



Article

Impact of the Degree Days of the Heating Period on Economically and Ecologically Optimal Thermal Insulation Thickness

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Abstract: The article proposes methods for determining the optimal thermal insulation thickness for economic and ecological reasons, depending on the number of degree days of the heating period. Life cycle assessment was used for the ecological analysis. Analyses were performed for selected variants typical of Polish conditions. The optimal thermal insulation thickness as well as the amount of economic and ecological benefits depends very much on the condition of the building without thermal insulation, but also on the heat source used and the thermal insulation material to be used. For each variant, the optimal thermal insulation thickness for ecological reasons is much greater than the optimal for economic reasons. Taking into consideration the climatic zone and the associated number of degree days of the heating period, the colder the zone, the greater the optimal insulation thickness, as well as economic and ecological benefits.

Keywords: optimal insulation thickness; maximum economic benefits; maximum ecological benefits; life cycle assessment; economic and ecological heating costs



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1. Introduction

Reducing the negative impact on the environment is a challenge for the world today. Trying to reduce CO₂ emissions in the construction sector is an important element of this challenge. These activities prove that the assumptions of the sustainable construction paradigm are implemented in practice. This is important because buildings and the construction sector are responsible for 45% of global CO₂ emissions [1]. The intensity of CO₂ emissions per square meter of building area is 0.38 tCO₂e/(m² year) during the construction of the building and 0.06 tCO₂e/(m² year) during the use phase of the building [2]. Considering the scale of this phenomenon, the problem of CO₂ reduction is significant. In 2013, EU countries emitted 3607 million tons of CO₂ into the atmosphere, which accounts for 10.8% of the global emissions of this pollutant [3]. Cost-effective strategy for reducing greenhouse gas emissions is to reduce the energy demand in the building sector [4]. Hence the priorities for 2030 in the EU are as follows [5]:

- at least 40% reduction in greenhouse gas emissions (compared to 1990),
- acquiring at least 27 percent of energy from renewable sources,
- at least 27% increase in energy efficiency.

EU also undertook the formulation of a long-term goal. The intention is to significantly reduce CO₂ emissions by 80–95% by 2050 compared to the levels from 1990. All activities aimed at energy efficiency and low-emission are to contribute to the development of the economy. They are also intended to contribute to the creation of new jobs and increase the competitiveness of Europe [6].

An important aspect of the heat demand in moderate climates, in which most European countries remain, is the number of degree days. It is assumed that if the outside air

temperature is lower than 18 °C, then heating the apartment building is necessary to ensure the so-called design internal temperature, which is 21 °C. It is assumed that the difference of about three degrees Celsius between the temperature of the outside and inside air “complements” the internal energy gains. Of course, the altitude of the internal temperature is a value determined individually depending on the so-called thermal comfort temperature.

Table 1 shows the number of heating degree days for Poland at the turn of 11 years. The highest value of the number of degree days was determined for 2010 (3920), the lowest is at the level of 3094 in 2014. The difference between the extreme years is 826 degree days, which has a significant impact on increasing energy demand. It is also impossible to accept an unambiguously logical rule resulting from global warming that the number of degree days tends to decline. The variability of the value of degree days in individual years and the energy demand in the building, and hence the determination of the optimal thickness of thermal insulation, is the research aspect of the following article.

Table 1. Number of heating degree days for Poland (annual data are calculated as sum of monthly data by Eurostat).

| Year | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|-------------|------|------|------|------|------|------|------|------|------|------|------|
| Degree days | 3176 | 3449 | 3920 | 3315 | 3550 | 3504 | 3094 | 3113 | 3286 | 3290 | 3125 |

Source: [7].

One of the first papers that proposed a method to determine the optimal thermal insulation thickness using life cycle cost was the work of Hasan [8]. The publication of Kaynakli [9] presents an overview of methods for determining the economically optimal thermal insulation thickness, some of them are based on the use of information about the degree days of the heating period. In the article [10], in addition to determining the economically optimal thickness of thermal insulation, the reduction of the building’s impact on the environment as a result of the implementation of cost-effective thermal insulation thickness was also examined. Similarly, in the study [11], a method of determining the optimal thickness for economic reasons was proposed. Additionally, the method of evaluating a thermal insulation investment for ecological reasons with the use of LCA was explained. The work [12] proposes methods for determining the optimal thermal insulation thickness for economic reasons based on economic heating costs and the optimal thermal insulation thickness for ecological reasons based on ecological heating costs. Duman et al. [13] proposed a method to determine the economically optimal thermal insulation thickness taking into account the degree days of the heating period. The analysis considered various: locations, thermal insulation materials and heat sources. In the literature on the subject, there are no articles considering the approach to determining the ecologically optimal thickness taking into account the degree days of the heating period. The economic and ecological conditions of a thermal insulation investment are an important signal for the investor in the context of the profitability of the planned investment.

The main gap in the research is the inability to determine the ecologically optimal thermal insulation thickness (taking into account the full impact on the environment, e.g., using LCA), based on the degree days of the heating period.

The aim of the article is to determine the economically and ecologically optimal thermal insulation thickness depending on the variable value of the number of degrees days. LCA was also used for the ecological analysis. Methods for economic and ecological evaluation based on the determination of the so-called net present value (NPV) of the investment were introduced. An additional goal was to check the introduced methods for example variants typical of conditions in Poland.

The rest of the article is structured as follows. In Section 2 methods for determining the optimal thermal insulation thickness for economic and ecological reasons are presented. The next section presents analyses for selected variants typical of Polish conditions. In Section 4, the obtained results were discussed, and in the last section—conclusions from the conducted research.

2. Methods of Determining the Optimal Thickness of Thermal Insulation

In this point, a method of determining the optimal thermal insulation thickness for vertical building walls depending on the number of degree days (DD) is proposed. These methods are based on the assumption that the performance of thermal insulation in a building is a certain investment for which we examine the profitability for economic and environmental reasons, respectively.

