Thermomodernization of a Residential Building to NZEB Level

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Abstract. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency introduces a zero-energy building standard, for which the energy balance per year is zero, i.e. the amount of energy obtained from renewable sources is equal to the annual demand. Each Member State shall establish a long-term renovation strategy to support the renovation of the national stock of residential and non-residential buildings, both public and private, into a highly energy efficient and decarbonised building stock by 2050, facilitating the cost-effective transformation of existing buildings into nearly zero-energy buildings. To achieve energy consumption at an appropriately low level in an existing building, you must adjust the heat transfer coefficients of the building envelope and the demand for primary energy to the requirements of the Technical Conditions for year 2021. Renewable energy sources, primarily from the sun, will also play a key role. A computational example of a single-family building shows which partitions are best modernized, what thickness of thermal insulation materials should be used to properly reduce heat transfer coefficients, and which installation systems to use to reduce the potential energy index (EP). It is also depicted as to how much the demand for usable energy in the building will decrease. This article aims to show residents of single-family buildings what steps should be taken to reduce energy consumption and thus - operating costs in an existing building to a minimum.

1. Introduction
In recent years, the construction sector has been experiencing very rapid changes due to the introduction of EU standards for "nearly zero-energy buildings (nZEB buildings)". In the light of Directive 2010/31/EC, the nZEB building means a building with very high energy performance determined in accordance with Annex I to the Directive. Almost zero or very low amounts of energy should be obtained to a very high degree from renewable energy, including renewable energy generated on site or nearby.

The introduction of the nZEB buildings standard is the responsibility of all member countries from next year. The nZEB buildings standard is characterized by energy saving during the construction and operation of buildings [1]. The nZEB standard will apply to all member countries from 2021. Designing and implementation of nZEB buildings is a new challenge for designers and contractors [2]. The selection of appropriate material and technological solutions is influenced by a lot of different factors, related to, among others with the location of the object [3]. While designing and implementing this type of buildings, characterized by excellent insulation of partitions and high tightness, one must not forget to provide comfort to the users of the buildings [4-6].

Reduction of energy consumption in the construction sector is necessary in many fields, among others in the investment process, but also in a much more energy-intensive process of using buildings and in the case of existing resources they amount to as much as 70% (Figure 1).
Polish requirements for almost zero-energy buildings were included in the Regulation of the
Minister of Infrastructure and Construction on the Technical conditions to be met by buildings and their
location, and they relate to primary energy and heat transfer coefficient through partitions. Table 1 presents requirements for primary energy, while Table 2 provides requirements for the heat transfer coefficient of selected building envelope elements [7].

### Table 1. Requirement 1 - value of primary energy EP index [kWh/(m² year)]

| No. | Type of building | Partial maximum values of EP<sub>H+W</sub> for heating, ventilation and DHW [kWh/(m² year)] | actually | from 1.01.2021* |
|-----|-----------------|-------------------------------------------------|----------|------------------|
| 1.  | Residential building: |                                               |          |                  |
|     | a) single-family | 95                                              | 70       |                  |
|     | b) multi-family  | 85                                              | 65       |                  |
| 2.  | Collective residential building | 85 | 75       |                  |
| 3.  | Public building: |                                               |          |                  |
|     | a) healthcare    | 290                                             | 190      |                  |
|     | b) others        | 60                                              | 45       |                  |
| 4.  | Industrial building | 90                                      | 70       |                  |

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

### Table 2. Requirement 2 –partitions and the technical equipment of the building must comply
with the requirements of thermal insulation specified by the U-value, at:

| No. | Type of partition and temperature inside room | Heat transfer coefficient U<sub>c(max)</sub> [W/(m²·K)] | actually | from 1.01.2021 |
|-----|-----------------------------------------------|-------------------------------------------------|----------|----------------|
| 1.  | External walls: with t<sub>i</sub> ≥ 16°C     | 0.23                                           | 0.20     |                 |
| 2.  | Roofs and floors: with t<sub>i</sub> ≥ 16°C   | 0.18                                           | 0.15     |                 |
| 3.  | Floor on the ground: with t<sub>i</sub> ≥ 16°C | 0.30                                           | 0.30     |                 |
| 4.  | Windows: with t≥ 16°C                         | 1.10                                           | 0.90     |                 |
| 5.  | Doors in external walls                       | 1.50                                           | 1.30     |                 |
In recent years, an increase in interest in energy-saving, passive or almost zero-energy construction has been noticed. This is due to the fact that the world is beginning to care more about the environment and energy saving. In the case of a new building, achieving the intended building standard is much easier. Everything can be predicted and plan at the design stage [8]. A more difficult situation is in the case of thermomodernization of an existing building, especially one that was created in the years when there were no regulations regarding heat transfer coefficients. This is often associated with very high costs or technical problems, therefore the most frequently chosen method of thermomodernization is only insulating the external walls of the building, in some cases (historic building) even from the inside [5]. New or improved thermal insulation materials or innovative technologies appear on the market limiting heat losses through partitions, which allow meeting the strict conditions of thermal insulation of partitions [8-10]. Unfortunately, the insulation of external walls does not always bring measurable effects. Another way to improve the reduction of energy consumption in buildings is to replace window frames with modern ones ensuring adequate thermal insulation through glazing several times, using gases with low thermal conductivity and ensuring proper tightness of the sash / frame connection as well as containing specialized low-emission coatings ensuring reduction of heat flow through radiation [11]. The last way is to change the central heating system to high-efficiency sources using renewable energy sources [12]. Of course, each option for improving the building's energy efficiency must be preceded by a cost-effectiveness analysis [12-14]. All these treatments allow to reduce energy consumption in the building, but in order to bring the building to the nZEB standard, it is necessary to combine all these elements [15].

