when performing simulations in DesignBuilder.

The building model was therefore verified in terms of the body of the building, heating demand, and electricity consumption. After inputting the real data into the program, the baseline scenario resulted in a heating demand value of **5570 kWh** and an electricity demand value of **5420 kWh**, which can be seen as a good conformity.

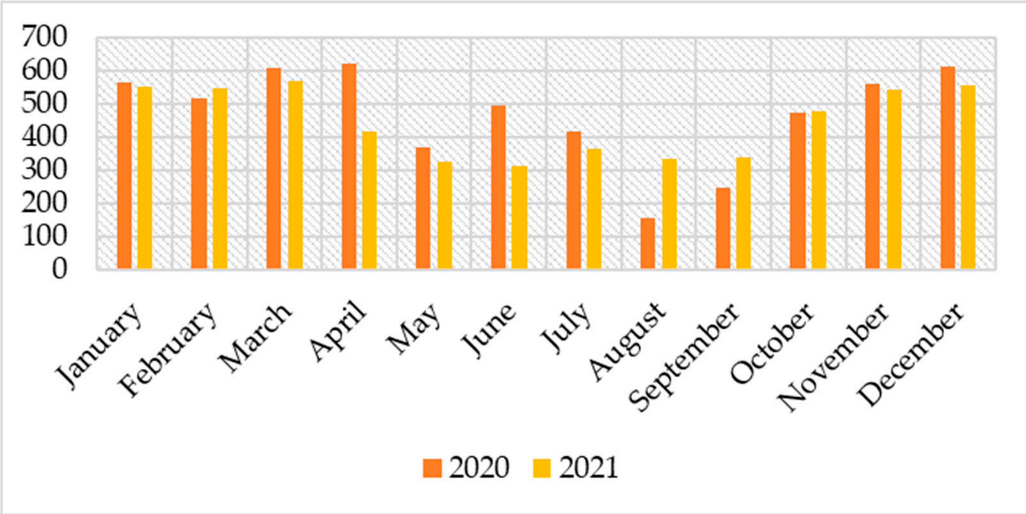


Figure 3. Electricity consumption in 2020 and 2021.

3.2. Heating Demand

The results of the heating demand calculations performed in the DesignBuilder software for each scenario are shown in Figure 4.

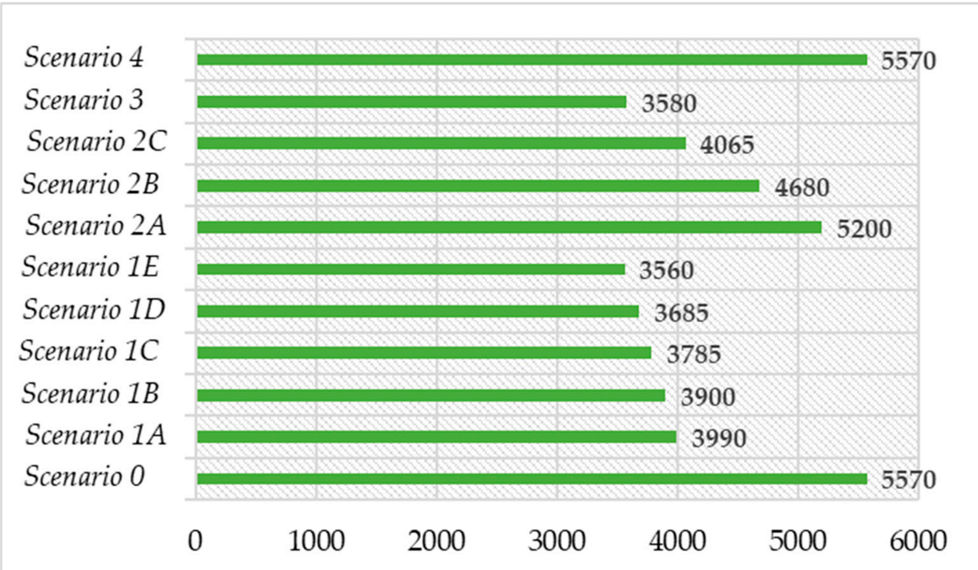


Figure 4. Heating demand of the building depending on the adopted scenario.

As can be seen, the lowest heating demand was achieved in Scenario 3, which involved increasing the thickness of the thermal insulation of the building envelope (a basic element of any thermal retrofit), and in Scenario 1E, which involved heating from 7^{00} to 17^{00} on a typical weekday. Compared to the baseline scenario, this was a reduction of as much as 36% in both cases.

Applying a heating schedule that provides heating from 7^{00} to 17^{00}, instead of from 5^{00} to 19^{00}, on a typical working day reduces annual heating demand by an additional 11%. By reducing the heating time during the day (relative to variant A), it was possible to reduce the building's heating demand by 2.3% to 3.5% for each consecutive hour.