2.1. Economic Analysis

Taking into account the economic aspects, the economic net present value of the investment [14] can be determined in relation to 1 m^2 of the wall area:

$$NPV = -(K_m \cdot d + K_w) + S_N \cdot K_c \cdot c \cdot DD \cdot (U_0 - \lambda / (d + \lambda / U_0)) \quad [\text{PLN}/\text{m}^2], \quad (1)$$

where:

K_m —cost of 1 m^3 of thermal insulation material [PLN/m^3],

K_w —costs of performing thermal insulation of 1 m^2 building wall surface [PLN/m^2],

d —thickness of the thermal insulation layer [m], $S_N = \sum_{j=1}^N \frac{(1+s)^j}{(1+r)^j}$ —cumulative discount factor,

N —number of years of thermal insulation use,

r —real annual interest rate,

s —real annual growth (in percentage) of heating costs,

K_c —cost of generating heat for a given heat source and fuel [PLN/Wh],

c —24 [h/day],

DD —number of degree days of heating period [$\text{K}\cdot\text{day}/\text{year}$],

λ —thermal conductivity of the thermal insulation material [W/mK],

U_0 —heat transfer coefficient of the wall without thermal insulation layer [$\text{W}/\text{m}^2\text{K}$].

In Equation (1), the first component relates to the economic investment costs and the second component relates to the profits.

Whereas $G_0 = K_c \cdot c \cdot DD$ [$(\text{PLN}\cdot\text{K})/(\text{W}\cdot\text{year})$] is related to annual economic cost of heating, referred to 1 m^2 of the surface of external wall.

However, $U = \lambda / (d + \lambda / U_0)$ [$\text{W}/\text{m}^2\text{K}$] is a heat transfer coefficient of the wall with thermal insulation layer.

Due to the thickness d , NPV is a strictly concave function, limited from above. Hence it is possible to determine its maximum value due to d . It is enough to determine the thickness d , for which the derivative of the NPV function is equal to 0. The optimal thickness of thermal insulation at which NPV reaches its maximum value is:

$$d_{opt} = \text{sqrt}(\lambda \cdot K_c \cdot c \cdot DD \cdot S_N / K_m) - \lambda / U_0 \quad [\text{m}]. \quad (2)$$

The further part of the article will examine how d_{opt} performs depending on DD for different variants of thermal insulation.

2.2. Ecological Analysis

Taking into account the ecological aspects, the ecological net present value [14] can be determined for 1 m^2 of the wall area:

$$NPV_E = -K_l \cdot d + N \cdot K_e \cdot c \cdot DD \cdot (U_0 - \lambda / (d + \lambda / U_0)) \quad [\text{Pt}/\text{m}^2], \quad (3)$$

where:

K_l —LCA analysis result for 1 m^3 of thermal insulation material [Pt/m^3],

K_e —LCA analysis result of obtaining 1 Wh of thermal energy for a given heat source [Pt/Wh],

other—as defined earlier.

As in the economic analysis, in Equation (3) the first component is related to the ecological investment costs and the second to profits.

However, $G_E = K_e \cdot c \cdot DD [(Pt \cdot K)/(W \cdot \text{year})]$ is related to annual ecological cost of heating, referred to 1 m^2 of the surface of external wall in question.

As in the economic case, NPV_E due to the thickness d is a strictly concave function, limited from above. Hence it is also possible to determine its maximum value due to d . The optimal insulation thickness at which NPV_E reaches its maximum value is:

$$d_{Eopt} = \text{sqrt} (\lambda \cdot K_e \cdot c \cdot DD \cdot N / K_I) - \lambda / U_0 \quad [\text{m}]. \quad (4)$$

In the further part of the article, the performance of d_{Eopt} depending on DD will also be examined for different variants of thermal insulation.

2.3. Use of LCA for Ecological Assessment

In ecological analysis, LCA was used to determine K_I and K_e . The LCA methodology is described in the international standards ISO 14040 [15] and ISO 14044 [16].

A number of commercial computer programs are used to assist in LCA calculations. The research used the Sima Pro version 8.2 program and the ReCiPe endpoint method, egalitarian version. This method is now widely used in scientific research [17–20]. The ReCiPe method, similarly to the Eco-indicator 99 method, enables the generation of a result using the weighing procedure in the unit [Pt] [21,22]. The database Ecoinvent 3 and European Life Cycle Database (ELCD) v3.1 were used. The system boundaries of the analysed products were adopted from the acquisition of raw materials to the gates of the production plant (“from the cradle to the factory gate”). The system boundaries ignore the remaining phases of the life cycle due to the high variability of the factors determining the environmental load, i.e., transport distance from the production plant to the warehouse/store, and then to the construction site, type of transport, size of cargo spaces, etc. As the functional unit, 1 m^3 for thermal insulation materials was accepted and for the analysed heat sources, the generation of 1 kWh of heat energy.

3. Performed Analyses

This section presents data for the considered variants. For these data, an economic and ecological analysis was carried out in accordance with the methods described in point 2.

3.1. Description of the Analysed Residential Building

The average usable floor space in single-family houses in Poland is 133.8 m^2 [23]. The analysis covered a one-story residential building with a usable attic, with a usable area of 117.94 m^2 . Made in brick technology with a gable roof. The roof pitch is 40° , heat transfer coefficient for the roof $U_r = 0.24 \text{ W/m}^2\text{K}$. The volume of the building is 709.55 m^3 . The building has double-glazed windows $U_w = 1.5 \text{ W/m}^2\text{K}$. The floor on the ground with the coefficient $U_f = 0.4 \text{ W/m}^2\text{K}$. The building has twelve lodgings, including seven rooms.

The analysis does not take into account the replacement of transparent partitions, so the solar gains do not change.

3.2. Data Accepted for Analysis

The research was performed for various variants of building outer walls, heat sources in heating systems and thermal insulation materials. Taking into consideration that Poland is divided into five climatic zones (see Figure 1), several locations in different climatic zones were selected, differing in the number of degree days of the heating season.



Figure 1. Poland's climate zones. Source: [24].

Table 2 presents data for selected variants of construction and thermal insulation materials and heat sources. The heat transfer coefficient U_0 takes into account all the layers in the building vertical partition before the thermal insulation is applied. The thermal insulation service life was assumed to be $N = 25$ years, while the rates $r = 5\%$ and $s = 2\%$.

