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EFFECT OF REFURBISHED THERMAL INSULATION OF EXTERIOR PARTITIONS IN A BUILDING ON THE PRIMARY ENERGY AND THE AIR POLLUTANT EMISSION FACTORS

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Abstract

The paper contains an analysis of a multi-flat building located in Lębork. The calculations made for the existing building as required to issue an energy performance certificate demonstrated its high energy consumption. Renovation of the thermal insulation of the building was simulated, including all partitions enclosing rooms with regulated temperature, independent from the outdoor environment, and other unheated rooms. The effect of the thermal insulation renovation on the Primary Energy Factor and the Air Pollutant Emission Factor was tested. It was proven that the analyzed refurbishment of thermal insulation was insufficient to fulfill the reference value of primary non-renewable energy input, which would ensure considerable savings on costs (amounts of fuels) of heating.

Introduction

In 2009, according to the Directive of the European Union 2002/91/EC (Official Journal of the European Communities L 1/65 of 2002) of 16 December 2002 on the energy performance of buildings, the Polish law imposed in certain cases an obligation to obtain an energy performance certificate of a building, also known as an energy certificate. A model certificate as well as a methodology for making relevant calculations are included in the Regulation of the Minister for Infrastructure of 6 November 2008 on the methodology of calculating energy performance of a building, a residential flat or a self-contained, technical and functional part of a building, and on methods of preparing energy performance certificates, including model certificates (Journal of Law of 2008, No 201, item 1240). The objective was to promote low energy consumption buildings, both new and renovated ones.

Role of an energy performance certificate

The role of an energy performance certificate is to provide an objective and independent opinion about the primary, final and usable energy demand of a given building. These types of energy comprise the energy demand for heating (in all buildings), hot water (in all buildings), ventilation and air conditioning (if a building is equipped with a cooling installation) and lighting (in public buildings).

The usable energy for heating is calculated in monthly balances during a heating season. The usable energy for cooling is calculated in monthly balances during a cooling season. The usable energy spent on hot water heating is calculated in an annual balance, as a product of the factors that significantly influence its value. A similar calculation method is deployed for calculating the energy expended on built-in lighting installation.

The final energy is balanced out at a building's exterior boundaries, and its value expresses the demand for energy to be delivered to the building, taking into account all losses due to the efficiency of all installation systems. The demand for non-renewable primary energy determines the total efficiency of a whole building. Apart from final energy, it includes an additional, non-renewable primary energy expenditure on delivering each of the used energy carriers (e.g. coal, heating oil, gas, electricity, renewable energies, etc.) to the building's boundaries as well as auxiliary energy necessary to power auxiliary devices.

The value of primary energy is most significantly shaped by the technical condition of exterior partitions in a building. According to the laws of physics, thermal energy flows from a medium of higher temperature to a medium of lower temperature. The higher the difference in temperatures, the faster the energy flow. Approximate heat losses through partitions and a ventilation system are presented in table 1.

Table 1

Per cent heat losses thorough ventilation and exterior partitions of a building

Type of loss	Percentage [%]
Ventilation	25–35
Exterior walls in contact with atmospheric air	20–30
Exterior partitions in contact with the ground	5
Roof	20–30
Exterior windows and doors	10–20

Source: the authors.

Of the total heat losses in a building, about 70–80% are the losses through exterior partitions, which separate the interior of the building, where the temperature is regulated independently from the external environment.

According to the methodology for issuing energy performance certificates of buildings, the coefficient of heat transmission through partitions is the sum of the product of the correction coefficient of a calculated difference in exterior and interior temperatures and heat losses through particular partitions, including linear thermal bridges – complaint with the norms PN-EN 12831 and PN-EN ISO 6946.

$$H_{\mathrm{tr}} = \Sigma_i \left[b_{\mathrm{tr},i} \cdot (A_i \cdot U_i + \Sigma_i\, l_i \cdot \Psi_i)\right] \quad [\mathrm{W/K}] \tag{1}$$

where:

$b_{\mathrm{tr},i}$ – correction coefficient of the calculated exterior-interior temperature difference for the i^{th} partition,

A_i – surface area of the i^{th} partition enveloping regulated temperature space, calculated from exterior dimensions, of the partition (dimensions of windows and doors are taken as dimensions of apertures in walls) [m^2],

U_i – coefficient of heat transmission through the i^{th} partition between the heated space and the exterior [$\mathrm{W/(m^2\ K)}$],

l_i length of the i^{th} linear thermal bridge [m],

Ψ_i – linear coefficient of heat transmission through a thermal bridge according to PN-EN ISO 14683 or calculated according to PN-EN ISO 10211 [W/(m K)].

