

Selected factors that impact low-energy buildings (NZEB)

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Abstract: The Directive 2010/31/EU introduces a new building standard (NZEB) in all member states of the European Union from 1.01.2021. In Poland, a low-energy building has been defined. The design, construction and use of such building is a complex process and requires knowledge of many aspects concerning building materials, general construction, building physics, installations, renewable energy systems and architectural design. Implementation of the current technical requirements in this area encompasses examining many parameters of an entire building but also of its external walls and joints. Defining them according to the applicable legal regulations and relevant standards evokes many questions and uncertainties regarding calculation procedures and interpretation of physical aspects. On the basis of conducted calculations and analyses, the authors have started a discussion on calculation methods in this field, proposing changes in legal regulations and calculation procedures.

The paper describes selected factors influencing low-energy buildings: physical parameters of building envelope elements, support of modern ventilation systems, energy performance parameters. The calculation part of the work concerns the analysis of physical parameters of the elements of low-energy building envelope and energy performance parameters of a buildings with consideration of energy saving and thermal insulation criteria. Formation of material systems of external walls and building joints requires taking into account innovative insulation materials and specific parameters of the air inside and outside of a building. The use of professional software for calculations and analyses provides reliable results.

Many coherent factors such as: architecture of a building, structural and material solutions of the external walls and their joints (elements of the building envelope), type and efficiency of the ventilation, central heating and hot water systems, use of renewable energy sources, integral management of the building in the field of energy production help to obtain optimal parameters of energy performance of the building and reduce emissions of CO₂ to the atmosphere.

Keywords: low-energy building, physical and energy parameters, legal requirements

1. Introduction

According to the national plan for increasing the number of buildings with low energy consumption [1], a low-energy building is a building that meets the energy saving and insulation requirements of the technical and operational regulations referred to in Article 7(1)(1) of the Building Law [2], i.e. in particular in Section X and Annex 2 of the Regulation [3] binding from 31 December 2020 (in case of buildings occupied and owned by public authorities from 1 January 2019).

To ensure that the amount of thermal energy required to use a building for its intended purpose can be maintained at a reasonably low level, two methods are proposed to meet the requirements of newly designed buildings:

- The first method consists in designing of a building with respect to the demand for non-renewable primary energy per unit of surface area with controlled temperature of the air in a building, residential unit or part of the building forming an independent technical and operational unit – EP [kWh/(m²·year)],
- The second method consists in designing the external walls of a building, so that the values of heat transfer coefficients U [W/(m²·K)] of external walls, windows, doors and installation technology meet the requirements of thermal insulation. Maximum values of EP_{max} and U_{cmx} (U_{max}) coefficients are specified in regulation [3]. In case of newly designed buildings, two requirements for energy saving and thermal insulation must be met simultaneously.

The paper presents an analysis of the influence of selected factors on the fulfilment of requirements of a low-energy building.

2. Identification of factors that influence low-energy buildings

Rational (optimal) energy demand of a building is based on the analysis of basic parameters regarding energy savings:

- EU – annual demand for usable energy, taking into account the objectives of heating and ventilation, domestic hot water and cooling and internal heat gains which depend on the type of space and a building, from sunlight to glazed areas – determined by the method of monthly balances for individual indoor and outdoor air parameters [kWh/(m²·year)],
- EK – annual final energy demand for the heating system, domestic hot water heating, cooling, built-in lighting (not applicable to residential buildings) and technical system (as auxiliary energy), including the average efficiency of the systems – determined on the basis of the components of the usable energy demand [kWh/(m²·year)],
- EP – annual non-renewable primary energy demand for the heating system, domestic hot water heating, cooling, built-in lighting installation (not applicable to residential buildings) with the addition of auxiliary energy use for the systems, taking into account coefficients of the input of non-renewable primary energy for the production and supply of the energy carrier or energy for technical systems w_i – determined on the basis of the components of the final energy demand [kWh/(m²·year)],
- E_{CO2} – specific CO₂ emissions from the combustion of fuels by the heating system, domestic hot water heating, cooling, built-in lighting and auxiliary equipment in technical systems [t_{CO2}/(m²·year)],
- U_{OZE} – share of renewable energy sources in annual final energy demand [%],

which are essential components of the energy performance to be determined on the basis of the Regulation [4].