Table 2. Data for construction materials, thermal insulation materials and heat sources.

| Construction Material | Cellular Concrete 400 (P1) | Lime and Sand Blocks SILKA E (P2) | Ceramic Hollow Blocks Max (P3) |
|--|----------------------------|-----------------------------------|--------------------------------|
| Thickness of walls [m] | 0.36 | 0.24 | 0.29 |
| Thermal conductivity λ [W/mK] | 0.11 | 0.55 | 0.19 |
| Heat transfer coefficient U_0 [W/m ² K] | 0.29 | 1.65 | 0.59 |
| Thermal Insulation Material | Mineral Wool (I1) | Polystyrene EPS (I2) | Polystyrene XPS (I3) |
| Thermal conductivity λ [W/mK] | 0.039 | 0.040 | 0.032 |
| K_m [PLN/m ³] | 226.60 | 143.00 | 502.00 |
| K_w [PLN/m ²] | 40.00 | 35.00 | 35.00 |
| Heat Source | Coal Boiler (S1) | Condensing Gas Boiler (S2) | Electricity Boiler (S3) |
| Efficiency | 82% | 94% | 99% |
| K_c [PLN/kWh] | 0.144 | 0.245 | 0.556 |

Table 3 presents the results of the LCA analysis for considered thermal insulation materials and heat sources.

Table 3. Results of LCA analysis.

| Thermal Insulation Material | I1 | I2 | I3 |
|-----------------------------|-------|-------|-------|
| K_I [Pt/m ³] | 19.10 | 6.77 | 31.90 |
| Heat Source | S1 | S2 | S3 |
| K_c [Pt/kWh] | 0.124 | 0.027 | 0.107 |

Table 4 summarizes the data on the degree days DD of the heating period, determined on the basis of data from Eurostat [7]. These are the average values for selected regions in Poland and for the whole of Poland, for the years 2003–2018 (16 years). As can be seen in the Lubuskie and Podlasie regions, the number of degree days is significantly different from the average for the whole country. Therefore, the location of the building (in relation to the climatic zone) is very important in the economic and ecological analysis.

Table 4. Average values of the degree days of the heating period for Poland and selected regions.

| | Degree Days DD [K·day/year] |
|-----------------------------|-------------------------------|
| Poland | 3 387 |
| Region | |
| Zachodniopomorskie (zone I) | 3 272 |
| Lubuskie (zone II) | 3 075 |
| Mazowieckie (zone III) | 3 448 |
| Podlaskie (zone IV) | 3 734 |

3.3. The Results of the Economic Analysis

At the beginning, the annual economic costs of heating G_0 were determined, depending on the region (degree days DD) and the heat source used (heat generation costs K_c), based on the data in Tables 2 and 4. The results are summarized in Table 5. As can be seen, these costs significantly depend on the heat source used. For the same region, they are about 4 times larger for S3 compared to S1.

Table 5. Annual economic heating costs G_0 [(PLN·K)/(W·year)].

| Region \ Heat Source | S1 | S2 | S3 |
|----------------------|--------|--------|--------|
| Poland | 11.705 | 19.916 | 45.196 |
| I | 11.308 | 19.239 | 43.662 |
| II | 10.627 | 18.081 | 41.033 |
| III | 11.916 | 20.274 | 46.010 |
| IV | 12.905 | 21.956 | 49.826 |

Then, the values of the optimal thermal insulation thickness for economic reasons were determined from the formula (2). Table 6 shows the results for the region with the lowest number of degree days (II), for the average value in Poland, and for the region with the highest number of degree days (IV). As can be seen, the thicknesses significantly depend on the region where the building is located. For the P2-S3-I2 variant, the difference in optimal thickness between regions II and IV is about 4.5 cm.

Table 6. Economically optimal thermal insulation thickness d_{opt} [m].

| Constr. Material | Region | Heat Source—Thermal Insulation Material | | | | | | | | |
|------------------|--------|---|-------|-------|-------|-------|--------------|--------------|-------|-------|
| | | S1-I1 | S1-I2 | S1-I3 | S2-I1 | S2-I2 | S2-I3 | S3-I1 | S3-I2 | S3-I3 |
| P1 | II | 0.045 | 0.090 | 0.000 | 0.099 | 0.160 | 0.032 | 0.217 | 0.311 | 0.104 |
| | Pol. | 0.053 | 0.102 | 0.004 | 0.111 | 0.175 | 0.039 | 0.235 | 0.333 | 0.114 |
| | IV | 0.063 | 0.114 | 0.010 | 0.123 | 0.190 | 0.046 | 0.253 | 0.356 | 0.126 |
| P2 | II | 0.155 | 0.204 | 0.090 | 0.210 | 0.273 | 0.123 | 0.328 | 0.424 | 0.195 |
| | Pol. | 0.164 | 0.215 | 0.095 | 0.221 | 0.288 | 0.130 | 0.346 | 0.446 | 0.205 |
| | IV | 0.174 | 0.227 | 0.101 | 0.234 | 0.304 | 0.137 | 0.364 | 0.470 | 0.217 |
| P3 | II | 0.113 | 0.160 | 0.055 | 0.167 | 0.230 | 0.088 | 0.286 | 0.381 | 0.160 |
| | Pol. | 0.122 | 0.172 | 0.060 | 0.179 | 0.245 | 0.095 | 0.303 | 0.403 | 0.170 |
| | IV | 0.131 | 0.184 | 0.066 | 0.191 | 0.260 | 0.102 | 0.322 | 0.426 | 0.182 |

The high values of optimal thermal insulation thicknesses for all S3 variants result from high heating costs with the use of an electric boiler. The heating costs with the use of such a boiler, in Polish conditions, are approximately 3.9 times higher than with the use of a coal-fired boiler. The cost of purchasing thermal insulation materials also plays an important role in the economic analysis. Due to the fact that EPS polystyrene (I2) is the cheapest of the considered thermal insulation materials, in each variant, the optimal thickness values are the highest for this thermal insulation material.

3.4. The Results of the Ecological Analysis

As in point 3.3, at the beginning, the annual ecological heating costs G_E were determined, depending on the region (degree days DD) and the heat source used (heat generation costs K_c), based on the data in Tables 3 and 4. The results are summarized in Table 7. As in the case of economic costs, ecological costs depend very significantly on the heat source used. For the same region, they are more than 4 times larger for S1 compared to S2.

