Energy and Cost Analysis of Adapting a New Building to the Standard of the NZEB

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Abstract. The idea of Sustainable Development means caring for the environment and the natural resources. Building and transport are the sectors with the highest energy consumption. Building is responsible for about 40% of total energy consumption. Thermal protection regulations for buildings are becoming more and more severe. The 2010/31 / EU Directive on the energy performance of the buildings imposes on the member states of the European Union the necessity to introduce a standard of buildings of almost a zero demand for energy (NZEB). The requirements for these buildings (NZEB) are determined for each member country of the European Union. In Poland, the requirements for buildings (NZEB) are included in the Technical Conditions. In the article, the authors present energy and cost analysis of adapting a building that meets current requirements to the requirements adopted for NZEB in Poland. The requirements for new buildings are formulated for the building envelopes and for the factor determining Primary Energy (PE). To improve thermal protection of the envelopes, for example, the insulation thickness should be increased, or windows of better coefficients should be used. To improve the PE coefficient, the amount of energy coming from Renewable Energy Sources should be increased. The improvement of thermal efficiency is associated with additional costs. The aim of the article is also to show that reducing the amount of energy necessary for heating a building is not enough to design a comfortable home. The authors pointed to the need of ensuring multi-criteria comfort in NZEB. Buildings of low energy demand are very tight and well insulated. Often, in such buildings a problem with solar energy excess appears and, consequently, the rooms are overheated. On the example of a residential building, the Authors show what costs should be covered to adapt the building to a standard that meets the requirements of the NZEB and a building comfortable for users. The analysis was carried out to improve thermal and vibrational comfort. This paper presents a fragment of research and development works carried out in under the project "Development of innovative modular construction technology, prefabricated on a wood base by Palettenwerk Kozik Sp.j." This is a new technology, developed in cooperation of PalettenWerk Kozik and Cracow University of Technology, with the support of the National Centre for Research and Development, which will have properties that significantly exceed the technology currently available on the market. Buildings made according to the developed technology with using laminated wood crosswise will be characterized by high thermal and acoustic insulation as well as high energy efficiency.
1. Energy requirements for buildings in Poland

Poland, similarly to other EU member states, introduces the assumptions of the Directive on the energy performance of buildings 2010/31/UE [1].

Directive 2010/31 / EU requires Member States to introduce a standard NZEB ( Nearly Zero Energy Building).

The definition in the Directive provides a general definition of NZEB „nearly zero-energy building”, as a building that has a very high energy performance, which are determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from sources produced on-site or nearby”.

Member States shall ensure that:
(a) by 31 December 2020, all new buildings will be nearly zero- energy buildings; and
(b) after 31 December 2018, new buildings occupied and owned by public authorities will be nearly zero-energy buildings.

Member States shall draw up national plans for increasing the number of nearly zero-energy buildings. These national plans may include targets differentiated according to the category of building. Implementation of the Directive is an amendment to the technical and construction regulations regarding the thermal protection of buildings. The amendment to the Technical Regulations [2] was introduced in 2014.

The Polish government has decided to introduce the NZEB standard in a way that gradually tightens the regulations for thermal protection.

The energy efficiency of buildings in Polish regulations is determined by two main requirements. Buildings must meet the minimum requirements specified for thermal insulation of external housing components, defined as the heat transfer coefficient U [W/(m²·K)] (table 1) and requirements for the non-renewable primary energy demand index EP [kWh / (m²·year)] (table 2).

Table 1. Requirement 1 –partitions and the technical equipment of the building must comply with the requirements of thermal insulation specified by the U-value

| Type of partition and temperature inside room | Heat transfer coefficient Uc(max) [W/(m²·K)] |
|---------------------------------------------|---------------------------------------------|
|                                            | from 1.01.2014 | from 1.01.2017 | from 1.01.2021 |
| External walls:                            |               |               |               |
| with ti ≥ 16°C                              | 0.25          | 0.23          | 0.20          |
| Roofs and floors:                          |               |               |               |
| with ti ≥ 16°C                              | 0.20          | 0.18          | 0.15          |
| Floor on the ground:                       |               |               |               |
| with ti ≥ 16°C                              | 0.30          | 0.30          | 0.30          |
| Windows:                                   |               |               |               |
| with ti ≥ 16°C                              | 1.3           | 1.1           | 0.9           |
| Doors in external walls                    | 1.7           | 1.5           | 1.3           |
Table 2. Requirement 2—value of primary energy EP index [kWh/(m² year)] should not be greater