In the article, the authors on the example of an existing building will present an attempt to modernize it to an almost zero energy standard.

2. Thermomodernization to the almost zero-energy standard on the example of a single-family house
The analyzed building was built in the 90s in traditional technology, put into use in 1995. The facility is located in Luborzyca near Krakow. The building has 3 floors, the lowest of which is partly recessed in the ground (Figure 2). The building was built on a rectangular plan with external stairs and a balcony, finished with a gable roof. There is a small unused space under the roof. The usable area of the building is 212.31 m², and the volume is 550, 72 m³. In 2016, the door and windows were replaced. The external roofing and dormer walls were replaced 5 years ago because it was originally made of asbestos containing harmful asbestos fibers. With the replacement of the outer layer, patches, counter battens and roofing membrane were replaced.

![Figure 2. Analyzed building](image)

Table 3 presents the characteristics of building partitions together with the building's heat transfer coefficients before thermo-modernization. The calculation of the total thermal conductivity coefficient includes thermal bridges calculated using the Therm 7.6 software.
Thermal bridges in a building partition are places where heat transfer coefficients with higher values are observed compared to the rest of it. In places where thermal bridges are located, more intense and uncontrolled heat transport is observed. In addition, in the case of a significant difference in temperature inside and outside the building, there is a phenomenon of local cooling of the partition, which at low external temperatures contributes to the lowering of the temperature of the internal partition below the dew point. The dew point is the temperature at which it would be necessary to cool the moist air in order for the condensation of the vapor contained in it to start, i.e. the relative humidity was 100%. This phenomenon favors condensation on the inner surface of the walls in buildings and carries the risk of mold and fungus development at a later stage. Condensation of water vapor on the internal surface of the partition depends only on the thermal insulation of this partition [16-17].

Table 3. Characteristics of existing partitions in the building

| No. | Type of partition | Description | Heat transfer coefficient |
|-----|-------------------|-------------|--------------------------|
| 1.  | external window   | PVC external window 5-chamber profiles, single-chamber panes | 0.89 |
| 2.  | Exterior doors    | Made of galvanized steel and filled thermal insulation | 1.4 |
| 3.  | Roof              | Metal roof tile on a wooden roof structure | 0.45 |
| 4.  | Floor on the ground | Made of furnace slag, cement screed, asphalt roofing felt and chipboard | 0.44 |
| 5.  | External wall     | Three-layer outer wall made of MAX hollow blocks insulated with an outer cladding made of checker brick with a thickness of 48.8 cm | 0.35 |
| 6.  | The wall in the basement | Three-layer, from slag-concrete blocks, insulated with a thickness of 46 cm | 0.37 |
| 7.  | External ceiling  | Made of reinforced concrete slab | 0.67 |
| 8.  | Straddle ceiling  | Made in the FERT-20 system with a thickness of 20 cm | 0.56 |

Table 4 contains a set of thermal bridges for external walls.

Table 4. List of bridges for external walls

| No. | Type of thermal bridge | Ψk [W/mK] | L k [m] |
|-----|------------------------|-----------|---------|
| 1.  | Roof / wall insulation inside | 0.50 | 6.38 |
| 2.  | Balcony slab / wall with insulation inside | 0.95 | 2.54 |
| 3.  | Exterior corner of the wall with insulation inside | -0.10 | 6.34 |
| 4.  | Inner corner of the wall with insulation inside | 0.15 | 2.67 |
| 5.  | Ceiling with wreath insulation / wall with insulation inside | 0.6 | 12.90 |
| 6.  | External ceiling 1     | 0.8 | 5.08 |
| 7.  | External ceiling 2     | 0.62 | 5.08 |

The building uses 2 heat sources, a gas boiler with a total system efficiency of 0.72 and a fireplace with a closed combustion chamber with an efficiency of 0.49 fired with biomass. The preparation of domestic hot water is carried out by a gas boiler. The building has no cooling system. For calculation purposes, the facility has been divided into 2 temperature zones. The first applies to unheated spaces.
such as a basement and has a temperature of 8 °C, the second applies to other heated spaces with a temperature of 20 °C.

