“In situ” measurements in energy saving building certificate

M. Fedorczak-Cisak, M. Furtak

***Abstract*—** Energy-saving building certification is a very important instrument which enables to judge the quality of buildings performance and their real influence on the environment and building users.

Access to the European Union forced Poland to implement building standards which take into account reduction of energy consumption. Like in other UE countries there is a high demand to design near zero-energy buildings.

The need for evaluation and guarantee that the erected buildings are of proper quality lead Małopolska Center of Energy-saving Buildings (MCBE) to develop energy- saving certificate (named MCBE Certificate). This very first energy – saving building certificate in Poland takes into account local climate conditions, local energy distributors coefficients and local architectural regulations.

MCBE certificate indicates three important areas: energy characteristics, carbon footprint (environmental impact) and in situ measurements of buildings connected with their real energy consumption. The first building to have passed the certificate procedure is Malopolska Laboratory of Energy Energy–saving Building (MLBE) in Cracow University of Technology.

The first part of the article shows certificate methodology developed in dynamic simulations.

The in situ studies which are the basis of issuing MCBE Certificate are presented in the second part of the article.

The study of insulating envelope tightness of a building has been described in more detail. It is the most important study which should be carried out before granting a building a certificate proving its energy saving quality.

The “in situ” measurements are one of the most important tasks of the Malopolska Centre of Energy Saving Building.

***Keywords*—**energy-efficient buildings, certificate buildings, Near Zero Energy Buildings (NZEB), “in situ” measurements.

I. ENERGY EFFICIENT BUILDING - CERTIFICATION OF BUILDINGS

BUILDING sector in Poland has been undergoing significant transformation which eventually will fulfill the obligations of Poland as a Member State in the EU in this field Implementation of 2002/91/EC Directive and its more detailed version 2010/31/UE [14] concerning energy performance of the buildings demands from us designing buildings of considerably lowered energy consumption – “near zero energy buildings” (NZEB). The process of designing buildings of so low energy consumption in comparison to the traditional objects affects construction and materials solutions as well as insulation systems which would provide structural safety and meet strict requirements of heat protection. Objects of almost zero energy demand require a specific approach both to the design process and to the realization and usage of the objects. Such buildings have very tight envelopes and their thermal insulation parameters are very restrictive. They are equipped with specialized installation systems, which to the maximum, active or passive, make use of renewable energy for example, by orienting the object onto the southern side and in this way harnessing solar energy. In result, these are objects of minimum demand for energy, both primary (providing information about non-renewable sources of energy consumption) and the final one, determining actual energy requirements of the building. Designing energy efficient buildings is a challenge for architects, especially in respect of providing appropriate thermal protection but also ensuring the comfort of using the building (Fig. 1) [5], [6], [7]. All the aspects of providing comfort for the users should be taken into consideration and very thoroughly analyzed during the process of designing energy efficient buildings [8-12].

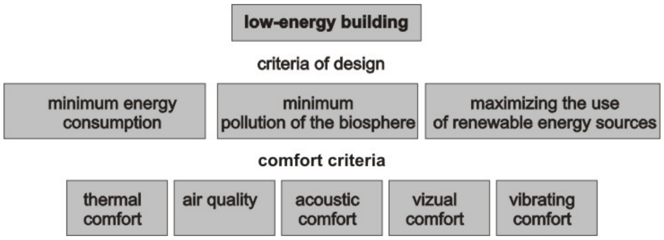

Fig. 1 The criteria considered in designing near zero energy buildings

In designing and erecting an energy saving building it is necessary to check its parameters for appropriate thermal insulation, energy demand, meeting comfort requirements or use of eco-friendly materials.

Certification is a guarantee that the design and construction of the object was an appropriate one and by evaluating

MCBE - MALOPOLSKA CENTER OF ENERGY-SAVING BUILDING
This investment is an innovative unit of Cracow University of Technology, whose aim is to establish a partnership network of cooperation between science and business. Such cooperation enables scientists and entrepreneurs to develop and implement new technologies in the field of energy efficient construction.

MLBE – MALOPOLSKA LABORATORY OF ENERGY-SAVING BUILDING
The independent scientific unit of Faculty of Civil Engineering of Cracow University of Technology dedicated to research of energy efficient systems and constructions.

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properly selected parameters it proves the standard the building was constructed in.

Certification process may comprise the conceptual and the design and construction processes as well as the use of the object.

All over the world there are certificates - assessments of buildings. One of the most important is the LCA method (life cycle assessment). This method assumes the building assessment throughout its whole life cycle. The processes of acquiring raw materials, building materials production and usage of the buildings significantly consume natural resources and are one of the main emitters of harmful substances. Although it is not possible to completely eliminate the negative impact of the building on the environment, such tools as LCA allow to minimize it. Rational use of resources and raw materials is possible carrying out a detailed analysis of the influence the designed building will have on the man, the climate and the environment.

The analysis is carried out both for the whole life cycle of the building as well as for different stages of its life: production of construction materials, building erection phase, usage of the building and its demolition, what makes it one of the most methodically advanced tools for environmental assessment. The analysis takes into account the most important environmental indicators, among others: the greenhouse effect, soil and water acidification, photochemical ozone synthesis ability, fresh water consumption.

Other certification methods developed in different countries are considerably simplified in comparison to the LCA [2]. They are all listed in table I. Presented evaluation systems as the main criterion assume the influence the building has on the environment, and they partly take into account social and economic aspects. Table II shows the main evaluation criteria taken into account in various certification systems.