Achieving the minimum value of the annual non-renewable primary energy demand indicator EP [kWh/(m²·year)], the basic energy saving parameter, depends on a number of consistent factors (Figure 1).

The design, construction and operation of low-energy buildings is a complex process and requires many calculations, computer simulations and technical-economic analyses.

Factors that impact low-energy buildings

architecture of the building: location of the building in relation to the directions of the world, compact body of the building (minimum A/V shape factor), size and location of transparent external walls, arrangement of rooms in the building depending on the calculated indoor air temperature, roof geometry, vegetation on the building plot

structural and material arrangements of external partitions and their joints (the building envelope elements): use of high quality and innovative thermal insulation materials (PIR, PUR, aerogels, vacuum, transparent insulations), school of designing of building joints in hygrothermal aspect using numerical programs; minimization of heat losses through external walls in one-dimensional (1D) and two-dimensional (2D) field and the risk of critical surface humidity and interlayer condensation

type and efficiency of ventilation system: hybrid or mechanical ventilation with heat recovery, mechanical ventilation with a thorough heat exchanger, supporting of existing natural ventilation systems – use of solar chimneys, high efficiency of systems – over 70%.

type and efficiency of central heating and hot water systems, use of renewable energy sources: high efficiency of systems – above 70%, support of central heating and hot water systems with renewable energy sources (solar energy, wind energy, geothermal energy)

integrated building management in the field of energy production and system-based energy management in a building – BMS

Fig. 1. Factors that shape low-energy buildings – authors' own study

3. Analysis of selected factors that influence low-energy buildings

The work included an analysis of selected factors that impact low-energy buildings: physical parameters of building envelope elements, support of modern ventilation systems, and parameters of energy performance.

3.1. Physical parameters of low-energy building envelope elements

A building consists of many building partitions and their joints of individual physical characteristics and is subject to changeable indoor and outdoor conditions. In many cases, the analysis of the external walls and construction joints in terms of construction and material, as well as execution technology does not usually raise objections at the design stage. On the other hand, the knowledge of hygrothermal (physical) parameters, related to the exchange of heat and humidity, helps to avoid many design and construction flaws and to ensure the appropriate parameters of the indoor microclimate during use (appropriate temperature, humidity and cleanliness of the air inside a building). Figure 2 shows a scheme for evaluating the quality of the building envelope elements in the hygrothermal aspect.

Additional heat fluxes, due to inadequately or insufficiently insulated bridges, may even exceed the values of basic fluxes occurring in a continuous (solid) partition without thermal bridges. The numerical procedure (with the use of software), required by PN-EN ISO 10211:2008 [5] raises a significant objection; it is unclear and difficult to use it in a reasonable

manner. The value of the coefficient Ψ gives linear (per 1mb) heat losses through the bridge, usually adopted with an assumption that the calculation area at a distance of two partition thicknesses from the bridge edge is extended. Therefore, several bridges frequently overlap in an external wall. In such case, it is not possible to sum up Ψ coefficients for particular geometry, e.g. pillar: window – connecting wall. In publications intended for professional physical calculations, e.g. in [6, 7] external walls, generally the values of Ψ coefficients are given in relation to the whole joint with thermal bridge, participating in heat flow. Determination of quantitative share of individual bridges in total heat losses through a partition requires separation of partial values of coefficients corresponding to branches of the joint within the tested partition. It can be obtained by additional numerical calculations, determining values of branch heat transfer coefficient. Calculation procedures in this respect are described in the papers [8, 9].

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- determination of the heat transfer coefficient U (U_{1D}) of a single flat wall
- determination of linear heat transfer coefficient Ψ of the joint in the 2D field
- determination of point heat transfer coefficient X of the joint in the 3D field
- determination of heat transfer coefficient taking into account linear (2D) and spatial (3D) thermal bridges U_{2D} , U_{3D}
- determination of the minimum temperature on the internal surface of the wall at the place of the thermal bridge $t_{\min,(2D)}$, $t_{\min,(3D)}$ at assumed temperatures inside and outside of a building
- determination of the temperature factor $f_{Rsi(2D)}$, $f_{Rsi(3D)}$
- determination of the possibility of interlayer condensation