Table 7. Annual ecological heating costs G_E [(Pt·K)/(W·year)].

| Region \ Heat Source | S1 | S2 | S3 |
|----------------------|--------|-------|-------|
| Poland | 10.080 | 2.195 | 8.698 |
| I | 9.737 | 2.120 | 8.402 |
| II | 9.151 | 1.993 | 7.897 |
| III | 10.261 | 2.234 | 8.854 |
| IV | 11.112 | 2.420 | 9.589 |

Then, the values of optimal thermal insulation thicknesses for ecological reasons were determined from the formula (4). Table 8 summarizes the results for the region with the lowest number of degree days (II), for the average value in Poland and for the region with the highest number of degree days (IV). As with the economic analysis, the thicknesses significantly depend on the region where the building is located. For most variants, the optimal thicknesses are very large (of 0.4–1.2 m) and obviously not technically possible. It should be noted that for each variant, the optimal thickness for ecological reasons is much greater than the optimal thickness for economic reasons (compare Tables 6 and 8).

Table 8. Ecologically optimal thermal insulation thickness d_{Eopt} [m].

| Constr. Material. | Region | Heat Source—Thermal Insulation Material | | | | | | | | |
|-------------------|--------|---|-------|-------|-------|-------|--------------|--------------|-------|-------|
| | | S1-I1 | S1-I2 | S1-I3 | S2-I1 | S2-I2 | S2-I3 | S3-I1 | S3-I2 | S3-I3 |
| P1 | II | 0.549 | 1.025 | 0.369 | 0.184 | 0.405 | 0.113 | 0.500 | 0.942 | 0.335 |
| | Pol. | 0.583 | 1.082 | 0.392 | 0.200 | 0.431 | 0.124 | 0.532 | 0.996 | 0.357 |
| | IV | 0.619 | 1.143 | 0.418 | 0.217 | 0.460 | 0.136 | 0.565 | 1.052 | 0.380 |
| P2 | II | 0.660 | 1.138 | 0.460 | 0.295 | 0.518 | 0.204 | 0.611 | 1.056 | 0.426 |
| | Pol. | 0.694 | 1.196 | 0.483 | 0.311 | 0.545 | 0.215 | 0.643 | 1.109 | 0.448 |
| | IV | 0.730 | 1.257 | 0.509 | 0.328 | 0.574 | 0.227 | 0.676 | 1.166 | 0.471 |
| P3 | II | 0.617 | 1.095 | 0.425 | 0.253 | 0.475 | 0.169 | 0.569 | 1.012 | 0.391 |
| | Pol. | 0.651 | 1.152 | 0.449 | 0.269 | 0.502 | 0.180 | 0.600 | 1.066 | 0.413 |
| | IV | 0.687 | 1.213 | 0.474 | 0.285 | 0.530 | 0.192 | 0.634 | 1.122 | 0.436 |

Analysing the results in Table 8, the highest values of the optimal thermal insulation thickness are accepted by the S1 variants due to the high value of the environmental impact of coal-fired solid fuel boilers, which are unfortunately often used in Poland. The lowest values of ecologically optimal insulation thicknesses are obtained in variants I3, for which the LCA analysis showed the highest environmental burden caused by their production.

4. Discussion

Due to the results obtained in point 3, the shape of the d_{opt} and d_{Eopt} depending on the degree days of DD was examined. Figures 2 and 3 show the graphs of the d_{opt} (DD) function based on Equation (2) and d_{Eopt} (DD) based on Equation (4) for selected variants P1-S2-I3 and P2-S3-I1. Additionally, points corresponding to regions II and IV are marked on the graphs. Significant differences in the optimal thicknesses between these regions can be seen precisely because of the difference in DD . For the P1-S2-I3 variant, the difference in the d_{opt} is 0.014 m, and in the d_{Eopt} is 0.023 m. Even greater differences are for the P2-S3-I1 variant, 0.036 m and 0.065 m, respectively. Obviously, the optimal thermal insulation thickness as a function of the DD variable is not a linear function only the square root function. According to Equation (2):

$$d_{opt}(DD) = a \cdot \sqrt{DD} - b,$$

where: $a = \sqrt{\lambda \cdot K_c \cdot c \cdot S_N / K_m}$ and $b = \lambda / U_0$, $a, b > 0$.

The same applies to the thickness that is optimal for ecological reasons.