| No. | Type of building            | Partial maximum values of EP_{H+W} for heating, ventilation and DHW [kWh/(m² rok)] |
|-----|-----------------------------|----------------------------------------------------------------------------------------|
|     |                             | from 1.01.2014 | from 1.01.2017 | from 1.01.2021* |
| 1   | Residential building:       |               |               |                |
|     | a) single-family            | 120           | 95            | 70             |
|     | b) multi-family             | 105           | 85            | 65             |
| 2   | Collective residential building | 95           | 85            | 75             |
| 3   | Public building:            |               |               |                |
|     | a) healthcare               | 390           | 290           | 190            |
|     | b) others                   | 65            | 60            | 45             |
| 4   | Industrial building         | 110           | 90            | 70             |

*From 1.01.2019 – in case new of buildings occupied by public authorities and owned by them

2. Energy and cost analysis of the building in wooden technology

2.1 Technology description

In the article, the Authors conducted an energy analysis for a model building. The building was designed in accordance with the requirements of energy efficiency for 2014 (novelization of technical conditions), then technological improvements were introduced so that the building met the requirements of the current WT2017, requirements for the Polish definition of NZEB buildings (WT 2021) and the requirements for the passive buildings.

The energy analysis was supplemented with a cost analysis, showing what additional costs the user has to bear in order to increase energy efficiency, and thus reduce the costs of use.

A building designed in modular prefabricated wood-based technology was adopted for the analysis (Figure 1).

The building is designed by one company with the substantive support of the Małopolska Center for Energy-efficient Building as part of the National Center for Research and Development program. The building is designed in innovative technology using glued sandwich wood. This technology is characterized by high thermal and acoustic insulation. It is a dry technology of construct buildings. In the construction joints, an innovative flexible joint was used, thanks to which the concentration peaks of stresses were reduced, the load transfer safety was increased and steel connectors causing point thermal bridges were eliminated.

The external walls are made in a frame construction in the BSO ETIC system with wood wool filling. The roof is made as a panel roof. The insulation of the roof is wool laid between rafters and additionally on a wooden grate. Windows and doors meet the requirements of WT2014, WT2018, WT2021 and requirements for passive buildings. The technical equipment installations are mechanical ventilation with heat recovery and heating technologies that allow achieving the assumed requirements.

2.2 Variants adopted for energy analysis

The analysis was made for 4 building variants that fulfil the requirements of WT2014, WT2017, WT2021 and the passive standard. Parameters of external partitions for particular variants are presented in Table 3.

2.3 Applied solutions of technical equipment of buildings in the analysed variants.
2.3.1. Variant 1. The building is equipped with a mechanical supply and exhaust ventilation system with 55% recovery efficiency. The source of heat and hot utility water in the building is a gas condensing
boiler. Domestic hot water is prepared in 85% capacity reservoir. The 70/55 °C condensing boiler is fired with natural gas with a production efficiency of 91%. The boiler's power is 11 kW. Space heating is carried out using centrally regulated radiators. Total system development is 58%. The building uses central preparation of hot utility water with a circulation.

![Figure 1. The geometric model of the building](image)

**Table 3.** List of heat transfer coefficients for the analysed variants

| Kind of wall               | heat transfer coefficients U [W/(m²·K)] |
|----------------------------|----------------------------------------|
|                            | WT 2014  | WT 2017  | WT 2021  | Passive standard |
| External wall (BSO facade) | 0.24     | 0.22     | 0.19     | 0.12             |
| Floor on the ground        | 0.29     | 0.29     | 0.29     | 0.1              |
| Roof                       | 0.20     | 0.17     | 0.15     | 0.13             |
| Windows                    | 1.3      | 1.1      | 0.9      | 0.8              |
| Doors                      | 1.7      | 1.5      | 1.3      | 1.1              |

2.3.2 **Variant 2.** The building is equipped with a mechanical supply and exhaust ventilation system with 55% recovery efficiency. The source of heat and hot utility water is a biomass boiler. Domestic hot water is prepared in a container. The power of the biomass boiler is 11 kW. The efficiency of heat generation is 87%. Space heating is carried out using centrally regulated radiators. Total manufacturing efficiency is 72%. The building uses central preparation of hot utility water with a circulation.