Fig. 2. Factors shaping the quality of external walls and their joints in the hygrothermal aspect – authors' own elaboration

Nowadays, hygrothermal calculations should use the extensive database, which is still to be created or completed in Poland, with the division for the local climate zones and individual towns. Determination of the temperature factor f_{Rsi} ($f_{Rsi(2D)}$, $f_{Rsi(3D)}$) [-] in analysed joint of external walls requires determination of minimum temperature on the internal surface of a wall and in the place of thermal bridge, assuming appropriate indoor θ_i and outdoor θ_e temperature. However, the required value of limiting temperature factor $f_{Rsi(kryt)}$ is determined as a function of temperature θ_i and moisture, φ_i , and the space it concerns. These parameters (indoor temperature and moisture level in the area) determine the value of the temperature factor $f_{Rsi(kryt)}$, the decisive limit in assessing the correctness of the joint design solutions. According to PN-EN ISO 13788:2003 [10], the temperature factor $f_{Rsi(kryt)}$ is calculated or adopted depending on the type of ventilation used in the building (gravitational ventilation – dominating in residential buildings or mechanical ventilation, being often a component of air conditioning systems, helping to shape freely the properties of the interior microclimate).

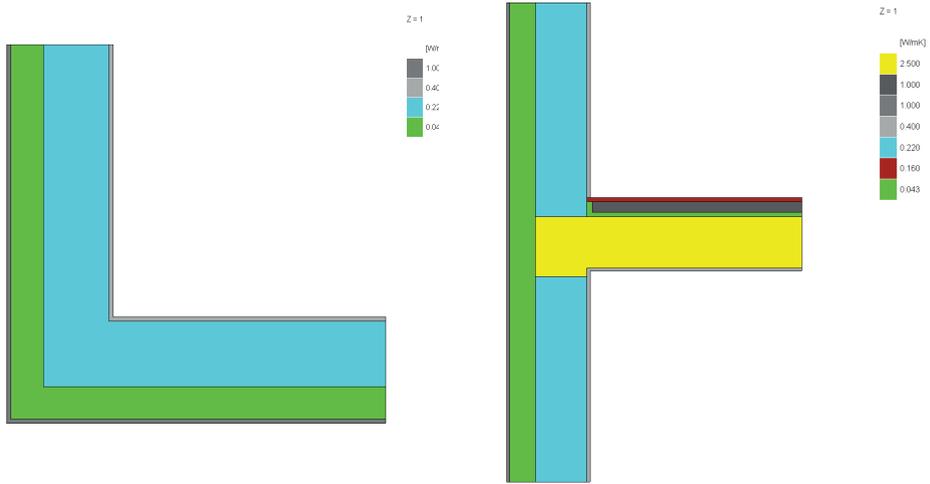
Taking into account real two- and three-dimensional (2D and 3D) heat transfers occurring in external walls may lead to significant differences in values of thermal parameters (heat transfer coefficient U , transmission heat loss coefficient H), which define the external walls of the same building. External walls with a large surface of windows openings or with some thermal bridges which are difficult to limit (balconies, lintels, corners) may have high U -values and pose a risk of moisture condensation on the internal surface of the partitions.

For the purpose of calculations, the joints of the external two-layer wall considered in four calculation variants were selected:

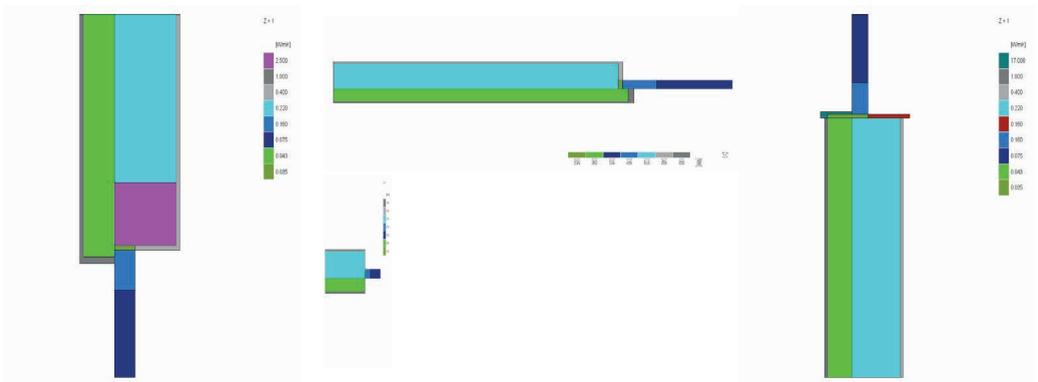
- Variant I: 24-cm thick cellular concrete block of $\lambda=0.17$ W/(m·K), 10-cm thick polystyrene boards; 15 cm by $\lambda=0.04$ W/(m·K),
- Variant II: 24-cm thick cellular concrete block by $\lambda=0.17$ W/(m·K), 10-cm thick polyisocyanurate (PIR) panels; 15 cm by $\lambda=0.022$ W/(m·K),
- Variant III: lime and sand block 24-cm thick by $\lambda=0.55$ W/(m·K), polystyrene plates 10-cm thick; 15 cm by $\lambda=0.04$ W/(m·K),
- Variant IV: lime and sand block 24-cm thick by $\lambda=0.55$ W/(m·K), polyisocyanurate (PIR) boards 10-cm thick; 15 cm by $\lambda=0.022$ W/(m·K).

The calculations of physical parameters were performed with the use of the KOBRU-TRISCO software [11], based on the following assumptions:

- the modelling of joints was performed in accordance with the principles described in PN-EN ISO 10211:2008 [5] and in the papers [8, 9],
- the heat transfer resistance (R_{si} , R_{se}) was adopted in accordance with PN-EN ISO 6946:2008 [12] for the calculation of thermal fluxes and in accordance with PN-EN ISO 13788:2003 [10] for the calculation of temperature distribution and the temperature factor $f_{Rsi(2D)}$,
- indoor temperature $\theta_i = 20$ °C (living room), outdoor temperature $\theta_e = -20$ °C (zone III),
- the values of heat conduction coefficient of construction materials λ [W/(m·K)] are based on the following tables in the paper [9],
- the following joints were selected: connection of external walls in a corner (Z1), connection of an external wall with a ceiling in section through a rim (Z2), connection of an external wall with a window in section through a window sill (Z3), connection of an external wall with a window in section through a lintel (Z4), connection of an external wall with a window in section through a frame (Z5) – Figure 3.



a) connection of the external walls in the corner b) connection of the external walls with ceiling with a rim



c) connection of an external wall with a window in section through a lintel d) connection of an external wall with a window in section through a frame e) connection of an external wall with a window in section through a window sill

Fig. 3. Examples of calculation models of the analysed construction joints – authors' own elaboration

The results of the calculations of physical parameters are presented in Table 1.

Table 1. The results of calculations of physical parameters of double-layer wall joints – authors' own elaboration

Physical parameters of external wall joints		Calculation variants of the joints							
		I ₍₁₀₎	I ₍₁₅₎	II ₍₁₀₎	II ₍₁₅₎	III ₍₁₀₎	III ₍₁₅₎	IV ₍₁₀₎	IV ₍₁₅₎
Z1	$U_{e(1D)}$	0.24	0.19	0.16	0.12	0.32	0.23	0.19	0.13
	Ψ_i	0.075	0.067	0.060	0.052	0.129	0.105	0.090	0.068
	$\theta_{min.}$	14.37	15.36	15.88	16.78	13.55	15.07	15.80	16.92
	$f_{Rsi(2D)}$	0.859	0.884	0.897	0.920	0.839	0.877	0.895	0.923
Z2	$U_{e(1D)}$	0.24	0.19	0.16	0.12	0.32	0.23	0.19	0.13
	Ψ_i	0.131	0.090	0.075	0.051	0.125	0.086	0.073	0.048
	$\theta_{min.}$	16.67	17.57	17.94	18.55	16.79	17.72	18.07	18.66
	$f_{Rsi(2D)}$	0.917	0.939	0.949	0.964	0.920	0.943	0.952	0.967
Z3	$U_{e(1D)}$	0.24	0.19	0.16	0.12	0.32	0.23	0.19	0.13
	U_w	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	Ψ_i	0.056	0.062	0.059	0.064	0.136	0.147	0.144	0.151
	$\theta_{min.}$	13.67	13.91	14.19	14.37	11.73	12.11	12.45	12.70
Z4	$f_{Rsi(2D)}$	0.842	0.848	0.855	0.859	0.793	0.803	0.811	0.818
	$U_{e(1D)}$	0.24	0.19	0.16	0.12	0.32	0.23	0.19	0.13
	U_w	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	Ψ_i	0.081	0.086	0.074	0.079	0.075	0.083	0.072	0.077
Z5	$\theta_{min.}$	14.76	15.29	15.80	16.15	14.90	15.49	15.97	16.34
	$f_{Rsi(2D)}$	0.869	0.882	0.895	0.904	0.873	0.887	0.899	0.909
	$U_{e(1D)}$	0.24	0.19	0.16	0.12	0.32	0.23	0.19	0.13
	U_w	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Z5	Ψ_i	0.052	0.059	0.054	0.060	0.061	0.070	0.063	0.069
	$\theta_{min.}$	13.66	14.05	14.50	14.79	14.16	14.70	15.20	15.56
	$f_{Rsi(2D)}$	0.842	0.851	0.863	0.870	0.854	0.868	0.880	0.889