The coefficient of heat transmission by ventilation is calculated as the product of the interior heat capacity of air per volume and the sum of the product of correction coefficients of the ventilation airflow and occurring ventilation flows:

$$H_{\mathrm{ve}} = \rho_a \cdot c_a \cdot \Sigma_k\, (b_{\mathrm{ve},k} \cdot V_{\mathrm{ve},k,\mathrm{mn}})\ [\mathrm{W/K}] \tag{2}$$

The achieved values of heat loss coefficients H_{tr} and H_{ve} enable calculation of total heat flows.

The total heat transmission through partitions and ventilation is calculated in monthly balances – due to different external monthly temperatures.

$$Q_{\mathrm{tr}} = H_{\mathrm{tr}} \cdot (\theta_{\mathrm{int},H} - \theta_e) \cdot t_M \cdot 10^{-3}\ [\mathrm{kWh/month}] \tag{3}$$

$$Q_{\mathrm{ve}} = H_{\mathrm{ve}} \cdot (\theta_{\mathrm{int},H} - \theta_e) \cdot t_M \cdot 10^{-3}\ [\mathrm{kWh/month}] \tag{4}$$

where:
Q_{tr} – total heat flow by transmission through walls over a month [kWh/month],
Q_{ve} – total heat flow by ventilation over a month [kWh/month],
H_{tr} – coefficient of heat loss by transmission through all exterior partitions [W/K],
H_{ve} – coefficient of heat loss through ventilation [W/K],
$\theta_{\mathrm{int},H}$ – exterior temperature for the heating season in a building or a flat according to the requirements defined in civil engineering and technical regulations [°C],
θ_e – average air temperature during the analyzed monthly interval according to the data supplied by the nearest meteorological station [°C],
t_M – number of hours in a month (during the heating season) [h].

The sum of total heat flow through transmission and ventilation is defined as heat losses.

$$Q_{H,\mathrm{ht}} = Q_{\mathrm{tr}} + Q_{\mathrm{ve}} \text{ [kWh/month]} \tag{5}$$

The demand for usable energy for heating and ventilation, in monthly balances, is calculated by taking into account the gains from solar radiation through glass panes (windows, skylights, glazed partitions) and internal gains (heat gains from occupants, household devices, etc.).

$$Q_{H,\mathrm{nd,n}} = Q_{H,\mathrm{ht}} - \eta_{H,\mathrm{gn}} \cdot Q_{H,\mathrm{gn}} \text{ [kWh/month]} \tag{6}$$

where:
$Q_{H,\mathrm{nd}}$ – amount of heat necessary to meet the heating demand of a building (a flat, part of a building) in a month or a year [kWh/month],
$Q_{H,\mathrm{ht}}$ – heat losses through transmission and ventilation in a month [kWh/month],
$Q_{H,\mathrm{gn}}$ – internal and solar heat gains in a month [kWh/month],
$\eta_{H,\mathrm{gn}}$ – heat gain utilization factor under the heating regime.

Values of monthly heat gains from solar radiation through windows in vertical partitions of a building should be computed from the formula:

$$Q_{s1,s2} = \Sigma_i\, C_i \cdot A^{3i} \cdot I_i \cdot g \cdot k_\alpha \cdot Z \text{ [kWh/month]} \tag{7}$$

where:
C_i – ratio of the glazed surface area to the total area of a window, which depends on the size and construction type of a window; the average value is 0.7,

A_i – surface area of a window or a French window within the inside diameter of the aperture in the partition [m^2],
I_i – value of solar energy within the analyzed month relative to the vertical plane in which a window of the surface area Ai is fitted, according to the data from the nearest solar radiation measuring station [kWh/(m^2 month)],
g – coefficient of the solar energy transmission through the glazed surface,
k_α – correction coefficient of the value Ii due to the inclination of the roof to the vertical wall, $k\alpha = 1.0$,
Z – coefficient of the shading of a building due to its orientation and shading components on the building facade.