Table I. Environmental assessments developed for different countries [1]

System	**Environment**	**Social aspects**	**Economic aspects**	**Under development**
EU Flower	YES	NO	NO	under development
BREEAM	YES	Partly	NO	for environmental assessment
LEED	YES	Partly	NO	the US is not adapted to the conditions of the EU
DGNB	YES	YES	Partly	Only Germany
SBTool	YES	YES	YES	research
CASBEE	YES	YES	YES	Only Japan

Table II. Environmental assessments developed for different countries

System	**Country**	**Rated issue**
BREEAM	U.K.	management comfort energy transport water consumption materials land use ecology waste
LEED	U.S.A.	sustainability the effectiveness of water management energy and atmospheric pollution materials and resources indoor environmental quality innovation and design process
GBTool	iiSBE	consumption of resources environmental burden Indoor environmental quality quality of service economy management transport and communication
CASBEE	Japan	quality of the building internal environment quality of service external Environment environmental burden energy raw materials and consumables external Environment

Since they are involved in each of the stages: design, erection and use of the buildings, all of the presented environmental assessment systems require a long period of time to prepare the final version of the certificate,

Each of the systems has been developed for the climatic conditions of the concerned country (the United Kingdom, the United States, Germany, Japan), taking into consideration not only the local climate, but also the base of construction materials available for a given country, or specific requirements of the buildings.

II. MALOPOLSKA ENERGY EFFICIENT BUILDING CERTIFICATE (MCBE)

Experts from Małopolska Center of Energy-saving Building (MCBE) in cooperation with Malopolska Laboratory of Energy-saving building (MLBE) recognizing the necessity of certification of buildings developed their MCBE Certificate. This document confirms high energy characteristics of a building, its solid construction and its minimal influence on the environment, and comfort and health for the users.

The certification process starts with the design stage, in which the MCBE team helps to determine the design parameters of the future investment. During construction phase experts from Cracow University of Technology check whether the building is built correctly, according to the design and construction assumptions and when it is already in use it will be checked

for the correctness of its execution and the interior environment quality.

Additionally, carbon footprint of the building will be specified to show what is its influence on the environment.

The building that meets the MCBE Certificate criteria means only positives for the user – starting from health, through better living comfort, the environment protection, up to fair savings for the owner. Such a building requires much less energy for heating and ventilation in comparison to the traditional technology, to a great extent it uses heat from a variety of renewable energy sources, it also uses natural light (Fig. 2).

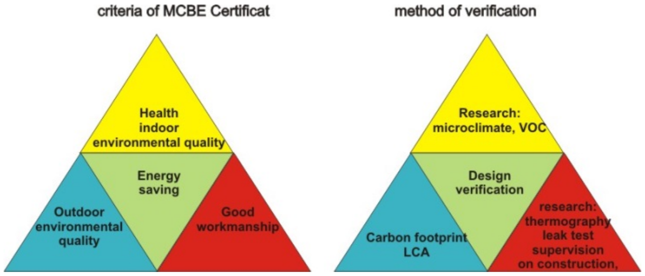

Fig.2 MCBE Certificate Criteria

III. DESIGN ASSUMPTIONS OF MCBE CERTIFICATE

To adopt a correct assumption about establishing the level of energy parameters and parameter limits for heat protection of the buildings for the MCBE certificate several energy simulations were carried out. The simulations included calculating the heating energy demand, domestic hot water preparation, cooling (if there is a cooling installation in the building) and lighting (in the case of public buildings) for different building types. As a calculation basis for the buildings certification in the Malopolska province, a method was used, adopted from the Regulation of the Minister of Infrastructure and Development from June 3rd 2014, on the methodology of calculating energy performance of a building and a dwelling.

Requirement calculations for primary and final energy were carried out on the monthly balance sheet method basis in accordance with the energy performance calculation methodology. [13-27].

A. Weather data

Malopolska province varies in terms of climatic conditions. There are three different climate zones that meet the standard PN-80/B-02403. MCBE experts assumed that the MCBE certificate will take into account different climatic conditions of Malopolska. The figure below shows the breakdown of the climate zones (Fig. 3).

Fig. 3 Climate zones in Malopolska

For calculations weather data from the website of the Ministry of Infrastructure and Development for meteorological stations representing the Malopolska province areas: Krakow climate zone III, Nowy Sacz climate zone IV and Zakopane climate zone V (Fig. 3). Meteorological data include the average multi-annual values of the open-air temperature, and solar radiation for particular months of the year.

Calculations were carried out for the following types of buildings:

- single family (in addition to phase 1- calculation according to current regulations, checking classes)

− three single-family houses of different A/V coefficient, one floor building, a building with a usable attic, a two floor building with unused attic,

- multi-family – four multifamily buildings with different A/V coefficient,

- residential building with a service part – one multi-family building with services on the ground floor,

- public building – two office buildings of different A/V coefficient, two school buildings of different A/V coefficient and one building of bigger floor height, for example a sports hall,

- commercial – two commercial buildings with different A/V coefficient.

Table III. Geometric data of the analyzed buildings

Model of building	**Usable area**	**The cubic capacity with controlled temp.**	**A/V**	**The degree of glazing in exterior walls**
	m2	m3	1/m	-
Single-family 1	150	367,5	0,66	0,09
Single-family 1 with garage	178,9	448,6	0,63	0,07

Single-family 2	122,1	310,9	0,73	0,09
Single-family 3	149,2	356,3	0,8	0,08
Multi-family 1	5286,7	13713,7	0,32	0,23
Multi-family 2	2627,3	6581,7	0,35	0,20
Multi-family 3	1956,1	4996,9	0,44	0,18
Multi-family 4	966,53	2404,8	0,47	0,16
services part	1956,1	5175,9	0,44	0,18
Living part	1480,3	3749,2		
Services part	475,8	1426,7		
Office 1	4952,8	17209,2	0,10	0,60
Office 2	11031,4	38873,4	0,12	0,59
Sports hall 1	633,4	2620,4	0,41	0,06
Commercial1	10062,1	83313,9	0,16	0,00
Commercial 2	2261,2	13197,4	0,26	0,06
School 1	2651	10668,7	0,18	0,07
School 2	2663,7	11156,4	0,31	0,07

In the analysis of all the buildings the following coefficient values of heat transfer through external walls were assumed, what is set in the table below (Table IV).