$U_{e(1D)}$ – external wall heat transfer coefficient [W/(m²·K)]
 U_w – window heat transfer coefficient [W/(m²·K)]
 Ψ_i – linear heat transfer coefficient [W/(m·K)]
 $\theta_{min.}$ – minimum temperature on the internal surface of a wall in place of a thermal bridge [°C]
 $f_{Rsi(2D)}$ – temperature factor, determined on the basis of $t_{min.}$ [-]

In the second stage of calculations, heat losses through the wall of the ground floor of the building (with a window of different size – Figure 4) were determined including linear thermal bridges according to own calculation algorithms. For calculations, the values of Ψ_i [W/(m·K)], specified in the first stage of calculations – Table 1, were used. The results of thermal parameters are summarised in Tables 2 and 3.

to the Regulation [4] is dubious because its application may result in a significant discrepancy of calculation results for a given building, depending on the approach of the designer (certifier).

Table 3. The results of calculations of heat losses through an external wall and window carpentry of a building including linear thermal bridges – authors' own elaboration

Calculation variant		Thermal parameters of analysed external walls				
		$U_c (U_{1D})/U_w$	$\frac{U_c \cdot A_i + U_w \cdot A_i}{U_w \cdot A_i}$	$\Sigma \Psi_i \cdot l_i$	$H_D = \frac{U_c \cdot A_i + U_w \cdot A_i}{\Sigma \Psi_i \cdot l_i}$	$U_{K(sr)} = H_D / A_{oi}$
$I_{(10)}$	A	0.24 / 0.90	3.71	0.87	4.58	0.37
	B		5.69	1.14	6.83	0.55
$I_{(15)}$	A	0.19 / 0.90	3.27	0.81	4.08	0.33
	B		5.40	1.03	6.43	0.52
$II_{(10)}$	A	0.16 / 0.90	3.02	0.64	3.66	0.29
	B		5.23	0.90	6.13	0.49
$II_{(15)}$	A	0.12 / 0.90	2.66	0.67	3.23	0.26
	B		5.00	0.85	5.85	0.47
$III_{(10)}$	A	0.32 / 0.90	4.40	0.96	5.36	0.42
	B		6.14	1.39	7.53	0.56
$III_{(15)}$	A	0.23 / 0.90	3.62	1.06	4.68	0.38
	B		5.63	1.31	6.94	0.56
$IV_{(10)}$	A	0.19 / 0.90	3.27	0.76	4.03	0.32
	B		5.40	1.19	6.59	0.53
$IV_{(15)}$	A	0.13 / 0.90	2.75	0.68	3.43	0.28
	B		5.06	1.14	6.20	0.50

A – an external wall with a window 1.2x1.5 m; **B** – an external wall with a window 3.2x1.5m
 $U_{c(1D)}$ – external wall heat transfer coefficient [W/(m²·K)]
 U_w – window heat transfer coefficient [W/(m²·K)]
 A_i – external wall surface area [m²]
 Ψ_i – linear heat transfer coefficient [W/(m·K)]
 l_i – length of a thermal bridge [m]
 H_D – heat loss by transfer coefficient [W/K]
 $U_{K(sr)}$ – average external wall heat transfer coefficient [W/(m²·K)]
 A_{oi} – surface area of an external wall in the axes of walls that are perpendicular to it [m²]