What is more, if only improving the heat transfer coefficients, "U", of windows were considered (part of Scenario 3), the reduction in heating demand would amount to 8%.

3.3. Heating Costs

Based on the results obtained from the heating demand of the building, as well as the unit prices of the energy carriers and the efficiency of the analysed heat sources, the cost of heating the building was calculated in each scenario and summarized in Table 5.

Table 5. The results of the heating costs of the building and its reduction in the adopted scenarios.

Scenario	Variant	Heating Costs [€]	Reduction Rate [%]
Scenario 0	–	389.9	–
Scenario 1	A	279.3	28%↓
	B	273.0	30%↓
	C	265.0	32%↓
	D	258.0	34%↓
	E	249.2	36%↓
Scenario 2	A	364.0	7%↓
	B	327.6	16%↓
	C	284.6	27%↓
Scenario 3	–	250.6	36%↓
Scenario 4	–	302.4	22%↓

The results show that the greatest savings in the heating costs of the service building can be achieved by implementing Scenario 3 (the improvement of the heat transfer coefficients, "U") and Scenario 1E. In case of heating demand (Table 3), the reduction reached the level of 36% in these cases. The other variants of Scenario 1 were also very favorable and allowed the reduction of heating costs by as much as 28–34%. The use of a ground source heat pump instead of a gas boiler (Scenario 4) reduced costs by 22%, while changing the indoor temperature (Scenario 2) saved between 7–27%, depending on the variant considered.

Furthermore, hypothetically considering a building where all the analysed scenarios were applied simultaneously (Scenario 1E + Scenario 2B + Scenario 3 + Scenario 4), the heating demand would only reach 1790 kWh, which would mean a reduction of as much as 68%. The cost of heating in such a case would be 97.2 € (75% lower than in the baseline scenario).

3.4. Ecological Analysis

Taking into account the emission factors of natural gas and electricity (Table 2), as well as the demand of the energy carrier to heat the building, the annual emissions of individual pollutants was estimated. The results of the ecological analysis for the adopted scenarios are shown in Figure 5.

Although heat pumps do not cause emissions on site, due to Poland's energy mix [33], according to which electricity is generated mainly by burning coal, they can contribute to significant emissions associated with their use, especially when they do not cooperate with a photovoltaic installation.

Therefore, for the purposes of the environmental analysis, an additional sub-scenario was assumed, involving the use of a heat pump as in Scenario 4, but where the total electricity required for its operation would be covered by photovoltaic panels. This was Scenario 4*.

The results show that the highest total dust emissions were estimated for Scenario 4 (with GSHP), with the lowest for Scenario 4* (GSHP + PV), Scenario 3, and Scenario 1E. Concerning carbon dioxide (CO_2), Scenarios 4*, 3, and 1E were characterized by the lowest emissions, while Scenarios 0, 4, and 2B had the highest. In terms of carbon monoxide (CO) emissions, the most favorable solution was to use a heat pump (Scenarios 4* and 4), while the least favorable was to leave the baseline scenario or implement Scenario 2A.

For nitrogen oxide (NO_x/NO_2) pollution, the lowest emissions occurred in Scenario 4*, 3, and 1E, and the highest in the baseline scenario. Very similar values were estimated for Scenarios 2B and 4.