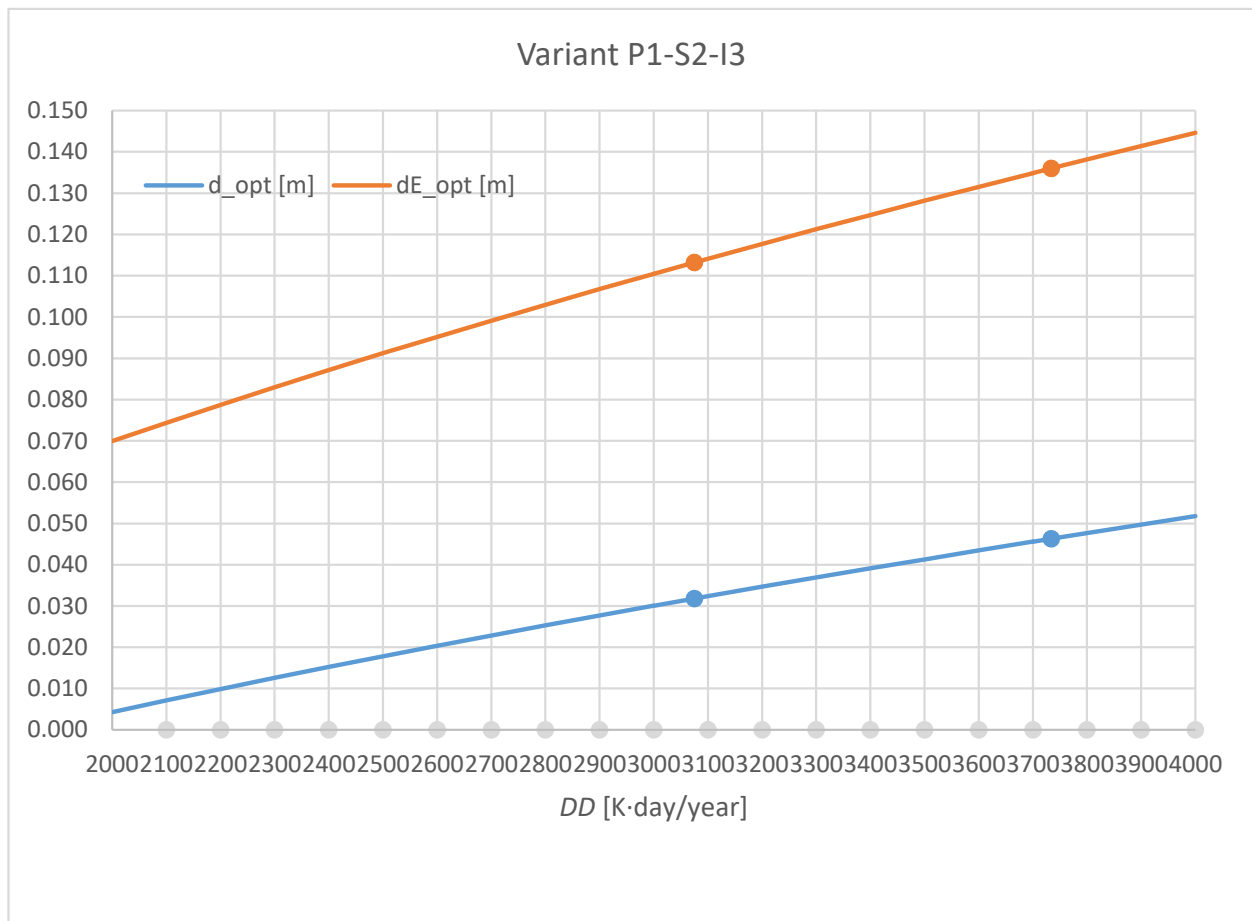


Figure 2. Optimal thermal insulation thickness d_{opt} and d_{Eopt} depending on the degree days DD for the P1-S2-I3 variant.

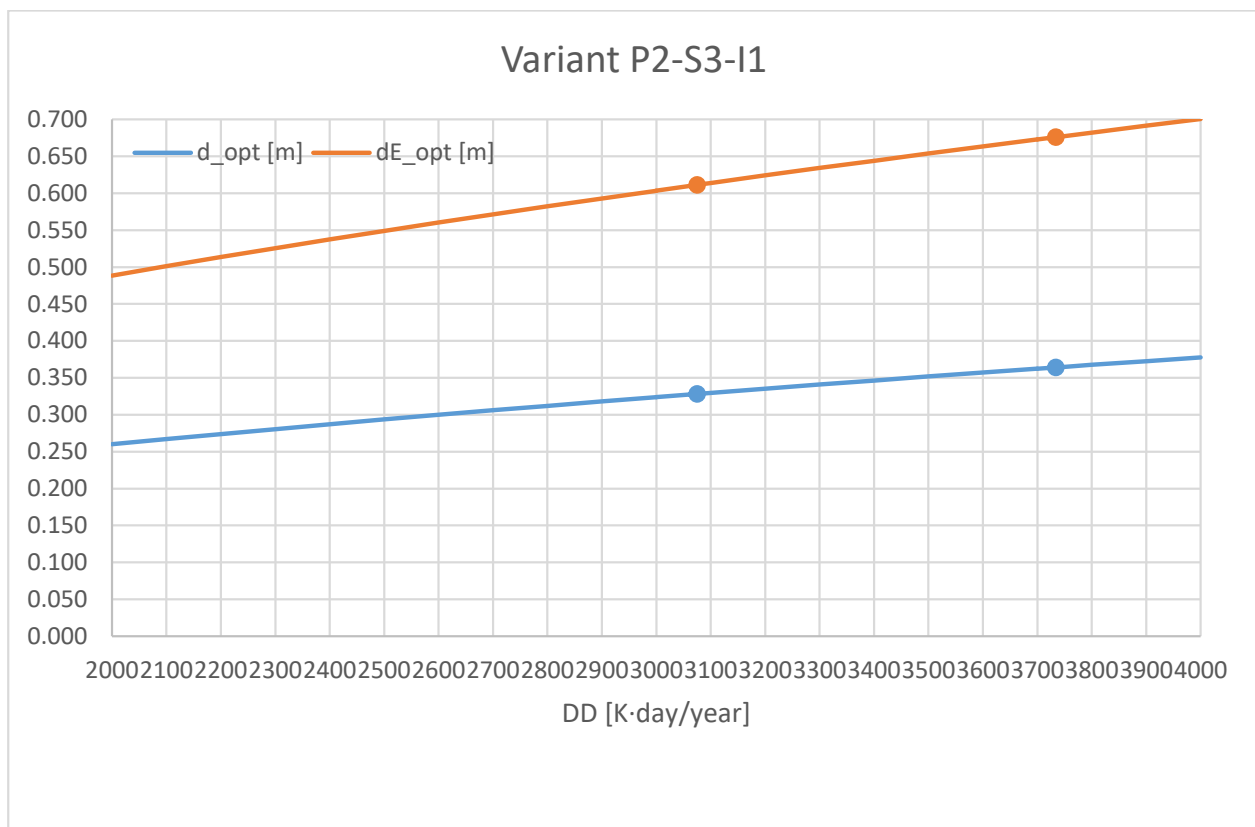


Figure 3. Optimal thermal insulation thickness d_{opt} and d_{Eopt} depending on the degree days DD for the P2-S3-I1 variant.

The net economic present values of $NPV(d)$ were also determined using the Formula (1) and the ecological net present values of $NPV_E(d)$ using Equation (3), depending on the thermal insulation thickness. The results depend significantly on the number of degree days of the heating period, therefore the graphs are presented for zone II, with the lowest number of degree days, and zone IV, with the highest number of degree days (see Table 4).