Table IV. Summary of heat transfer coefficients through external walls

Type of partition	**Coefficient heat transfer U**
	[W/m2K]
External wall	0,15
ground floor	0,20
The ceiling above unheated space	0,15
The roof above unheated space	0,25
Windows	0,9
External walls	1,3

B. *Heating system*

The calculation of the final and primary energy demand was carried out for two commonly used solutions. The first was the central heating installation powered by gas, while the other one was supplied by the local heat distribution network. The tables below show partial efficiencies used in calculations.

C. *Ventilation system*

In the analysis includes two types of ventilation are taken into consideration: natural and mechanical intake-exhaust ventilation, with heat recovery of maximum efficiency up to 80%. The tightness of the building in the case of natural ventilation is n50 = 3.00 1/h while in the case of mechanical ventilation it is n50 = 1.5 1/h. In the technical conditions it is noted that in the building of up to 9 stories gravitational or mechanical ventilation can be used. In higher buildings mechanical exhaust or intake-exhaust ventilation should be used. Therefore, in the multi-family buildings 1 and 2 instead of natural ventilation, mechanical exhaust ventilation was used. The tightness of the building in the case of exhaust ventilation is n50 = 1.5 1/h.

D. *Hot water preparation system*

Calculation of the final and primary energy demand was carried out for two commonly used installation solutions. The first one was the gas installation for preparing hot water, while the other one was supplied by the local heat distribution network. The tables below show partial efficiencies applied in the calculations.

E. *Non-renewable primary energy coefficients*

Non-renewable primary energy coefficients are in accordance with the regulation referring to energy characteristics of the building and data provided on the websites of the heating companies and are as follows:

− network gas = 1.1;
− eclectic energy w = 3.0;
- MPEC-Krakow 2013w = 0.62;
- Nowy Sacz w MPEC = 1.3;
- Geotermia Podhalańska w = 0.39.

As a result of the carried out analyses the following values were assumed for buildings that meet the assumptions of Malopolska Energy-saving Building Certificate.

Table V. Parameter values for Malopolska Energy-efficient Building Certificate and method of verification

Parameters		**Method of verification**
Coefficient U [W/m2K]		
External walls: a) $t_i \geq 16^{o}C$ b) $8^{o}C \leq t_i < 16^{o}C$ c) $t_i < 8^{o}C$	0,15 0,45 0,90	architectural and building documentations
External Roofs a) $t_i \geq 16^{o}C$ b) $8^{o}C \leq t_i < 16^{o}C$ c) $t_i < 8^{o}C$	0,15 0,30 0,70	architectural and building documentations
Ground floors a) $t_i \geq 16^{o}C$ b) $8^{o}C \leq t_i < 16^{o}C$ c) $t_i < 8^{o}C$	0,20 1,20 1,50	architectural and building documentations
External windows a) $t_i \geq 16^{o}C$ b) $t_i < 16^{o}C$	0,9 1,4	architectural and building documentations
External doors	1,3	architectural and building documentations
Energy consumption [kWh/m^{2}a]		
Coefficient EP (Primary Energy)	70	energy performance

Parameters		**Method of verification**
Coefficient EU (Use of Energy) single family building	60	energy performance
Coefficient EU (Use of Energy) multifamily building	40	energy performance
„In situ" tests		
Leak test	Yes	In situ
Air quality	Yes	In situ
Thermovision	Optional	In situ
Thermal comfort	Optional	In situ

The value of the indicator of Energy Use of a building which satisfies the assumptions of the MCBE Certificate, taking into account the climate zones in Malopolska.

Table VI. Reference indicator of energy demand for heating and cooling EU'_{ref} taking into account of the correction value factor related to the location of the building ΔE

Type of building	**Reference indicator of primary energy demand $EU'_{ref} = EU_{ref} \Delta E$ [kWh/(m^{2}rok)]**			
	Kraków	Nowy Sącz	Tarnów	Zakopane
Single-family building	60,0	58,8	56,4	74,3
Multifamily buildings	40,0	39,2	37,6	49,5
single-family houses with a system of cooling	62,5	61,3	58,8	77,4
multi-family buildings with the installation of cooling	42,5	41,7	40,0	52,6
public buildings	60,0	58,8	56,4	74,3
public buildings with cooling installation	65,0	63,7	61,1	80,5

The value of primary energy ratio of the building which satisfies the assumptions of the MCBE Certificate, taking into account the climate zones in Malopolska.

Table VII. Primary energy demand reference indicator to heating and cooling EP'_{ref} taking into account of the correction value factor related to the location of the building ΔE

Type of building	**Reference indicator of primary energy demand $EP'_{ref} = EP_{ref} \Delta E$ [kWh/(m^{2}rok)]**			
	Kraków	Nowy Sącz	Tarnów	Zakopane
Single-family	70,0	68,6	65,8	86,6
Multi family	70,0	68,6	65,8	86,6
single-family houses with a system of cooling	75,0	73,5	70,5	92,8
multi-family buildings with the installation of cooling	75,0	73,5	70,5	92,8
public buildings	120,0	117,6	112,8	148,5
public buildings with cooling installation	145,0	142,1	136,3	179,5

IV. Malopolska Laboratory of Energy–saving Building

The first object granted MCBE Certificate is a super innovative building - Malopolska Laboratory of Energy-Saving Building.

It is a building erected in the center of Cracow, adapted to the surrounding existing buildings.

The building is realized in pole-plate technology.