2.3.3 **Variant 3 and Variant 4.** The building is equipped with a mechanical supply and exhaust ventilation system with 85% recovery efficiency. The source of heat and hot utility water is an air / water heat pump. Domestic hot water is prepared in an 85% capacity reservoir.

2.4 **Energy analysis results**

Table 4 presents the results of the energy analysis for all variants. The achieved indicators of Primary Energy EP [kWh/(m²·year)], End Energy EK [kWh/(m²·year)] and Energy Consumption EU [kWh / (m²·year)] have been summarized.

**Table 4.** Energy analysis results

| Variant  | Coefficient EP [kWh/(m²·year)] | Coefficient EK [kWh/(m²·year)] | Coefficient EU [kWh/(m²·year)] |
|----------|-------------------------------|---------------------------------|---------------------------------|
| WT2014   | 116.7                         | 93.71                           | 56.42                           |
| WT2017   | 91.50                         | 96.86                           | 48.83                           |
| WT2021   | 68.61                         | 22.67                           | 33.55                           |
| Passive  | 66.04                         | 22.013                          | 31.59                           |
2.5 Results of the investment costs

2.5.1. Heating and domestic hot water installations. In the analysis of improving the energy efficiency of subsequent variants, the investment cost of the heating system and hot water preparation with storage tanks as well as the costs of annual energy / fuel consumption were taken into account. Average prices were adopted in the 2017/2018 season [3].

For the variant W3 and W4, two solutions of the heating installation were adopted:
  - An air to water heat pump uses heat contained in the ambient air or in the exhaust air. It is mounted inside or outside the building.
  - The brine-to-water heat pump uses the ground as the primary source of energy, using collectors or ground probes. Heat is extracted from the ground using vertical or horizontal ground heat exchangers.

Table 5. Investment costs for heating installations and domestic hot water preparation. for WT2014, WT2018, WT2021 standards

| Variant | Requirements | Heat source | The cost of boiler [PLN] | The cost of installation c.h. [PLN] | Annual costs fuel [PLN] | Sum of costs (only the investment costs) [PLN] |
|---------|--------------|-------------|--------------------------|---------------------------------|------------------------|------------------------------------------|
| W1      | WT2014       | gas condensing boiler (G20 gas) | 7 000 | 13 000 | 2106 | 20 000.00 |
| W2      | WT2017       | pellet boiler | 10 000 | 12 000 | 1155 | 22 000.00 |
| W3      | WT2021       | air / water heat pump | 25 000 | 16 000 | 819 | 41 000.00 |
| W4      | Passive standard | brine / water heat pump | 40 000 | 16 000 | 689 | 56 000.00 |

The cost of replacing the heating system itself is 9% in the case of replacing the gas boiler with a pellet boiler, about 90% in the case of replacing the gas boiler with an air heat pump - about 150% if we exchange it for a ground heat pump.

2.5.2. External partitions - walls, roof. For the cost analysis, there have been adopted variants of increasing thermal insulation of external walls, roof insulation and flooring in accordance with point 2.2. The average market price for 1 m² of thermal insulation material was assumed.

The surface of non-transparent partition in the analysed building is:
  - External wall (façade BSO) – As = 189 m²
  - Roof Ad = 145 m²

The cost of improving the thermal insulation of the elements of the external building envelope is summarized in Table 6. The table only shows the cost of increasing the thickness of thermal insulation of walls and roof. The cost of 300,000 [PLN] / 68 181.82 [EUR] includes the costs of constructing a building in the WT2014 standard.