3.2. Improvements to modern ventilation systems in buildings

According to the Regulation [3], the ventilation should ensure appropriate quality of the indoor environment, including the air exchange rate, cleanliness, temperature, relative humidity, and the speed of air movement in a room. These recommendations should be fulfilled while observing all applicable regulations concerning the mentioned installation. The ventilation system may be designed as mechanical or gravitational in rooms intended for people, in rooms without windows that can be opened, as well as in other rooms where, for health, technological or safety reasons, air exchange is necessary. Taking into account the amount of energy used in mechanical ventilation systems, it is worth to consider alternative solutions that allow, however, to maintain the existing regulations and provide a comfortable indoor environment. The first issue related to the ventilation system is the amount of ventilation air that should be supplied to the rooms according to the standard PN-83/B-03430/Az3:2000 [13].

The growth of construction industry resulted in sealing of buildings, which worsened the air flow in the rooms, while at the same time the needs of their users have changed. Consequently, their requirements increased and the search for appropriate gravitational

ventilation system solutions began. Some of the numerous ways of supporting gravity ventilation include:

- Chimney cowls, which primary task is to increase the vacuum in the exhaust duct using wind speeds. At a very low wind speed, the covers and ventilators cause additional resistance to the air flow. Increase in wind speed contributes to an increase of the total pressure. They are affected by the difference in air density and the negative pressure generated in the ventilator casing, which results in higher intensity of ventilation in the facility.
- Double-glazed walls (two-layer walls), which when exposed to sunlight cause an increase in the temperature in the interlayer space. The outer layer additionally serves as a wind screen and an acoustic screen; the air void between the glass layers serves as a circulation channel. The air heated in the interlayer space circulates upwards and goes outside the building. The upward airflow leads out the used, warm air, sucking in cool air from outside at the bottom.
- Glazed atriums and passages are located inside a building. The air heated in the upper part of the atrium is led out through the circulation openings, which are located in the roof section. The created negative pressure causes the so-called chimney effect, which results in sucking air from the lower parts of the building. The air flow in the upward direction causes the fresh air from the bottom to enter the building. This air is brought in through the openable windows in the facade. Glazed atrium is a transverse-ventilation system. The air entering through the windows flows transversely through the rooms. Then, after being heated, it goes up in the atrium space to be led out of the building.
- Solar chimneys are devices that support gravitational ventilation in a building where the convection effect of air heated by solar energy is used. The principle of operation of solar chimneys is similar to that of traditional chimneys. A characteristic feature is strengthening of natural displacement ventilation using passive solar heating. The energy of insolation is obtained in a natural way, thanks to the heat and mass exchange processes. The efficiency of the solar chimney depends on the temperature within the chimney duct. The amount of heat transmitted from the sunlight has a direct influence on the temperature, and this is connected with the incident angle of the sunrays on the surface. Therefore, the inclination angle of the solar chimney is a very important parameter to determine the intensity of natural ventilation. Since the 1990s, research has been conducted on this subject. Scientists have been trying to determine the optimum angle values by various methods. However, it is a very complex issue, as the air flow is influenced not only by insolation but also by other factors such as wind speed and air humidity [14].

3.3. Energy performance parameters of a building

When determining the annual final energy demand for a building or a part of a building for the EK heating system [$\text{kWh}/(\text{m}^2 \cdot \text{year})$], the efficiencies are taken into account resulting from: regulation and use of the heat in the heated space ($\eta_{\text{H,e}}$), transfer of heat from the heat source to the heated space ($\eta_{\text{H,d}}$), heat accumulation in the capacitive elements of a heating system ($\eta_{\text{H,s}}$), the heat generated from an energy carrier or the energy supplied to the heat source ($\eta_{\text{H,g}}$). The heating installation in a building shall comply with technical building regulations and take into account technical knowledge regarding energy-saving