Geometric parameters:

- Usable area of the building: 1,039.39 m^2
- Cubature of the building: 5 050.41m^3
- Number of floors in the building: 5
- Building height: 19.24 m
- Roof geometry - flat roof

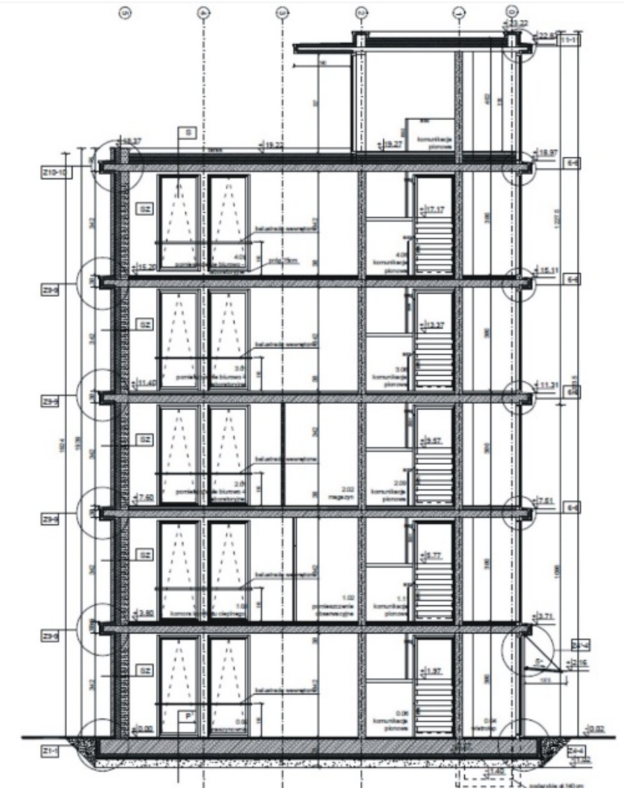

Fig. 4 Cross-section of the MLBE building

MLBE building is fully automated and it is a laboratory to test energy-saving technologies "in situ".

MLBE is equipped with the research systems:
- 6 independent heating sources
- 14 independent climate zones
- 3 thermal wells (125 m)
- 2 ground heat exchangers
- 3000 sensors

Table VII, IX. Thermal parameters MLBE

Type of partition	**Coefficient heat transfer U**[W/m2K]
External wall	0,12
Ground floor	0,10
Roof	0,13
Windows	0,70
External door	0,80

Energy consumption coefficient	**[kWh/m^{2}a]**
EP	119,6
EU$_{H+W}$	13,6

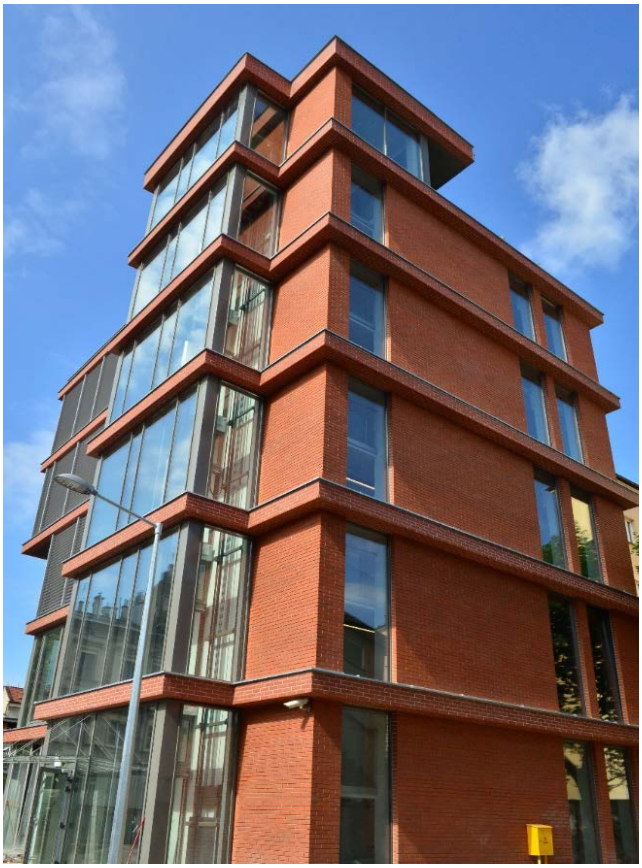

Fig. 5 View of the MLBE building. Laboratory of energy efficient technology

V. “IN SITU” STUDIES AS A PART OF MCBE CERTIFICATE

The in situ studies are one of the most important tasks of the Malopolska Certificate of Energy Saving Building.

Table X. Studies carried out during actual exploitation of the building required for the MCBE Certificate

Studies of the existing building state				
Type of studies		Certificate MCBE STANDARD	Certificate MCBE PREMIUM	Process of verification
Tightness study		yes	yes	– study during exploitation
Interior air quality (concentration of contaminants from the building materials)		yes	yes	– study during exploitation
Thermo-visual study (failures detection)		no	yes	– study during exploitation
Winter climate study (t_e<-5^{0}C)		no	yes	– study during exploitation
Winter climate study (t_e>+20^{0}C)		no	yes	– study during exploitation
Microclimate in winter		-	-0,5<PMV<0,5	– study during exploitation
Microclimate in summer	With cooling	-	-	– study during exploitation
	Without cooling	-	-	-

*Microclimate study should be carried out in representative rooms destined for continual presence of people (more than 30 minutes. Calculations according to PN-EN ISO 7730. In summer and winter time at least one room on the northern and eastern sides of the building should be chosen. Additionally, at least one room with the largest glazing of the building envelope should be checked, as well as a corner room. Before carrying out microclimate measurements the choice of the rooms has to be approved of by the MCBE scholarly team.

The in situ studies allow to check whether the realized building fulfills design assumptions.