Figure 4 shows the $NPV(d)$ graph for the P1-S2-I3 variant. According to the results presented in Table 6, the maximum NPV value in zone II is achieved for $d_{opt} = 0.032$ m, and in zone IV for $d_{opt} = 0.046$ m. Let us note, however, that for this variant the maximum NPV value is negative ($= -30$ PLN/m² for zone II, $= -25$ PLN/m² for zone IV). This means that for economic reasons the investment is unprofitable for the investor. This is due to the fact that the P1 wall has good thermal insulation properties even without a thermal insulation layer ($U_o = 0.29$ W/m²K). Moreover, the thermal insulation material I3 is by far the most expensive of the considered materials.

Figure 5 shows the $NPV(d)$ graph for the P2-S3-I1 variant. For this variant, the situation is completely different from the previous one. Optimal thicknesses are much larger, $d_{opt} = 0.382$ m in zone II and $d_{opt} = 0.364$ m in zone IV (see Table 6). The investment is very profitable for economic reasons, the NPV value is PLN 993/m² for zone II and PLN 1231/m² for zone IV. The reason is that the P2 wall without thermal insulation has very bad thermal insulation properties ($U_o = 1.65$ W/m²K). Moreover, the thermal insulation material I1 is more than twice cheaper than I3, and the heating costs are more than twice as high with the use of the S3 heat source compared to S2 (see Table 2).

Figure 6 shows the $NPV_E(d)$ graph for the P1-S2-I3 variant. According to the results presented in Table 8, the maximum NPV_E value in zone II is reached for $d_{Eopt} = 0.113$ m, and in zone IV for $d_{Eopt} = 0.136$ m. Due to environmental reasons, the investment is profitable. The maximum value of NPV_E is positive (approximately 3.7 Pt/m² for zone II and approximately 5.3 Pt/m² for zone IV).

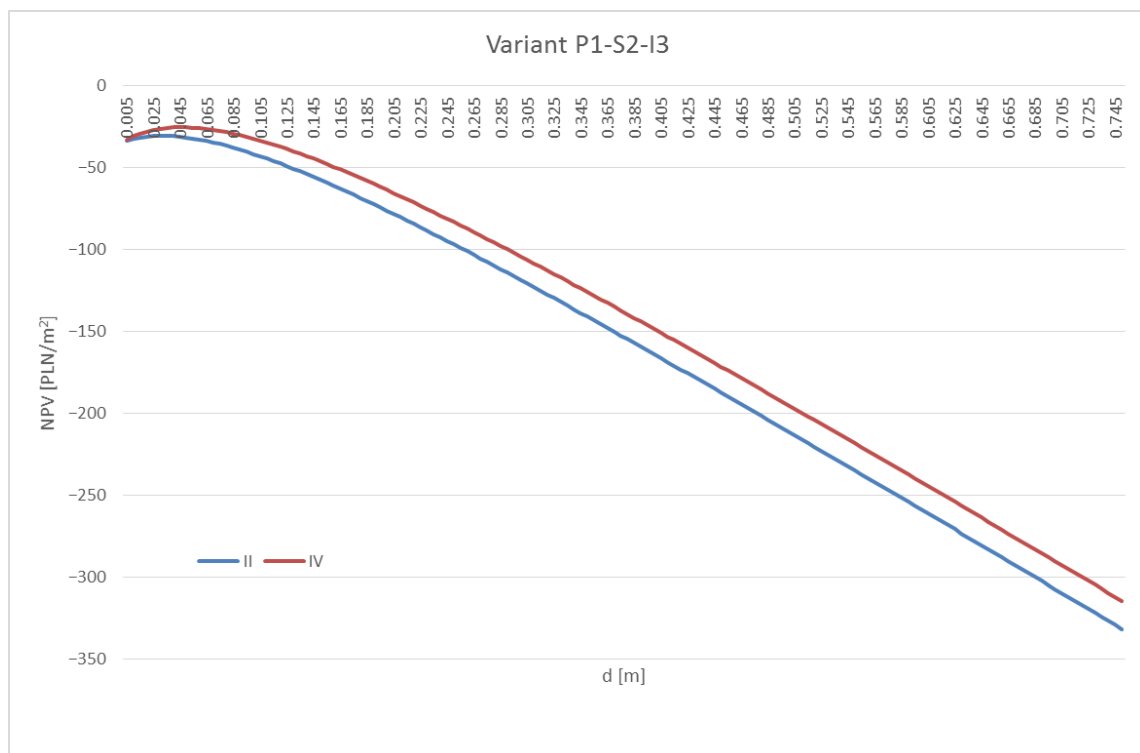


Figure 4. NPV values depending on the thickness of thermal insulation for variant P1-S2-I3 in zones II and IV.