2.5.3. External partitions – windows. For the cost analysis, the windows meeting the requirements of WT2014, WT2018 and WT2021 were adopted. The average market costs of window purchase and assembly were adopted. The data is presented in Table 7. The table presents the average cost for windows made of aluminium, PVC and wooden frame in various energy standards. For further analysis, windows in a wooden frame were adopted. The window area in the analysed building is 29 m².
Table 6. The cost of improving the thermal insulation of the elements of the external building envelope

| Variant | Requirements | External walls | Roof |
|---------|--------------|----------------|------|
|         | Coeff. U [W/(m²K)] | The cost of improvement to a higher standard (PLN)/(EUR) | Coeff. U [W/(m²K)] | The cost of improvement to a higher standard (PLN)/(EUR) |
| W5      | WT2014       | 0.24 base      | 0.20 base |
| W6      | WT2017       | 0.22 576/128   | 0.17 2030/461 |
| W7      | WT2021       | 0.19 1775/403  | 0.15 4753/1080 |
| W8      | Passive      | 0.12 2155/489  | 0.13 7830/1779 |

Table 7. The cost of a window with assembly for reference windows in various window frames

| Requirements | Coefficient Uw [W/(m²K)] | The total cost of windows along with assembly [PLN]/[EUR] |
|--------------|---------------------------|----------------------------------------------------------|
| WT2014       | 1.3                       | 18 476/4 199                                             |
| WT2017       | 1.0                       | 25 004/5 682                                             |
| WT2021       | 0.9                       | 26 120/5 936                                             |
| Passive      | 0.8                       | 30 553/6 943                                             |

2.6 Energy and cost analysis to improve the comfort of using rooms.
In point 2, the building has been analysed for various energy efficiency options. A building that meets the assumptions of the building with almost zero energy consumption was obtained, in accordance with Polish technical conditions. When designing and implementing energy-efficient buildings, account should be taken of ensuring the comfort conditions of users [4]. It is possible using specialized software for dynamic analyses of internal conditions in buildings [5].

The standard [6] defines the input parameters of the internal environment for the design and assessment of the energy performance of buildings. The standard [6], based on results of work [7], provides levels of thermal comfort acceptable by users. In point 3, the authors analysed what impact on the energy efficiency and global costs of elements has improving thermal comfort and vibration comfort in the analysed building.

3. Thermal and vibrant comfort

3.1. Thermal comfort
In section 3.1. authors have included the results of the thermal comfort analysis, consisting of the average monthly temperature, humidity and PMV (Predicted Mean Vote) in the seven-point Fanger scale. The high PMV coefficient indicates that the rooms are overheating, and low, and their insufficient warming in relation to the activities to which the rooms are intended [7,8]. The analysis was carried out for selected rooms, because thermal comfort is strictly dependent on the purpose of individual rooms, not on the parameters of the entire building. The analysis was performed for a computational model, assuming parameters as for energy performance and without using any diaphragms or shading elements for windows.
Table 8. PMV scale: A seven-level scale of environmental assessment

| +3 hot  | +2 warm | 0 neutral | -1 little chilly | -2 chilly | -3 cold  |

The desired comfort results for rooms are in the range of -0.5 <PMV <+ 0.5. Sample results of PMV comfort analyses for selected rooms are shown in Fig. 2.3.

The analysis of thermal comfort and average temperature has shown that the rooms have very high values of overheating. The results in the summer months go beyond the fixed PMV scale. This is due to the lack of shade elements on the windows. Due to the significant overheating of buildings, shading solutions for windows should be used. The installation of external blinds was assumed for the analysis - assuming use when the internal temperature reaches 24 degrees.

The improvement of thermal comfort is clear after introducing shading elements that are external blinds. Providing thermal comfort affects the health and well-being of users. The cost of purchasing and installing blinds for the analysed building is approximately PLN 9 100/EUR 2 068. In figure 4 specifies the percentage increase in the costs of increasing thermal comfort conditions for various energy standards of the analysed building.
3.2. Vibrational comfort
Requirements for vibrational comfort are precisely described in [9]. Analysed building is located very close to express road “Zakopianka”, the distance is about 10 m, so building is in the zone of dynamic influences which for road excitation is about 25 m [10]. Moreover, analysed building is timber framed construction which has timber floor very sensitive for vibration both inside and outside excitation [11]. It is almost certain that it will be a need to protect residents of analysed building against vibrations. There are two proposals of building protection from vibrations caused by road excitation: vibro-acoustic floor and partition on the way of propagation. Both methods including costs with installation are described below.