The studies carried out during the actual usage are also a basis to qualify the building as the energy saving one, comfortable and friendly for the users.

The in situ studies prove that the process of the building construction was the correct one and that the attempted aims of minimizing energy consumption and optimization of the user's comfort were achieved.

The studies carried out in the buildings in the actual usage scale are not simple. Many problems can be encountered. When carrying out the in situ studies conditions when they can be realized have to be carefully selected (e.g. in the case of thermovision – winter months). Also measurement and results interpretation errors should be taken into account.

In this part of the article the authors describe the basic test - measuring the tightness of the building envelope that should be done on energy-efficient buildings. They also provide examples of their studies carried out on various types of buildings and conclusions.

VI. TESTING THE BUILDING ENVELOPE TIGHTNESS BY PRESSURE MEASURING METHOD

A. *Tightness study*

In the existing buildings the quality and accuracy of the construction works largely influence the actual energy demand. Inaccurate and often incompatible with the design documentation, construction of the buildings often causes execution errors, such as thermal bridges. Thermal bridges in a building envelope can be construction elements (reinforced concrete piles, lintels, strengthening beams) but also gaps and cracks resulting from inaccurate assembling.

Uncontrolled flow of the air through the gaps and cracks in the building envelope negatively affects thermal insulation performance and durability of the envelope. It also reduces the comfort of usage, caused by drafts, dust and dirt getting into the rooms.

In detecting such failures and leaks in the external envelopes a non-invasive tightness test (so called Blower Door Test) or tracer-gas leak method is used.

In Polish technological regulations [13] there are values required of the coefficient of the amount of air filling the building in an hour at 50 Pa difference in pressures between the inside and outside conditions.

The permitted values depend on the type of ventilation:
Buildings with gravitational ventilation: $n_{50} \leq 3,0$ [1 / h]
Buildings with mechanical ventilation $n_{50} \leq 1,5$ [1 / h]

Table XI. Air tightness requirements in other European countries

EU countries	**Necessary tightness 50 Pa**	
	Gravitation ventilation	Mechanical ventilation
Poland	3,0 [1/h]	1,5 [1/h]
Lithuania	3,0 [1/h]	1,5 [1/h]
Germany	3,0 [1/h] or 7,8 [m^3/h] per [m^2] floor area	1,5 [1/h] of 3,9 [m^3/h] per [m^2] floor area
Czech Republic	4,5 [1/h]	Without recuperation: 1,5 [1/h] With recuperation: 1,0 [1/h]
UK	New buildings, Public buildings 500 [m^2]: 10 [m^3/m^{2}h]	
Holland	Residential : 200 [dm^3/s] (10 Pa) No residential: 200 [dm^3/s] per 500 [m^3] (10 Pa)	
Sweden	No requirements	
Estonia	No requirements	
Latvia	3,0 m^3/h per [m^2] heating floor area	
Finland	4,0 [1/h]	
Norway	3,0 [1/h]	
Danish	1,5 [l/s] per [m^2] floor area	

Admittedly, in Polish regulations there is no obligation to perform tightness tests. The requirements in [13] are given in order to consider them in the calculations, for example in energy performance of the building.

However, the necessity of performing the test appears at the time of applying for a subsidy for realization of energy saving buildings with energy demand below 40 [kWh/m2a] (NF40) and below 15 [kWh/m2a] (NF15) [27].

Building envelope tightness of $n_{50} \leq 0{,}6$[1/h] level is required for buildings which are to be granted the certificate of passive buildings. In this case apart from accepting in the calculations such a tightness, it is also necessary to carry out the in situ tests.

The amount of air exchange coefficient n_{50} is determined according to the standard PN –EN 13 829 [23]. The concept of tightness determined in the standard DIN 4108-7 in which tightness was identified as a feature of the material, of the building envelope or of its part. The aim of testing the building tightness according to as pressure ventilation method is to determine air permeability of the object envelope or its fragment. The standard distinguishes two testing methods: A and B.

Method A refers to the building in use. It involves closing all the holes in the building, e.g. windows, doors, openings of chimney conduits, sewage installations. Testing tightness by means of method A requires opening of the doors in the tested part of the building in such a way that all the tested object or its part reacts to the changes in pressure as if it were one zone.

Method B is a method in which the envelope of the building is tested, it additionally demands closing all the adjustable openings and plugging the remaining deliberately made openings.

Additionally, tightness test can be carried out by sub-atmospheric or over-pressure methods. It is important that the difference in pressures between the inside of the building and its outside is 50 Pa. To obtain reliable results it is necessary to carry out the test by two methods and thus get the average of the measurements.

The standard [23] does not specify which method should be chosen. Most often, for the wholly sealed building envelope the test is carried out by method B. It would be a correct and complex solution to carry out the test for both A and B methods in overpressure as well as sub-pressure and get the average result.

B. *Measurements results*

The main idea of testing air tightness of the building is to determine the amount of $n_{\Delta pr}$ air exchange in the conditions of pressure difference, colloquially known as coefficient of multiple air exchange rate.

$$n_{\Delta pr} = \frac{V_{\Delta pr}}{V} \qquad \{1\}$$

$V_{\Delta pr}$ – average air stream leakage value measured in the overpressure and sub-pressure conditions [m^3]

V – inside cubic capacity [m^3]

Average air leakage stream $V_{\Delta pr}$ in the conditions of pressure difference is calculated from:

$$V_{\Delta pr} = C_L(\Delta p_r)^n \qquad \{2\}$$

where:

C_L – air leakage coefficient, dependent on the inside air density in overpressure condition and on the outside in sub-pressure conditions and on the air density in standard conditions[m3/(h·Pa^n)]

Δp_r – reference pressure [Pa]

n – flow exponent, determined separately for over- and sub-pressure

When determining the value of the generated pressure difference Δp it is necessary to take into account the influence of the difference in pressures in the zero flow condition, subtracting their average from each of the measured pressure differences during measurements.

$$\Delta p = \Delta p_m - \frac{\Delta p_{01} + \Delta p_{02}}{2} \qquad \{3\}$$

where:

Δp_m – measured pressure difference [Pa]

Δp_{01} – average of all pressure difference values in zero flow before testing [Pa]

Δp_{02} – average of all pressure difference values in zero flow after testing [Pa].