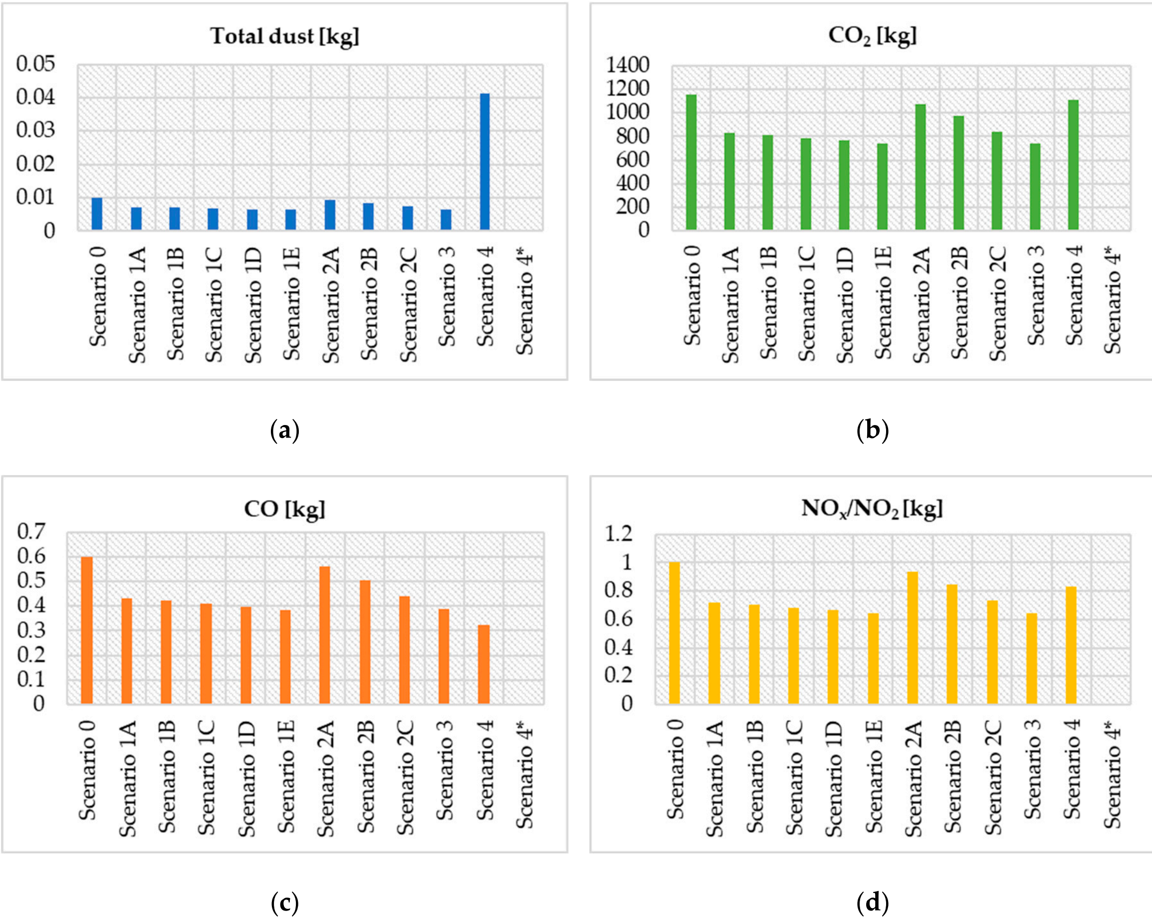


Figure 5. Ecological analysis of the scenarios adopted: (**a**) total dust emission; (**b**) carbon dioxide emission; (**c**) carbon monoxide emission; (**d**) nitrogen oxide emission.

Since the use of PV installation in combination with heat pumps allows for the total elimination of the analysed pollutants connected with the heating of the building, as an additional part of this analysis the number and power of photovoltaic panels required to meet the electricity needs of the building (for lighting, appliances, and heat pump operation) were also preliminarily estimated using a Hewalex calculation tool [34]. The calculations took into account the location of the building (annual solar radiation: 897 kWh/m^2), orientation to the world, roof angle and material, as well as total electricity demand. It was calculated that, assuming a 20% direct PV energy consumption, 31 panels would need to be installed, with a peak installation capacity of 11.94 kWp with a 10 kW 3-phase inverter. On the other hand, considering the supply of energy to the heat pump alone, 17 panels with a peak installation capacity of 6.55 kWp with 3-phase inverters of 6 kW would be needed.

Moreover, if one were to analyse an optimal scenario simultaneously combining the assumptions of the Scenarios 1E, 2B, 3, and 3, the annual emissions would be:

- 0.013 kg of total dust (25% more compared to Scenario 0);
- 356.7 kg of carbon dioxide (69% less compared to Scenario 0);
- 0.104 kg of carbon monoxide (83% less compared to Scenario 0);
- 0.267 kg of nitrogen oxide (73% less compared to Scenario 0).

In such a situation, the emissions of all the pollutants, excluding total dust, would be the lowest compared to the other scenarios, except for Scenario 4*.

3.5. Investment Costs

For each scenario, the investment costs of the adopted measures were also considered, taking into account the Polish market and conditions. Scenarios 1 and 2 are no-cost solutions and are mainly related to optimizing energy management. Estimated capital expenditures for increasing the thermal insulation of the building envelope and replacing windows, doors, and garage doors, based on price lists [35,36], are provided in Table 6.

Table 6. Investment costs for Scenario 3.

Thermal Insulation				
Type	**Thickness [m]**	**Area [m^2]**	**Unit price [€/m^2]**	**Cost [€]**
ground floor	0.05	145	2.26	328.3
roof	0.10	205	4.53	927.9
external walls	0.08	415	3.62	1503.0
Windows and Doors				
Type	**Dimensions [m]**	**Quantity [pcs.]**	**Unit price [€]**	**Cost [€]**
triple-glazed window	1.5 × 1.5	8	284.2	2273.6
triple-glazed window	1.8 × 1.5	1	226.6	226.6
triple-glazed window	0.4 × 0.9	1	120.7	120.7
triple-glazed window	0.4 × 0.8	4	115.4	461.6
garage doors	3.0 × 2.5	2	1088.1	2176.2
glazed doors	0.9 × 2.0	1	271.3	271.3
mortar, mesh, and glue (an additional 10% of the cost): 828.9 €				
				Total cost: 9118.1 €

Using information obtained in-house from contractors for northeastern Poland, as well as the values adopted according to [37], the labor cost of thermal upgrading was estimated as an additional 100% of the cost of materials. Thus, the total cost of insulating the building, including materials and labor, was estimated at about 18,240 €.