3.2.1 Vibro-acoustic floor. Vibrations in vibro-acoustic floor are damped through use of vibro-insulation mats. These mats could be placed under the ceiling in three different ways: on the whole floor, under the joists - strips of mats are used and under the joists but only pointwise. Every three variants have
advantages and disadvantages. First one is the most expensive solution which cost about 300 €/m², the second one costs less (about 40 €/m²) but it leaves empty pass, which could be problematic from acoustic point of view, the third solution is the cheapest (5 €/m²) but it could be problematic from both acoustic and vibrational reason. The best choice for the analysed building will be strips of vibro-insulation mats under the joists and stone wool placed in empty pass. That solution should cost no more than 55 €/m², which means that for analysed building with about 180 m² of floors total cost of vibro-acoustic floor is equal 9 900 €. It should be mentioned that in some situations vibro-acoustic floor could be not enough to ensure necessary vibrational comfort, in that kind situations partition in the ground is needed.

3.2.2 Vibro-insulating partition in the ground. Localization of the building allows to design and built partition in the ground which should protect building and its residents from road vibration. To protect single building partition should be three times longer than the length of the facade from the side of dynamical excitation. Proposal of localization of partition in the ground for analysed building is shown in Figure 5.

![Figure 5](https://example.com/figure5.jpg)

**Figure 5.** Localization of partition in the ground

Anti-vibration palisade was chosen as partition in the ground because of costs of such construction. Palisade is much cheaper than wall in the ground and it could be the same effective. For the length of 30 m it will cost about 175 000 €, which of course is expensive solution but sometimes the only one that can provide vibrational comfort in buildings located very close to transport vibrations.

| Variant     | Total cost [PLN]/[EUR] | Total cost [%] |
|-------------|------------------------|----------------|
| W1 (WT2014) | Total cost 300 000/68 181 | 100%          |
| W2 (WT2017) | 311 125/70 710         | 104%          |
| W3 (WT2021) | 335 172/76 175         | 108%          |
| W4 (Passive)| 358 062/81 377         | 119%          |
Table 10. The percentage increase in the purchase and assembly costs of external blinds for various energy standards of the analysed building

| Variant     | Cost of the building without blinds [PLN]/[EUR] | Cost of the blinds [PLN]/[EUR] | Total cost [PLN]/[EUR] | Cost percent [%] |
|-------------|-----------------------------------------------|--------------------------------|------------------------|-----------------|
| W1 (WT2014) | 300 000/68 181                                | 9 100/2 068                    | 309 100/70 250         | 103%            |
| W2 (WT2017) | 311 125/70 710                                | 9 100/2 068                    | 320 225/72 778         | 103%            |
| W3 (WT2021) | 335 172/76 175                                | 9 100/2 068                    | 344 272/78 243         | 103%            |
| W4 (passive)| 358 062/81 377                                | 9 100/2 068                    | 367 162/83 445         | 103%            |

Table 11. The percentage increase of costs due to improved vibrational comfort

| Variant     | Cost of the building, [PLN] | Cost of Vibro-acoustic floor, [PLN] | Total cost, [PLN] | Percentage increase of costs [%] |
|-------------|-----------------------------|-------------------------------------|-------------------|---------------------------------|
| W1 (WT2014) | 300 000/68 181              | 43 560/9 900                        | 343 560/78 081    | 111%                            |
| W2 (WT2017) | 311 125/70 710              | 43 560/9 900                        | 354 685/80 610    | 111%                            |
| W3 (WT2021) | 335 172/76 175              | 43 560/9 900                        | 378 732/86 075    | 110%                            |
| W4 (passive)| 358 062/81 377              | 43 560/9 900                        | 401 622/91 277    | 109%                            |

4. Conclusions
The single-family residential building in Variant WT 2014 was adopted as the basis for the cost analysis. The usable area of the building is 120 m². The price for 1 m² of the building is PLN 2,500 (EUR 625). The total price of the building is PLN 300,000 (68 181 EUR). Additional costs of raising the building to the WT 2017 standard, WT 2021 and the passive standard are presented in tables 9. The cost of improving thermal comfort is summarized in Table 10. The cost of improving vibratory comfort is summarized in Table 11. Analyzes of the improvement of thermal and vibration comfort were made for the WT2014 standard.

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