Additional indicators which can be calculated using the above values are air permeability and leakage of air flow unit w_{50}.

$$q_{50} = \frac{V_{50}}{A_E} \quad \text{and} \quad w_{50} = \frac{V_{50}}{A_F} \qquad \{4\}$$

where:

V_{50} – stream of air leakage in the conditions of pressure difference 50 Pa [m^3]

A_E – area of the tested envelope of inside cubic capacity [m^2]

A_F – net floor area of the tested inside cubic capacity [m^2]

The results of air tightness, as most laboratory or in situ measurements, may be affected by an error dependent on different factors. These may be errors caused by incorrect calibration of the used equipment, disorders in pressure readings influenced by gusts of wind or incompetent values calculation.

Thermo-visual tests can be helpful in detecting leakage. They are described in the subsequent part of this article. The examples of thermal bridges detection in tightness tests are illustrated in Fig. 6.

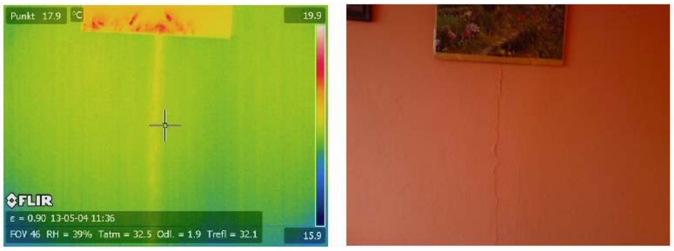

Fig. 6 Thermal bridge formed in the place of vertical connection of prefabricated units of the so called concrete panel units W-70 [10]

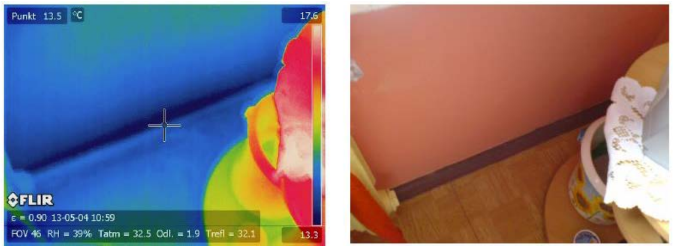

Fig. 7 Thermal bridge formed at the connection of the flor with the external wall exposed thanks to the pressure built up inside the object [10]

Thermo-visual tests are carried out according to PN-EN 131874 standard:

Thermal properties of a building – Quality detection of thermal failures in the building envelope – Infrared method.

VII. AIR TIGHTNESS TESTSTING IN OBJECTS OF VARIOUS PURPOSES.

The studies were carried out for a Master Thesis needs [3].

Retrotec Door Fan Q4E measurement set was used in the tests, it included Retrotec 3300SR ventilator, digital differential micro-manometer Retrotec DM-2 and FanTestic 5.6.3.33 software.

The studies were carried out on ten objects. In the table geometrical data of the tested object are presented.

Table XII. Parameters of analyzing buildings

No.	**Parameters of buildings**				
	Type	High [m]	Cube V [m^3]	Area of external partition s A_E [m^2]	Area of floor A_F[m^2]
1	Single family	8,9	542	602,8	134,1
2	kindergarten	7,0	1 880	1 535	525
3	a house built of wooden logs	7,43	348	219	115,2
4	a single dwelling	15	252,5	109,8	96
5	educational hall	5,7	2 986	1 799,3	586,7

TEST 1 SINGLE FAMILY DETACHED HOUSE

When taking the measurements the building was in the stage of completion, no ventilation equipment was installed. The test was carried out by means of method B. In the case of test no 1 the whole testing procedure was presented, other tests present only the final results.

Fig. 8 Passive house in Januszowice

Tightness measurement results by means of B method at overpressure and sub-pressure presents table XIII.

Table XIII. Air tightness testing. Januszowice – B method – overpressure, sub-pressure

	Result	95% Trust range		Uncertainty
Air flow for 50 Pa, **Q_{50} [m^3/h]**	**517,90**	**509,6**	**526,3**	**+/- 1,6%**
Number of air exchanges for 50 Pa, n_{50} [1/h]	**0,955**	**0,937**	**0,9736**	**+/- 1,9%**
Permeability for 50 Pa, **q_{50} [m^3/h.m^2]**	**0,859**	**0,843**	**0,875**	**+/- 1,9%**
Air Leakage area for 50 Pa, **w_{50} [cm^2]**	**3,862**	**3,788**	**3,9352**	**+/- 1,9%**

Table XIV. Air tightness testing. Januszowice – B method – sub-pressure, sub-pressure

	Result	95% Trust range		Uncertainty
Air flow for 50 Pa, **Q_{50} [m^3/h]**	**568,82**	**564,6**	**573,1**	**+/- 0,7%**
Number of air exchanges for 50 Pa, n_{50} [1/h]	**1,049**	**1,036**	**1,063**	**+/- 1,2%**
Permeability for 50 Pa, **q_{50} [m^3/h.m^2]**	**0,9436**	**0,932**	**0,955**	**+/- 1,2%**
Air Leakage area for 50 Pa, **w_{50} [cm^2]**	**4,2418**	**4,1888**	**4,2948**	**+/- 1,2%**

Taking average values n_{50} from the received in two variants measurements we get the result 1,005 [h-1], which falls into the required tightness range for the buildings with mechanical ventilation, being $n_{50} \leq 1,5$ [h-1].