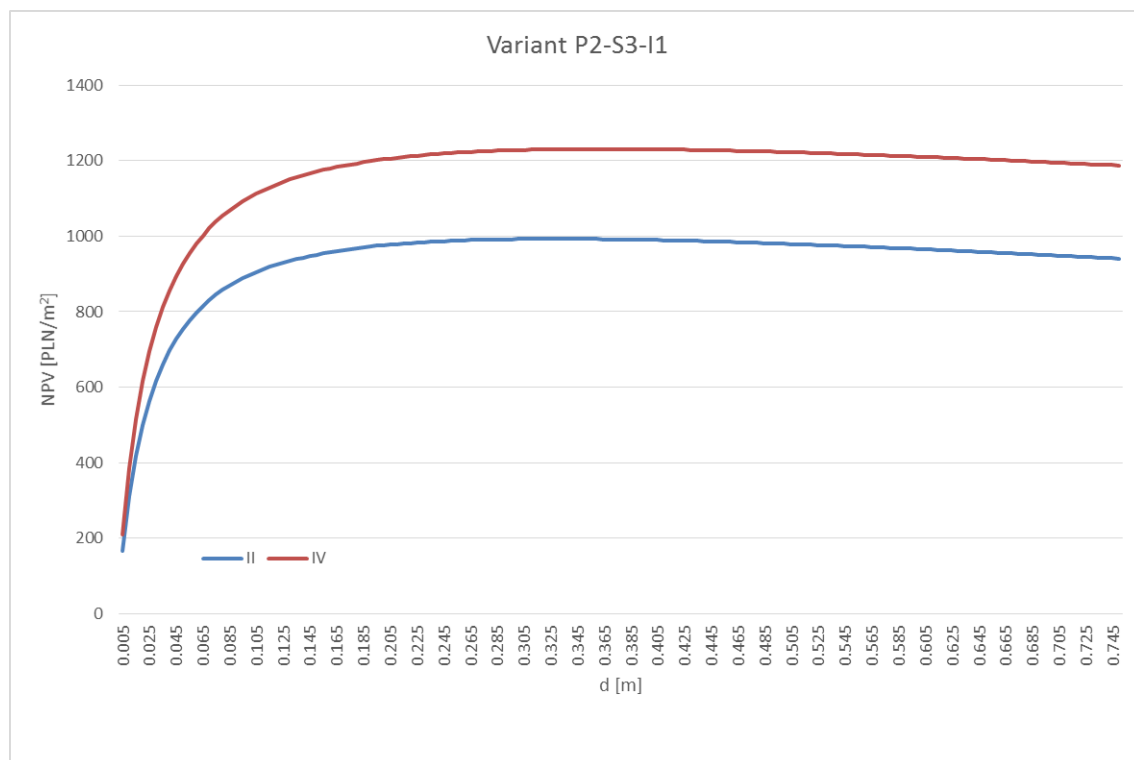


Figure 5. NPV values depending on the thickness of the thermal insulation for variant P2-S3-I1 in zones II and IV.

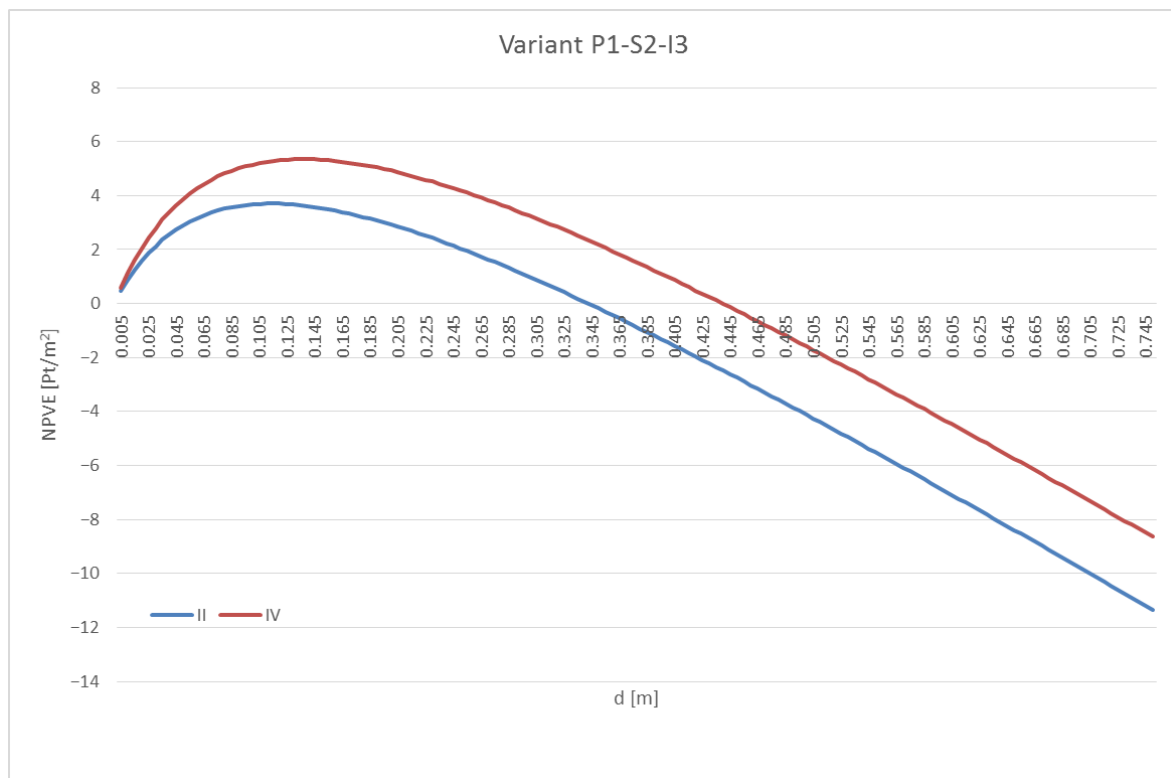


Figure 6. NPV_E values depending on the thickness of thermal insulation for variant P1-S2-I3 in zones II and IV.

Figure 7 shows the $NPV_E(d)$ graph for the P2-S3-I1 variant. For this variant, the optimal thicknesses are much larger, $d_{Eopt} = 0.611$ m in zone II and $d_{Eopt} = 0.676$ m in zone IV (see Table 8). The investment is very profitable for ecological reasons, the NPV_E value is approximately 302 Pt/m² for zone II and 369 Pt/m² for zone IV. The reason for such a large difference between these variants (P1-S2-I3 and P2-S3-I1) is that the P2 wall without thermal insulation has much worse thermal insulation properties than the P1 wall. Moreover, the ecological costs of K_I for thermal insulation material I1 are almost two times lower than for I3, and the ecological costs of obtaining heat are about 4 times higher with the use of the S3 heat source compared to S2 (see Table 3).

It should be emphasized that for each variant, the optimal thickness of thermal insulation for ecological reasons is much greater than the optimal thickness for economic reasons. Similar conclusions were obtained in the study [12], where methods based on economic and ecological heating costs were introduced to determine the optimal thermal insulation thickness.

What thickness of the thermal insulation to choose depends on what criterion is taken into account, whether economic or ecological. The optimal thermal insulation thickness as well as the size of the benefits measured by NPV and NPV_E indexes very much depend on the condition of the building without thermal insulation, but also on the heat source used and the thermal insulation material to be used.