Value of internal heat gains is calculated from the equation:

$$Q_{\text{int}} = q_{\text{int}} \cdot A_f \cdot t_M \cdot 10^{-3} \text{ [kWh/month]} \tag{8}$$

where:
q_{int} – heat load of internal gains in a given room [W/m^2],
A_f – is the total floor area of rooms in a building or a flat where temperature is regulatedą [m^2],
t_M – number of hours in a month (during the heating season)]h].

As seen from dependence (1), when the value of coefficient U for construction partitions (walls, roof, windows, doors) declines, so does the value of the heat loss coefficient and, consequently, the value to the total heat flow through transmission and the value of the heat amount necessary to fulfill the heating demand of the building – dependence (6). This is reflected in the values of the final and primary usable energy needed for heating and ventilating the buildings, and in the values of the PE and FE factors.

Description of the building

The analyzed building (Fig. 1) is a multi-family, four-storey building, with two aboveground floors, a partly habitable attic and a basement. The building was constructed in 1961. The basement is not heated. In the basement, there are cellars and 11 car garages used by the building's residents. There are 16 flats in the building, situated on three floors. Three heated staircases lead to the flats. The roof is a timber, hipped construction covered with ceramic roof tiles. The building is of traditional masonry brick construction. It is fitted with the following installations:

– electric installation – repaired in 1999;
– gas installation – refurbished in 1997;
– central heating;
– sewage installation.

In 2000, the building's thermal insulation was improved by replacing old windows with new PVC ones.

Specification of the building's characteristics:
The net floor area of the building – 1169.80 m^2;
The usable floor area of the flats – 727.90 m^2;
The cubage of the building – 4 840 m^3;
The length of the building 34.73 m;
The width of the building – 11.15 m.

Fig. 1. The analyzed building
Source: the authors.

The exterior partitions, which separate the building's interior with regulated temperature and other unheated rooms from the exterior environment, consist of:
The exterior walls – 42 cm thick:
– cement and lime plaster 1.5 cm,
– a wall of face hollow blocks 25 cm,
– an air cavity 2 cm,
– a wall of solid clay bricks 12 cm,
– cement and lime plaster 1.5 cm.

The interior staircase wall – 30 cm thick:
- cement and lime plaster 1.5 cm,
- a wall of ceramic solid brick 25 cm,
- cement plaster 1 cm,
- structural cement 2.5 cm.

The ceiling above the basement – 35 cm thick:
- pinewood floor parquet on asphalt pitch 2.5 cm,
- cement screed 4 cm,
- DSM floor system 27 cm,
- cement and lime plaster 1.5 cm.

The floor above the second floor – 47.5 cm thick:
- rockwool 15 cm,
- cement screed 4 cm,
- DSM floor system 27 cm,
- cement and lime plaster 1.5 cm.

Walls between rooms in the attic – walls adjacent to the attic – 35 cm thick:
- cement and lime plaster 1.5 cm,
- a wall of face brick 18 cm,
- Styrofoam 15 cm,
- dry set wall plaster mesh 0.5 cm.

The exterior walls of the dormer windows – 42 cm thick:
- cement and lime plaster 1.5 cm,
- a wall of face hollow blocks 25 cm,
- an air cavity – 2 cm,
- a wall of solid clay brick 12 cm,
- cement and lime plaster 1.5 cm,

The exterior oblique walls (at the roof) – 28 cm thick:
- cement and lime plaster 1.5 cm,
- a wall of solid clay brick 25 cm,
- cement and lime plaster 1.5 cm.

The roof above the dormer windows:
- cement and lime plaster 1.5 cm,
- chipboard and cement board 6 cm,
- rafters 14 cm,
- a well-ventilated air cavity,
- battens 3 cm,
- ceramic roof tiles.