As a result of the simulation, based on the heating loads it was assumed that a 6 kW heat pump would be needed to cover the heating needs of the service building under analysis (Scenario 4). According to the manufacturers' price lists [38–40], the cost of ground source heat pumps of this capacity, including the necessary additional equipment, ranges from 30,000–50,000 zł, which, taking into account the euro exchange rate on 10 October 2022, is 6170 €–10,280 €. For the purposes of this analysis, a value from the middle of this range (8250 €) was assumed. In this case, the cost of the other hydraulic components of the system and labor (which includes drilling and installation) should also be taken as an additional 100% of the cost of purchasing the heat pump [41–43]. Thus, the total cost of implementing the heat pump, including equipment and labor, was estimated at approximately 16,500 €.

When considering the additional purchase of photovoltaic panels to cover the heat pump's electricity needs while providing environmental benefits (Scenario 4*), it is necessary to add about 3265 € for the purchase of the panels [44] and about 1000 € for their installation [45].

4. Conclusions

Based on the results of the analysis, it can be concluded that the most favorable way to reduce heating costs in an existing service building located in Bialystok is to improve the heat transfer coefficients, "U", of its external envelope (**Scenario 3**) and reduce the hours the building is heated (**Scenario 1E**). Adopting these scenarios reduced heating costs by as much as 36% and also achieved a relatively low estimate of pollutant emissions such as total dust, carbon dioxide and carbon monoxide, and nitrogen oxide. Moreover, merely replacing the windows would reduce heating costs by 8%.

The introduction of a heating schedule adapted to the occupancy of the building on a typical working day (**Scenario 1**) also turned out to be an economically and environmentally beneficial solution. This is consistent with the findings of [15]: that it does not make sense to supply heating energy to a building when no occupant or user is present and that energy consumption during unoccupied hours can sometimes be even more significant than during occupied hours.

The lowering of heating in all rooms by 0.5 °C, 1 °C, or 2 °C, assumed in **Scenario 2**, made it possible to reduce heating costs by 7–27%. Compared to the other scenarios, this average result is quite favorable. Especially considering that this measure does not require financial outlays and is only related to the subjective feelings of the thermal comfort of the building users, it can be considered worthwhile.

On the other hand, the use of heat pumps (**Scenario 4**), which are currently singled out as a key technology needed for energy transition [46], made it possible to reduce heating costs by 22% while not interfering with the body of the building. Unfortunately, since fossil fuels still dominate the Polish energy mix, devices that use electricity to operate are also a significant source of air pollution. Therefore, in order to achieve real economic and environmental benefits, heat pumps should be used in combination with photovoltaic panels (PV), which would provide the clean energy required for their operation. To prove this, a **Scenario 4*** was introduced in the environmental analysis, through which it could be seen that the use of a heat pump in combination with PV panels allows for the total elimination of harmful emissions into the atmosphere. This also confirms that how the electricity required to drive heat pumps is generated is particularly important and unfortunately often overlooked in heat pump analyses. It is also worth noting that the implementation of a heat pump (as in thermal upgrading [47]) is a solution that requires high investment costs.

Furthermore, hypothetically assuming an optimistic scenario in which all the objectives of Scenarios 1E, 2B, 3, and 4 would be implemented simultaneously, it would be possible to reduce heating costs by 75% and emissions of most pollutants by 69–83%. Simultaneous implementation of all scenarios or scenarios 3 + 4 and 1E + 4 would also lower the required capacity of the heat pump by about 1–1.5 kW, resulting in a reduction in investment costs of up to 10%, which was also estimated in [12].

It should also be emphasized that, regardless of the solution used, lowering the energy demand of the building resulted in a reduction in the emissions of most pollutants analysed, making the building "greener" and in accordance with principles of sustainable development. This is particularly important from the point of view of recent regulations and aspirations of the European Union [48], as well as the generally developing trend of environmentally friendly construction.

The present conclusions could be the basis for assessing the impact of individual measures on reducing both the cost of heating buildings and the amount of harmful pollutants emitted into the atmosphere. They could provide valuable information when choosing a method to increase the energy efficiency of buildings, as well as serve as an introduction to the analysis of selected solutions in terms of investment costs.

Conducting this type of analysis could also be particularly important at the current time when the prices of individual energy carriers have risen dramatically, and studies from several years ago no longer reflect the actual cost of heating.

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