However, the carried out test referred to a building designed according to passive standard, for which the required tightness is determined as $n_{50} \leq 0,6$.

Table XV. Final results of research in Januszowice

	Result	95% Trust range		Uncertainty
Air flow for 50 Pa, **Q_{50} [m^3/h]**	**543,5**	**537,0**	**549,5**	**+/- 1,2%**
Number of air exchanges for 50 Pa, n_{50} [1/h]	**1,005**	**0,9870**	**1,020**	**+/- 1,6%**
Permeability for 50 Pa, **q_{50} [m^3/h.m^2]**	**0,901**	**0,887**	**0,915**	**+/- 2,0%**
Air Leakage area for 50 Pa, **w_{50} [cm^2]**	**4,052**	**3,989**	**4,115**	**+/- 2,0%**

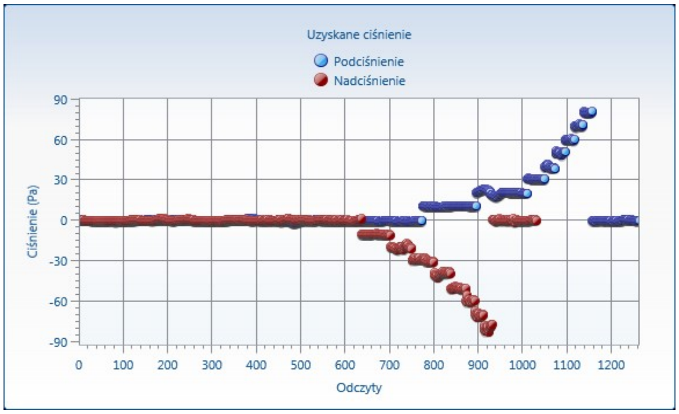

Fig. 9 Overall setting up of enforced pressure, depending on the readings. Januszowice

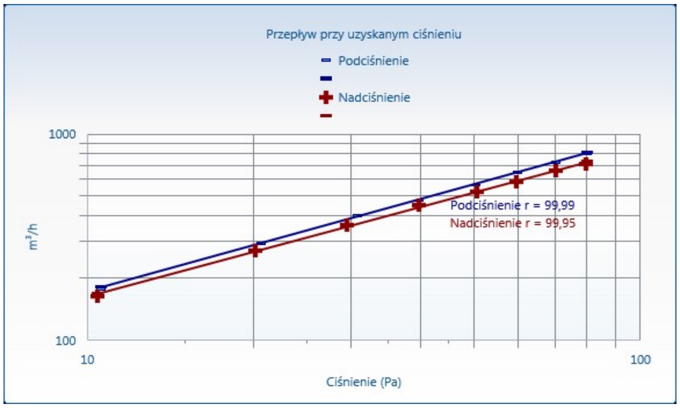

Fig. 10 Overall diagram of air leakage depending on pressure Januszowice

It was expected to achieve tightness of $n_{50} \leq 0,6$[1/h] level. The result exceeds the permitted -multiple value of air exchange for passive buildings. In this case the building envelope has to be checked in order to find the leakage and seal it. Detection in which smoke was used proved that window and door woodworks were done properly and the places of cut through in the building envelope were properly sealed. Irregularities were localized in installation cut through the partitions separating the rooms from the installation shaft, causing uncontrolled air flow. Additional checking of the sealing showed that in result of sub-pressure test there followed peeling off the tapes and foils from ventilation openings.

Fig. 11 Leakage caused by improper finishing of the sewage installation cut through the partition [author's own source]

TEST 2 THE KINDERGARTEN BUILDING

The test was carried out when the building was fully finished, furnished and ready to be used. The analyzed object had all the installations fixed: ventilation, electric, water and sewage. The kindergarten had mechanical ventilation, therefore it was assumed that n_{50} value achieved would be lower or close to 1,5 [h^{-1}]. The test was carried out by B method. All the openings in the building envelope were plugged and sealed. All doors and external windows were opened in contrast to the internal ones, thus allowing to create a uniform, in respect to pressure, zone.

Fig. 12 Tested kindergarten and nursery in Baranów [3]

Total test results present an average from the sub- and overpressure methods.

Table XVI. Total results on research Baranów

	Result	**95% Trust range**		**Uncertainty**
Air flow for 50 Pa, **Q_{50} [m^3/h]**	**5340**	**5215**	**5465**	**+/- 2,4%**
Number of air exchanges for 50 Pa, n_{50} [1/h]	**2,840**	**2,685**	**3,000**	**+/- 5,5%**
Permeability for 50 Pa, **q_{50} [m^3/h.m^2]**	**3,479**	**3,287**	**3,671**	**+/- 5,5%**
Air Leakage area for 50 Pa, **w_{50} [cm^2]**	**10,172**	**9,610**	**10,734**	**+/- 5,5%**

The achieved result was $\boldsymbol{n_{50}}$ **= 2,840*[1/h]***. Such tightness is not enough for the buildings with mechanical ventilation. Leakage detection in the building envelope revealed that the main factors causing an increased value of –multiple air coefficient were errors in window woodwork, precisely in the external glazed façade in the dining room and doors and windows in the remaining rooms.

Fig. 13 Sub-pressure conditions, in connection with spot caused smoke on the outside of the building allowed to detect leakages by the observer in the inside. Here: air leakage at the lower edge of the glazed façade

TEST 3 A HOUSE BUILT OF WOODEN LOGS

The test was carried out when the building was fully finished, furnished and prepared to be used.

The test was carried out by B method. The expected result, due to gravitational ventilation installed, was to be n_{50} = 3,0 [1/h].