The central heating and hot water supply system

The building is connected to the municipal heat distribution network (hard coal). Inside the building, there is a c/h heat exchanger. Hot water is boiled in

Junkers boilers located in each flat. The general technical state of the boilers is average.
Windows
The old windows were replaced in all the building with three-chamber PVC windows of U_f = 1.5 W/m^2 K for the window frame; double glazed with U_g = 1.1 W/m^2 K for the glazing.
Location of the building: Lębork (climatic zone I).

Analysis of the actual energy performance situation

The data collected during our on-site visit were entered into a computer programme called ArCadia Thermo Pro 4.1.76 Edu. Having run the computations, values of the U factor [W/m^2 K] for particular exterior partitions, separating the regulated-temperature cubage from the external environment, were achieved, such as U = 1.01 W/m^2 K for the 42-cm-thick exterior walls, U = 1.57 W/m^2 K for the 30-cm-thick exterior walls of the staircases, U = 1.52 W/m^2 K for the 35-cm-thick floor above the basement, U = 0.28 W/m^2 K for the 47.5-cm-thick floor above the second floor (separating residential flats from the unheated attic), U = 0.25 W/m^2 K for the 35-cm-thick walls of residential flats in the attic adjacent to the unheated attic, U = 1.01 W/m^2 K for the 42-cm-thick exterior walls in the dormer windows, U = 1.88 W/m^2 K for the 28-cm-thick exterior oblique walls(sides of the dormer windows), and U = 0.93 W/m^2 K for the ceiling (floor) above the dormer windows.

The calculations yielded the value of the consumed non-renewable primary energy PE = 372.9 kWh/(m^2 year) against the reference PE = 139.48 kWh/(m^2 year).

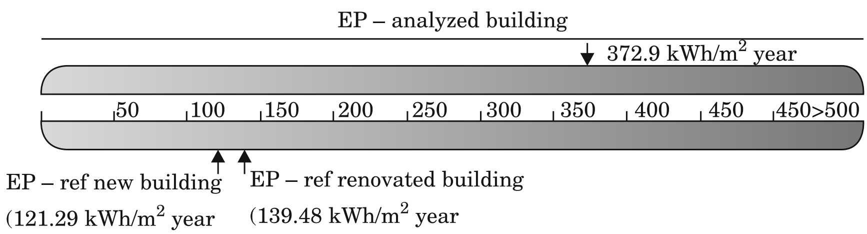

Fig. 2. Value of the consumed, non-renewable primary energy for the analyzed building
Source: ArCadia Thermo PRO, educational version, Intersoft.

Below, the final energy value for the existing condition of the building is specified alongside the quantities of fuels needed to supply the households with heating and hot water, according to the reference norms.

Table 2

Values of the final energy for the actual energy performance situation

Type of fuel – c/h	Share %	$\eta_{H.tot}$	H_u	Unit	$Q_{K.H}$ [kWh/year]	Fuel consumption B	Unit
Fuel – coal	100.0	0.63	7.70	kWh/kg	178 829.47	23 224.61	kg/year
Type of fuel – hot water	Share %	$\eta_{W.tot}$	H_u	Unit	$Q_{K.W}$ [kWh/year]	Fuel consumption B	Unit
Fuel – natural gas	100.0	0.36	9.97	kWh/m^3	69 371.32	6 958.01	m^3/year

H_u – heating value
Source: the authors, using ArCadia Thermo PRO, educational version, Intersoft.

In order to simulate the amounts of pollutants emitted to the environment depending on the type of fuel used in the central heating and hot water systems, an application of the programme ArCadia Thermo PRO, educational version, called The Eco Effect, was used. From the input data, it helps to calculate amounts of emitted airborne SO_2, NOX, CO, CO_2, ash, soot and B-a-P. This kind of analysis is necessary when an investment project is audited in order to apply for EU funds or for support from the Polish Environmental Protection Fund. Calculations of the emission of pollutants rely on the information and instructions published by the Ministry of the Environmental Protection, Natural Resources and Forestry 1/96, titled Emission factors of pollutants introduced to air from fuel combustion for energy generation. The above indices also include auxiliary electric devices necessary to keep central heating and hot water systems working.