Climatic data from the Krakow-Balice meteorological station were used for calculations. In the state before thermo-modernization, the indicator of the annual demand for non-renewable primary energy EP, useful energy EU and final energy EK was 184.10 [kWh/(m²·year)], 142.8 [kWh/(m²·year)] and 261.5 [kWh/(m²·year)], respectively. The specific volume of CO₂ emissions was ECO₂ 0.02874 [tCO₂/(m²·year)]. The first indicator defines the amount of non-renewable energy that should be used to meet the needs of the building, while the second indicator defines the energy that should be supplied to the building. The differences between them result from the method of heating and losses in carrier transport. The demand for the building itself is determined by the EU usable energy index, which tells about the amount of energy needed to maintain certain temperature conditions inside the building, taking into account losses through partitions and ventilation, as well as internal and solar gains, as well as the demand for energy needed to prepare hot utility water. The differences between final energy and usable energy result from the quality of internal heating and heat transfer systems. In order for the indicators to be comparable, they are given per 1m² of surface at a set temperature.

2.1. Thermomodernization variants
In order to bring the building to almost zeoenergetic standards, the authors analyzed 3 variants of thermomodernization checking which of them will ensure will achieve the required parameters. The first 2 variants concerned the insulation of partitions, the third option also modernized the central heating system. The results of the analyzes are presented below.

2.1.1. Variant 1. The first proposed variant is the most frequently chosen thermomodernization solution in the case of single-family housing and it relates to the insulation of the external walls of the building and the external ceiling. For this purpose, typical polystyrene with a heat transfer coefficient of 0.04 [W/mK] was adopted for the analysis. The insulation thickness was adjusted so that the modernized partition meets the conditions of nZEB buildings. In the case of a wall next to the entrance door, the maximum thickness of foamed polystyrene that could be used is 3 cm, due to the way the door is mounted. In addition, it was decided that the wall at the external stairs will be insulated with only half the thickness of the required layer, in order to limit the reduction of the width of the stairs. For the ceiling above the outer space, it was necessary to add a 20 cm thick layer of insulation material. Table 5 presents the list of parameters for variant 1.

| No. | Type of partition                     | Before modernization | After modernization |
|-----|--------------------------------------|----------------------|--------------------|
| 1   | Basement wall                        | 0.37                 | 0.19               |
| 2   | External wall (ground floor, first floor) | 0.35                 | 0.19               |
| 3   | Wall by the door                     | 0.35                 | 0.28               |
| 4   | Wall by the stairs (zone I)          | 0.35                 | 0.25               |
| 5   | Wall by the stairs (zone II)         | 0.35                 | 0.24               |
| 6   | External ceiling                     | 0.67                 | 0.15               |

The use of this type of modernization allowed the EP to be reduced by 40.1 [kWh/(m²·year)]. Before thermo-modernization, the EP index was 184.1[kWh/(m²·year)], while 144.0 [kWh/(m²·year)]. Other indicators of final and usable energy were 190.6 and 101.5 [kWh/(m²·year)], respectively. This treatment did not even allow the current requirements regarding the primary energy index of 95.0 [kWh/(m²·year)] to be achieved.
2.1.2. Variant 2. In this variant, an attempt was made to change the thermal insulation material used to insulate the walls, at which it was impossible to apply a thicker layer of insulation (wall at the door and stairs) for PIR foam with better heat conduction parameters ($\lambda = 0.026$ [W/m·K]). The insulation of the ceiling separating the unheated attic from the heated area was also used. The remaining modernization operations previously carried out remained unchanged. Table 6 presents modernized partitions together with before and after heat transfer coefficients.

Table 6. List of heat transfer coefficients

| No. | Type of the partition          | Heat transfer coefficient $U$ [W/(m$^2$·K)] | Before modernization | After modernization |
|-----|--------------------------------|---------------------------------------------|---------------------|-------------------|
| 1.  | Basement wall                  |                                             | 0.37                | 0.19              |
| 2.  | External wall (ground floor, first floor) |                                             | 0.35                | 0.19              |
| 3.  | Wall by the door               |                                             | 0.35                | 0.25              |
| 4.  | Wall by the stairs (zone I)    |                                             | 0.35                | 0.22              |
| 5.  | Wall by the stairs (zone II)   |                                             | 0.35                | 0.21              |
| 6.  | External ceiling               |                                             | 0.67                | 0.15              |
| 7.  | Straddle ceiling               |                                             | 0.56                | 0.14              |

Changing the insulation material and insulation of the inter-zonal ceiling did not improve the situation much. The EP index improved by only 6.3[kWh/(m$^2$·year)] compared to the previous variant. This change did not bring significantly favorable results and in economic terms it is more costly due to the higher costs of PIR foam.