solutions. The system to be designed shall be a high-efficiency system. Highly efficient heat sources should be planned, and every effort should be made to reduce losses resulting from the transmission of the heating medium. If there is a heat discharge tank, the accumulation losses should be minimal and the elements responsible for heat regulation and use should be optimally selected. Maximum possible efficiencies can be achieved in accordance with [15], among others, through using condensing boilers, heat pumps with a high coefficient of performance (COP), appropriate routing of the heating medium distribution pipes (compact installation) and their proper thermal insulation, correct insulation of buffer tanks, as well as charging and discharging control selected for their specific operation and use, low-temperature surface, radiator or mixed heating systems, selection of regulation and control technology ensuring the highest efficiency of regulation in a given system structure and usage, use of high-efficiency auxiliary pumps with low power consumption resulting in low auxiliary energy consumption.

The annual non-renewable primary energy demand EP [kWh/(m²·year)] determines the total efficiency of a building. It refers to the energy contained in the sources, including fuels and carriers, necessary to cover the final energy demand, taking into account the additional investment to deliver this energy to the perimeter of a building. The value of non-renewable primary energy input factor for generating and delivering an energy carrier or energy for technical systems shall be taken from the data provided by the supplier of that energy carrier or energy. Low values indicate little need for non-renewable primary energy EP and the determination of the energy class of the building.

Table 4 summarises the energy performance parameters of three analysed buildings, defined on the basis of the procedures presented in the Regulation [4].

Table 4. Comparative analysis of energy performance parameters of selected buildings – authors' own elaboration

Analysed parameters of the building	Building I	Building II	Building III
The type and destination of the building	Residential, one-family Bydgoszcz	Residential, one-family Bydgoszcz	Residential, one-family Bydgoszcz
External walls of the building	$U_c < U_{cmax/2014-2017/}$	$U_c < U_{cmax/2014-2017/}$	$U_c < U_{cmax/2014-2017/}$
Ventilation system	Gravitational, Ventilation with diffusers	Gravitational, Ventilation with diffusers	Gravitational, Ventilation with diffusers
Rooms area with controlled air temperature (heated or cooled area) A_f [m ²]	121.25	85.50	291.00
Indicator of annual usable energy demand EU [kWh/(m ² ·rok)]	48.13	76.58	63.15
Seasonal average efficiency of the heating system	0.693 ¹⁾	0.735 ³⁾	0.693 ⁵⁾
Seasonal average efficiency of the hot water preparation system	0.442 ²⁾	0.531 ⁴⁾	0.312 ⁶⁾
Annual final energy demand indicator EK [kWh/(m ² ·year)]	57.43	116.78	143.83
Indicator of the input of non-renewable primary energy for the generating and delivering of an energy carrier or energy for technical systems w_i ³⁾	Bituminous coal ($w_i=1.1$) biomass ($w_i=0.2$)	Heating oil ($w_i=1.1$) biomass ($w_i=0.2$)	Bituminous coal ($w_i=1.1$)
Indicator of annual non-renewable primary energy demand EP [kWh/(m ² ·year)]	70.50	110.95	158.20
Specific emission of CO ₂ [t _{CO2} /(m ² ·year)]	0.02	0.03	0.06
Share of renewable energy sources in annual final energy demand [%]	9.40	20.00	0.00

¹⁾ heat generation efficiency – **0.82** (coal boiler produced after 2000, fireplace), heat transfer efficiency – **0.96** (central heating from a local heat source, located in the heated and insulated building), heat accumulation efficiency – **1.0** (without buffer tank), regulation efficiency and heat utilisation – **0.88** (water heating with panel radiators, central and local regulation, floor heating in the ground floor)

²⁾ heat generation efficiency – **0.65** (two-function eco-pea boiler), heat transfer efficiency – **0.80** (central water heating in a one-family house), heat accumulation efficiency – **0.85** (hot water storage tank produced after 2005)

³⁾ heat generation efficiency – **0.87** (low-temperature liquid fuel boiler of 50kW nominal output, fireplace), heat transfer efficiency – **0.96** (central heating from a local heat source, located in the heated and insulated building), heat accumulation efficiency – **1.0** (without buffer tank), regulation efficiency and heat utilisation – **0.88** (water heating with panel radiators, central and local regulation, floor heating in the ground floor)