Table 3

Parameters of the emission of pollutants in the existing state of the building – c/h and h/w

Parameters of the emission of pollutants – the c/h and h/w systems	Unit	SO_2	NO_x	CO	CO_2	ASH	SOOT	B-a-P
	kg/year	445.9	32.1	1 047.6	60 114.7	244.0	8.1	0.3

Source: the authors, using ArCadia Thermo PRO, educational version, Intersoft.

Analysis of the energy performance after the thermal insulation renovation

In order to improve the building's energy performance, we tested simulated refurbishment of thermal insulation of all partitions enveloping heated parts of the building which at present do not fulfill the maximum value U_{max} according to the 2008 Technical Conditions.

In our model, the exterior walls and the floor above the basement were insulated with EPS70 Styrofoam boards, of the coefficient λ = 0.042 W/m K.

The roof above the habitable part of the attic was insulated with a single layer of rockwool, of the coefficient λ = 0,035 W/m K.

Exterior walls – 42 cm thick:
- cement and lime plaster 1.5 cm,
- a wall of face hollow block 25 cm,
- an air cavity 2 cm,
- a wall of ceramic solid brick 12 cm,
- cement and lime plaster 1,5 cm,
- EPS70 Styrofoam- 15cm.

The floor above the basement – 35 cm thick:
- Pinewood floor parquet on asphalt pitch 2.5 cm,
- Cement screed 4 cm,
- DSM floor system 27 cm,
- Cement and lime plaster 1.5 cm,
- EPS70 Styrofoam – 10 cm.

Exterior walls in the dormer windows – 42 cm thick:
- Cement and lime plaster 1.5 cm,
- A wall of face hollow blocks 25 cm,
- An air cavity – 2 cm,
- A wall of solid clay brick 12 cm,
- Cement and lime plaster 1.5 cm,
- EPS70 Styrofoam – 15 cm.

Exterior oblique walls (at the roof) – 28 cm thick:
- Cement and lime plaster 1.5 cm,
- A wall of solid clay brick 25 cm,
- Cement and lime plaster 1.5 cm,
- A wall of ceramic solid brick 25 cm,
- Cement and lime plaster 1.5 cm,
- EPS70 Styrofoam – 15 cm.

The roof above the dormer windows:
- Cement and lime plaster 1.5 cm,
- Chipboard and cement board 6 cm,
- Rafters 14 cm / roockwool 14 cm,
- Battens 3 cm,
- Ceramic roof tiles.

The modelled improvement of the partitions lowered the PE to 249.4 kWh/(m^2 year), which means 33.12% savings relative to the analyzed initial value. Unfortunately, it does not modify the PE value so as to meet the requirements set in the 2008 Technical Conditions.

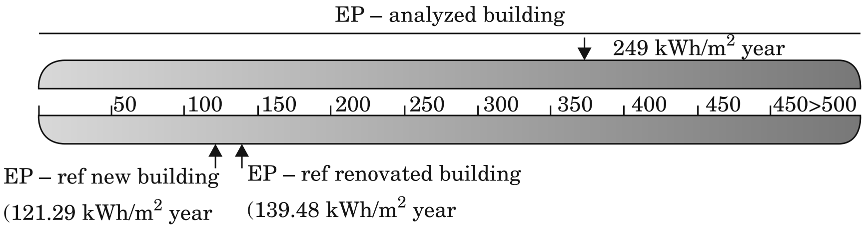

Fig. 3. Value of non-renewable energy input for the analyzed building after the proposed renovation of the thermal insulation of partitions
Source: ArCadia Thermo PRO, educational version, Intersoft.

Below, we present the final energy value of the building after the thermal insulation renovation and the amounts of fuel needed to supply the building with heat and hot water, according to the norms.

Table 4
Values of final energy for the building after thermal insulation renovation

Type of fuel – c/h	Share %	$\eta_{H.tot}$	H_u	Unit	$Q_{K.H}$ [kWh/year]	Fuel consumption B	Unit
Fuel – coal	100.0	0.63	7.70	kWh/kg	95 285.67	12 374.76	kg/year
Type of fuel – hot water	Share %	$\eta_{W.tot}$	H_u	Unit	$Q_{K.W}$ [kWh/year]	Fuel consumption B	Unit
Fuel – natural gas	100.0	0.36	9.97	kWh/m^3	69 371.32	6 958.01	m^3/year

H_u – heating value
Source: the authors, using ArCadia Thermo PRO, educational version, Intersoft.