Fig. 14 Tested house built of wooden logs [3]

Table XVII. Results in house built of wooden logs

Research metods	**Wynik badań n_{50} [1/h]**
subpressure	22,85
overpressure	16,05
Total results	19,45

Technology of building a house of wooden logs means connecting tree trunks by means of e.g. hemp ropes. This technology does not allow to achieve a complete tightness of the envelope, because in many places misfits occur and air can get through. It could have been additionally sealed with e.g. structural foam, however, such a solution would spoil a traditional character of the technology used in building houses of wooden logs.

TEST 4 A SINGLE FLAT IN A BLOCK OF FLATS

In the case of carrying out pressure tests in big objects, it is possible to test tightness of particular single flats, the results of which may illustrate a general tightness level of the whole building. Although the standard [5] permits such a solution, it is difficult to determine, however, what influence the neighbouring rooms may have on the measurement results of a given flat. The test was carried out in a single flat in the attic of a block of flats.

Fig. 15 Block of flats in which the tested flat is situated [Source: Grzegorz Zaręba]

The flat is on the top floor of a six storey block of flats built with a basement. In the building there are 27 flats localized on the left side of a single stair case.

The test was carried out according to method B.

Table XVIII. Total results on research Bobrowskiego

	Result	95% Trust range		Uncert ainty
Air flow for 50 Pa, **Q_{50} [m^3/h]**	**1465**	**1370**	**1565**	**+/- 6,3%**
Number of air exchanges for 50 Pa, n_{50} [1/h]	**5,805**	**5,280**	**6,330**	**+/- 9,0%**
Permeability for 50 Pa, **q_{50} [m^3/h.m^2]**	**13,34**	**12,14**	**14,552**	**+/- 9,0%**
Air Leakage area for 50 Pa, **w_{50} [cm^2]**	**15,26**	**13,88**	**16,644**	**+/- 9,0%**

The tested flat had gravitational ventilation, therefore the expected result was the value close to 3 [1/h], however, as it can be seen from table XVIII -multiple of air exchange was twice as much, that is 5,8 [1/h].

Significant leakages were noticed in the places of window sills connections with the walls, in which the speed reached 4,15 [m/s]. In most cases the leakage was caused by cut through of the inside partitions or outside envelopes. Such a situation may prove the air getting through the wall layers to the leakages in the roof layers (the flat is at the top attic floor), in the place of balcony fixing or at the lower level than that of the tested flat, what was impossible to be detected.

TEST 5 TIGHTNESS OF ENERGY EFFICIENT HALL

The test was carried out on the first in Poland almost zero energy hall. The annual energy demand of the object is about 12 kWh/m^2.

Fig.16. Low Energy hall in a School Complex of Vocational Education in Bielawa [Source : author's own archive]

The test was carried out by method B. The expected tightness result below 0,6 exchanges per hour.

Table XIX. Total results on research Bielawa

	Result	95% Trust range		Uncertainty
Air flow for 50 Pa, **Q_{50} [m^3/h]**	**1950**	**1920**	**1970**	**+/- 1,1%**
Number of air exchanges for 50 Pa, n_{50} [1/h]	**0,653**	**0,620**	**0,6870**	**+/- 5,1%**
Permeability for 50 Pa, **q_{50} [m^3/h.m^2]**	**1,084**	**1,029**	**1,140**	**+/- 5,1%**
Air Leakage area for 50 Pa, **w_{50} [cm^2]**	**3,325**	**3,155**	**3,496**	**+/- 5,1%**

The analysis of the hall envelope, using thermo-visual measurements was done simultaneously with the measurements of tightness. On the basis of thermograms the zones that underwent cooling due to air movement can be seen.

One of the leakage causes was the point at which the envelope was cut by ventilation installation equipped with heat recovery.

Window woodwork fastening was checked by thermos-visual method. Making use of thermo-vision and anemometric probe fissures were found in between the hollow bricks of the window openings.

Table XX. All analysis research

Research	**Expected result n_{50} [1/h]**	**In situ tests result n_{50} [1/h]**	**Cause of leakage**
1	0,60	1,005	- irregularities in the places of installations cut through - peeling off of the tapes and foil from ventilation openings
2	1,50	2,840	- errors in window woodwork assembling
3	3,0	19,45	- technology making required tightness impossible to achieve
4	3,0	5,805	- leakage in places of connecting window sills with the walls - cut through the inside partitions or external envelopes
5	0,60	0,6535	- improper assembling of the windows

VIII. SUMMARY

Many factors are decisive in the building being energy efficient. First of all the design of the building has to be prepared according to the regulations of integrated design. There have to be accepted proper designing assumptions referring to heat permeability coefficients and to the choice of installation systems, what greatly influences the amount of used energy. Equally important is the quality of the materials used to erect a building and the care of its execution.

Constructing energy efficient building requires a great care and knowledge of the regulations. Each element is essential and influences actual energy consumption.

In Poland, as the process of energy efficient buildings introduction is in its early stage, there is lack of specialists who can properly design and construct an energy efficient building.

Execution verifications should be carried out by means of the in situ tests. The in situ tests are indispensable to prove the quality and energy efficiency level of a building. Study results presented in the article explicitly show that the assumed at the design stage tightness of the external walls (building envelope), which has a direct influence on energy consumption at the stage of usage, was not achieved in any case. Therefore the tests have to be incorporated into the system of energy efficient buildings certification, which is the case of the Certificate.

Whether the building is energy-efficient is decided by many factors. First, the design of the building must be made in accordance with the principles of integrated design. Appropriate design assumptions must be taken on the heat transfer coefficients and energy consumption. Just as important is the quality of the materials used for its construction and execution stage care. A comprehensive review of the whole process, both the executive and the design is a difficult task for the investor, because it requires knowledge of many engineering disciplines. Certification of energy-efficient buildings is a necessary part of the verification of the buildings for adequate heat protection and comfort of the rooms.

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