⁴⁾ heat generation efficiency – **0.83** (low-temperature liquid fuel boiler of 50kW nominal output), heat transfer efficiency – **0.80** (central water heating in a one-family house), heat accumulation efficiency – **0.80** (150 l tank)

⁵⁾ heat generation efficiency – **0.82** (coal boiler produced after 2000), heat transfer efficiency – **0.96** (central heating from a local heat source, located in the heated and insulated building), heat accumulation efficiency – **1.0** (without buffer tank), regulation efficiency and heat utilisation – **0.88** (water heating with panel radiators, central and local regulation)

⁶⁾ heat generation efficiency – **0.65** (solid fuel two-function boiler), heat transfer efficiency – **0.60** (central water heating in a one-family house), heat accumulation efficiency – **0.80** (hot water tank produced in the years 2001-2005)

Precise determination of the energy performance of a building requires comprehensive knowledge of many technical issues and calculation procedures in this area. The value of the EU coefficient depends mainly on the energy balance of a building (heat gain and loss analysis). Whereas the value of EK coefficient depends on the value of EU coefficient and average seasonal efficiency of heating system and hot water preparation. As a final result of the calculations, after taking into account the ratio of the input of non-renewable primary energy for the generation and supply of energy carrier or energy for technical systems w_1 , the EP coefficient is obtained. To meet the requirements for achieving the standard of low-energy building in terms of the EP-value (e.g. for a one-family building, less than 70 kWh/(m²·year)), it is necessary to design the building envelope and joints that ensure minimum heat loss by transfer ($U_c \leq U_{cmax}$), to select appropriate components for central heating, hot water, ventilation, cooling (with particular emphasis on efficiency) and to use a renewable energy source. Detailed analyses concerning the influence of thermal quality of external walls of a building on their energy demand (EU, EK, EP) are also described in detail in the paper [16].

4. Summary and conclusions

The design, construction and use of low-energy buildings is a complex process and requires knowledge of a wide range of issues in the field of building materials, general construction, building physics, building installations, renewable energy systems and architectural design.

Proper design of the building envelope (external walls and building joints) consists in meeting the hygrothermal requirements specified in the regulation [3]. In engineering calculations in the hygrothermal aspect, the authors propose to use professional catalogues of thermal bridges. Lowering the limit values of U_{max} heat transfer coefficients without taking into account heat fluxes in the (2D) and (3D) field, i.e. thermal bridges, actually allows greater heat losses through external walls and their joints. Moreover, it is justified to determine the limit values of linear heat transfer coefficient Ψ_{max} at the level of 0,05÷0,10 W/(m·K) depending on the characteristics of an analysed joint.

The humidity requirements according to the regulation [3] should be checked by appropriate calculation methods, and in particular it should be determined:

- Temperature factors of joints in building envelope to confirm the requirement: $f_{Rsi} \geq f_{Rsi(kryt)}$. All joints must be verified by two- or three-dimensional calculation (depending on their type). The mentioned calculations are the essence of realization of the condition of preventing critical surface moisture on the building envelope.
- Volume of annual moisture of the building envelope as a result of diffusion of steam to assess their ability to resist inter-layer condensation.

Analysing the joints of external walls (Table 1), it can be concluded that there is no risk of critical surface moisture because the calculated values of temperature factors f_{Rsi} [-] are greater than the limit value of temperature factor $f_{Rsi, (kryt.)}$ [-]. The (critical) threshold value of the temperature factor, taking into account the parameters of indoor and outdoor air, of the analysed calculation variants is $f_{Rsi, (kryt.)} = 0,78$.

Reasonable (optimal) energy demand for a building consists in considering many factors, among others: minimising transmission heat losses – applies to building envelope elements, limiting heat loss resulting from ventilation while ensuring appropriate parameters of the interior microclimate (temperature, humidity and air cleanliness), designing innovative technical solutions for installations based on renewable energy sources. All these activities and aspects

result in minimizing the energy demand and consumption (during use) and CO₂ emissions to the atmosphere.

On the basis of calculations, computer simulations and analyses, it should be emphasized that an energy-efficient building is a building in which applied design and technical solutions enable it to be used at low energy consumption, while ensuring comfortable hygienic and sanitary conditions.

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