Parameters of the emission of pollutants:

Table 5
Parameters of the emission of pollutants for the building after thermal insulation renovation – c/h and h/w

Parameters of the emission of pollutants – the c/h and h/w systems	Unit	SO_2	NO_x	CO	CO_2	ASH	SOOT	B-a-P
	kg/year	237.6	21.3	559.4	38 415.0	130.0	4.3	0.2

Source: the authors, using ArCadia Thermo PRO, educational version, Intersoft.

For comparison, the value of the final energy for the central heating system (thermal insulation renovation modifies only this value) will decrease by nearly 46.72% after the tested renovation. Fuel consumption will decrease by 46.72% relative to the initial value.

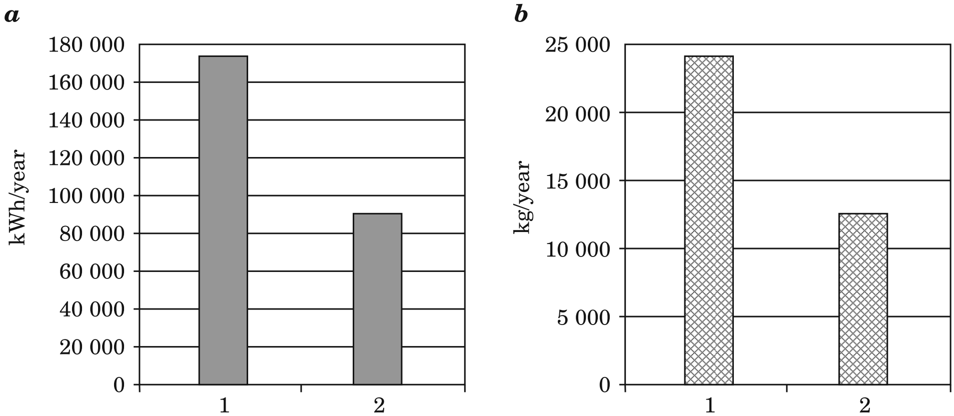

Fig. 5. Values of *a* – final energy, *b* – fuel consumption: 1. before and 2. after thermal insulation renovation

Source: the authors.

The modelled renovation of the building's thermal insulation also reduced the parameters of the emission of contamination. The change in presented in Table 6.

Table 6

Per cent change in parameters of the emission of pollutants after the renovation of thermal insulation – c/h and h/w

Change in parameters of the emission of contamination – c/h and h/w systems	Unit	SO_2	NO_x	CO	CO_2	ASH	SOOT	B-a-P
	[%]	46.71	33.64	46.60	36.10	130.0	46.72	33.33

Source: the authors, using ArCadia Thermo PRO, educational version, Intersoft.

Summary

The value of primary energy is an important source of information about the energy performance of a building. If the factor of non-renewable energy input is high, the user will know that the maintenance costs of the building are high as well. A low value of the PEF tells us that a given building will be inexpensive to maintain. Our analysis clearly demonstrates that improved thermal insulation has a significant impact on the PEF. The analyzed building, after renovation of its thermal insulation consisting in added insulation of the exterior partitions, which separate the building's space with the regulated temperature and other unheated interior space from the outdoor climate, considerably lowered the value of the PEF. As this factor corresponding to the non-renewable primary energy input decreases, so does the emission of airborne pollutants.

However, the results of our analysis prove that renovation of thermal insulation such as refurbished insulation of exterior partitions, which envelope heated and unheated rooms inside a building from the external environment, does not improve the building's energy performance well enough to fulfill the rigorous reference values given in the Regulation of the Minister for Infrastructure on technical conditions to be fulfilled by buildings and their orientation (Journal of Law2002 no 75 item 690 with further amendments). Thus, in order to meet these requirements, a major refurbishment of the central heating and hot water supply systems, which at present also generate high losses, is needed.

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