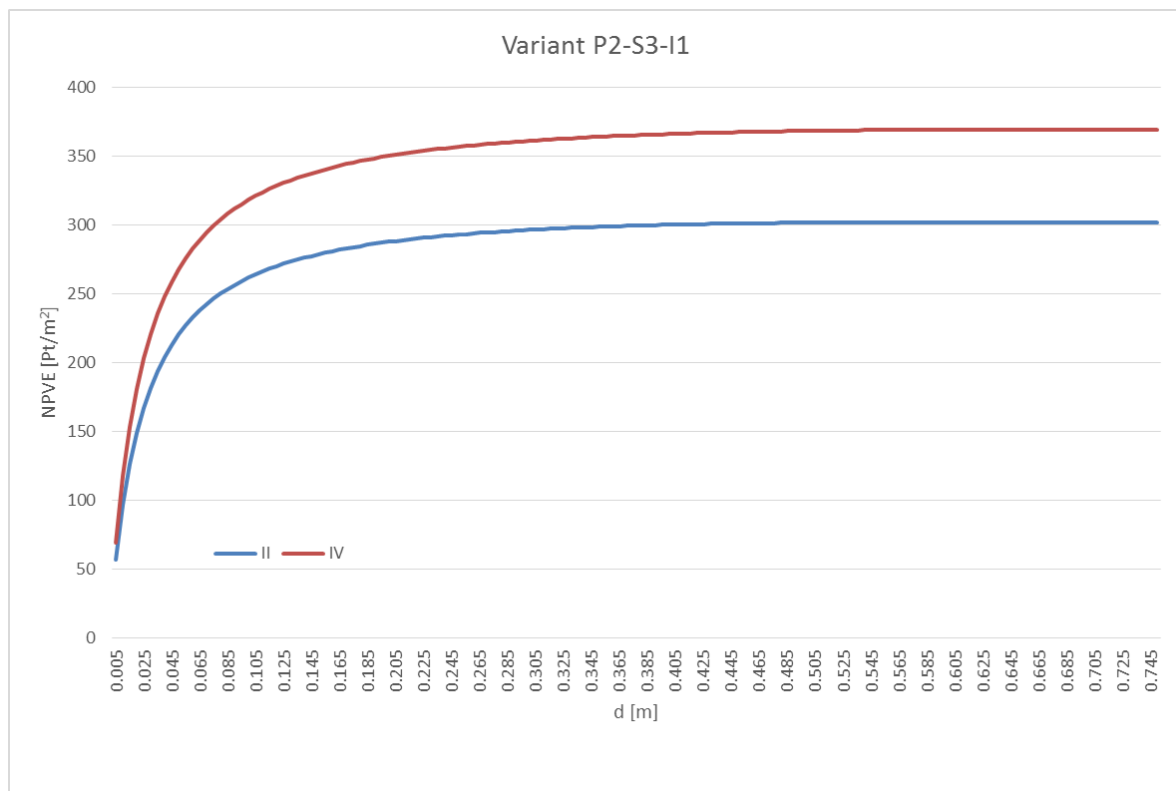


Figure 7. NPV_E values depending on the thickness of thermal insulation for variant P2-S3-I1 in zones II and IV.

5. Conclusions

Based on the assumptions of the sustainable development paradigm, which takes into account three aspects (economic, ecological and social) of equal importance, it cannot be concluded that the (economically unjustified) use of thicker insulation of building walls is appropriate. As a result of the performed analyses, results were obtained which suggest that from the ecological aspect, the thickness of the thermal insulation may be much greater than the thickness resulting from the economic analysis. The decision rests with the investor who, by definition, expects measurable economic benefits when investing. The investor's approach is a key element here, because the environmental benefit resulting from the use of thicker insulation may also be an end in itself, set by him. The investors' approach to the construction of new houses or the thermal modernization of old houses should be created by decision-makers. In Poland, there is a system of subsidies to thermal modernization investments, but it is the system aimed at covering a specific (one-time) amount of financial expenditure allocated for this purpose. One might wonder if, in addition, policy makers could not introduce a real estate tax reduction on buildings that meet the conditions of passive buildings. The economic benefits of tax cuts for such buildings would not necessarily offset the capital expenditure, but would provide an incentive for investors.

By analyzing the legal requirements for building vertical partitions in Poland, it should be noted that the value of the heat transfer coefficient for new buildings is constantly lowered and in 2020 the $U \leq 0.23 \text{ W/m}^2\text{K}$ standard applies. From 1 January 2021, the requirements for the heat transfer coefficient $U \leq 0.20 \text{ W/m}^2\text{K}$ will increase [25]. The actions of decision makers in Poland are focused on the implementation of the assumptions of the EU in terms of improving the efficiency of energy use, which directly generates specific environmental benefits.

The ecological benefits of thermal insulation of building walls are not only a cleaner environment, but also lower consumption of natural resources used to generate thermal energy in the building. The aspect of improving the condition of the environment was confirmed by

the LCA analysis. Despite the increased pressure on the environment as a result of the need to produce more thermal insulation, this surplus is compensated in most of the analysed variants during the use phase of the building. For thermal insulation with the highest environmental impact value (I3), the ecologically optimal thicknesses are the lowest.

Based on the results of the above analysis, it can be concluded that investors who choose the ecologically optimal insulation thickness cannot, in every case, count on a return on the invested capital. Taking into account the high level of air pollution in Poland [26], the actions of investors may also be ecologically justified. The difference in costs between the optimal insulation thickness, based on an economic analysis, and the ecological optimal thickness should be compensated by decision makers, for example in the form of investment subsidies. It should be noted that the optimal insulation thickness in both cases is not a constant value, but it can be determined and valorized over a specific period of time.

An important aspect influencing the demand for thermal energy is also the location of the building in a specific climate zone. It is obvious that in the “colder” climatic zone there is a greater demand for thermal energy. However, it should be noted that the NPV and NPV_E for each building located in such zone is much higher than the buildings located in the “warmer” zone.

The article does not analyse the third aspect of sustainable development, which is the social aspect. It should not be understood that this aspect is not a significant element of the thermal modernization process. It is the investor who decides whether the purpose of thermal modernization is to obtain economic benefits, or regardless of finances, the investor sets the goal of maximizing environmental benefits. Motivating investors to such behaviour is on the part of decision-makers, but also results from environmental education of the whole society. The pro-ecological approach cannot be postponed in time to the next few years, it should be introduced now, due to the constantly deteriorating condition of the environment.

The proposed method of determining the optimal (economically and ecologically) insulation thickness may be an instrument in the hands of decision-makers in the context of estimating the amount of subsidies for a thermal modernization investment. It can also be an indication for individual investors who intend to perform thermal insulation of their buildings in the selection of the optimal thermal insulation thickness.

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