2.1.3. Variant 3. In the above variants, it has been proved that the modernization of the building envelope and ceiling elements alone does not allow achieving the expected EP index, therefore in this variant the authors introduce an air-water heat pump as an additional source of energy based on renewable sources. The total efficiency of the heat pump is 2.09. The proposed solution assumes the operation of the pump in a hybrid system in combination with a gas boiler already installed. This solution allows you to reduce the pump power, and thus reduce the investment cost. Modernization also does not involve removing the fireplace, which will still be used to partially meet the needs of heating. This decision is dictated by relatively low costs and uninterrupted operation at low temperatures. The efficiency of existing heating systems remains the same 0.49 and 0.72 for the fireplace and gas boiler, respectively. Table 7 contains a list of heat transfer coefficients before and after modernization for variant 3.

Table 7. List of heat transfer coefficients

| No. | Type of the partition          | Heat transfer coefficient $U$ [W/(m$^2$·K)] | Before modernization | After modernization |
|-----|--------------------------------|---------------------------------------------|---------------------|-------------------|
| 1.  | Basement wall                  |                                             | 0.37                | 0.19              |
| 2.  | External wall (ground floor, first floor) |                                             | 0.35                | 0.19              |
| 3.  | Wall by the door               |                                             | 0.35                | 0.28              |
| 4.  | Wall by the stairs (zone I)    |                                             | 0.35                | 0.25              |
| 5.  | Wall by the stairs (zone II)   |                                             | 0.35                | 0.24              |
| 6.  | External ceiling               |                                             | 0.67                | 0.15              |
| 7.  | Straddle ceiling               |                                             | 0.56                | 0.14              |

After introducing improvements related to the modernization of walls and ceilings and the addition of an additional heating source, the primary energy index dropped to 69.0 [kWh/(m$^2$·year)].
3. Results and discussions
Table 8 presents the results of the analysis of heat transfer coefficients before and after modernization. The obtained coefficients were compared with the requirements of almost zero-energy buildings. Table 9 shows the energy consumed in the building before and after modernization.

Table 8. List of heat transfer coefficients

| No. | Type of the partition         | Heat transfer coefficient U [W/(m² K)] |
|-----|-------------------------------|--------------------------------------|
|     |                               | Before modernization | After modernization | NZEB requirements |
| 1.  | Basement wall                 | 0.37                   | 0.19                 | 0.45              |
| 2.  | External wall (ground floor, first floor) | 0.35                   | 0.19                 | 0.2               |
| 3.  | Wall by the door              | 0.35                   | 0.28                 | 0.2               |
| 4.  | Wall by the stairs (zone I)   | 0.35                   | 0.25                 | 0.45              |
| 5.  | Wall by the stairs (zone II)  | 0.35                   | 0.24                 | 0.2               |
| 6.  | External ceiling              | 0.67                   | 0.15                 | 0.15              |
| 7.  | Straddle ceiling              | 0.56                   | 0.14                 | 0.15              |

Table 9 summarizes the energy used by the building before and after thermo-modernization.

Table 9. Energy analysis results

| No. Indicators                              | Before modernization | Variant 1 | Variant 2 | Variant 3 |
|--------------------------------------------|----------------------|-----------|-----------|-----------|
| 1. Coefficient EP [kWh/(m²-year)]          | 184.1                | 144.0     | 137.7     | 69.0      |
| Coefficient EK [kWh/(m²-year)]             | 261.5                | 190.6     | 179.5     | 119.5     |
| Coefficient EU [kWh/(m²-year)]             | 142.8                | 101.5     | 95.1      | 95.1      |
| CO₂ emissions [t CO₂/(m² rok)]             | 0.02874              | 0.02292   | 0.02200   | 0.00718   |
| 5. The share of RES in the annual final energy demand | 46.32% | 41.47% | 40.36% | 69.28% |

4. Conclusions
A single-family building built in the 1990s has been modernized to obtain the standard of the nZEB building. Three different variants of thermo-modernization improvements were introduced. Analyzes have shown that a comprehensive modernization is needed regarding both insulation of external walls and ceilings as well as modernization of the heating system including renewable energy sources. The results of the analyzes are summarized in Table 8. In this particular building, to obtain the nZEB standard, external walls had to be insulated with 10 cm thick polystyrene and a thermal conductivity coefficient λ = 0.04 [W/mK], in the case of the ceiling above the external space it was necessary to add a layer of insulation material 20 cm thick. The required heat transfer coefficient could not be achieved in only one case, on the wall in which the door is mounted. This is only due to technical issues.

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