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How to achieve Nearly zero-energy buildings standard

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Subject review

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The implementation of the Nearly zero-energy buildings (NZEB) standard has enabled significant developments in the design and realisation of external building envelopes, which have the greatest influence on the quality of buildings in the sense of energy efficiency. Experience has shown that prerequisites for good-quality realisation of works mainly include competent and motivated workforce, appropriate equipment, and good communication between all participants in construction. Basic principles of architectural and civil engineering design and realisation of NZEB projects are presented, and problems occurring and possibly resulting in construction damage are presented in the paper.

Key words:

Nearly zero-energy building, NZEB, energy efficiency, external building envelope, thermal bridges, airtightness, infrared thermography

Pregledni rad

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Kako postići standard zgrade gotovo nulte energije

Implementacijom standarda zgrade gotovo nulte energije (NZEB) došlo je do značajnog razvoja projektiranja i izvođenja vanjske ovojnice zgrade koja ima najveći utjecaj na kvalitetu zgrade u smislu energetske učinkovitosti. Praksa pokazuje da za kvalitetno izvođenje radova treba kompetentna i motivirana radna snaga, odgovarajuća oprema i dobra komunikacija između svih sudionika u građenju. U radu su prikazani osnovni principi arhitektonsko-građevinskog projektiranja i izvođenja NZEB-a te su predočeni problemi koji se javljaju i mogu rezultirati građevinskom štetom.

Ključne riječi:

zgrada gotovo nulte energije, NZEB, energetska učinkovitost, vanjska ovojnica zgrade, toplinski mostovi, zrakonepropusnost, infracrvena termografija

Übersichtsarbeit

Bojan Milovanović, Marina Bagarić

Wie erreicht man ein Niedrigstenergiegebäude

Die Umsetzung des NZEB-Standards (Nearly zero-energy building) hat zu einer bedeutenden Entwicklung bei der Planung und Konstruktion der Außenhülle des Gebäudes geführt, die den größten Einfluss auf die Energieeffizienz des Gebäudes hat. Die Praxis zeigt, dass eine qualitativ hochwertige Arbeit eine kompetente und motivierte Belegschaft, angemessene Ausrüstung und eine gute Kommunikation zwischen allen am Bau beteiligten Parteien erfordert. Die Arbeit stellt die Grundprinzipien der Architektur- und Konstruktionsplanung und des Baus eines NZEB vor und zeigt die Probleme auf, die auftreten und zu Bauschäden führen können.

Schlüsselwörter:

Niedrigstenergiegebäude, NZEB, Energieeffizienz, Gebäudeaußenhülle, Wärmebrücken, Luftdichtheit, Infrarot-Thermografie

1. Introduction – Nearly zero-energy buildings (NZEB), what are they and why is NZEB standard introduced

It is estimated that buildings account for approximately 40 % of the total energy consumption in the European Union, and so the aim is to reduce energy consumption in building construction. The obligation to build in accordance with requirements for Nearly zero-energy buildings has been specified in Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings (recast) [1], and provisions contained in this Directive have been included in the regulatory framework of the Republic of Croatia through Technical Regulation on Energy Economy and Heat Retention in Buildings (Official Gazette, issues 128/15, 70/18, 73/18, 86/18) [2].

Nearly zero-energy building (NZEB) has a very high energy performance. This nearly zero or very low amount of energy required is to a significant extent obtained from renewable sources, including renewable energy that is produced on the building itself or nearby [2].

NZEB requirements must be fulfilled by all new buildings for which the application for building permit is submitted after 31 December 2019, while new buildings owned by public authorities should have already been designed as NZEBs if the application for building permit was submitted after 31 December 2017.

Public buildings are public sector owned buildings in which public activities are performed (upbringing, education, teaching, science, culture, sport, health care, social welfare), buildings in which activities of state, local and regional self-government public bodies and organisations are performed, including those where activities of legal persons with public authority are performed, residential buildings for communities, citizens' association buildings, and buildings of religious communities [3].

According to the EPBD Directive, member countries are required to set up the minimum requirements for energy performance of new buildings, but also for existing buildings undergoing major renovations. European Commission does not specify minimum requirements of Nearly zero-energy buildings, i.e. it is up to member countries to define such requirements according to their possibilities, based on cost-optimal analyses.

Based on "Reports on Minimum Requirements for Energy performance of Buildings in Continental and Littoral Croatia", energy performance requirements for the achievement of Nearly zero-energy standards have been set according to the building type, i.e. for single-family houses, multi-residential buildings, office buildings, educational buildings, store buildings, hotels and restaurants, hospitals, and sports halls.

According to these minimum specifications, clear requirements have been set for all new buildings, as defined by specific annual consumption of heating energy and specific annual consumption of primary energy. The requirements have been defined for a total of nine building types, and this for continental and littoral weather zones (Table 1) [2].

When designing and constructing residential buildings and non-residential buildings (office buildings, educational buildings, hospitals, hotels and restaurants), it is necessary to ensure that the annual heat energy required for cooling per unit of useful floor area amounts to $Q''_{C,nd} \le 50$ kWh/(m^2·a). At the same time, non-residential office buildings, educational buildings, hospitals, hotels, and restaurant buildings with the share of the window area in the total façade area $f > 30$ % must be designed and constructed in such a way that the annual heat energy required for cooling is $Q''_{C,nd} \le 70$ kWh/(m^2·a). In addition, if the calculated E_{prim} [kWh/(m^2·a)] is by at least 20 % lower than the maximum value allowed by Technical Regulation [2], it shall be considered that the requirements for $Q''_{H,nd}$ [kWh/(m^2·a)] and for $Q''_{C,nd}$ [kWh/(m^2·a)], as specified in Technical Regulation, have been duly fulfilled.

In addition to the above-mentioned requirements for $Q''_{H,nd}$ and E_{prim}, NZEB requirements are also defined by:

Table 1. Maximum allowable values for Nearly zero-energy buildings heated and/or cooled to the temperature of 18 °C or more [2]

BUILDING TYPE	$Q''_{H.nd}$ [kWh/(m^2·a)]						E_{prim} [kWh/(m^2·a)]	
	NZEB						NZEB	
	continental, $\Theta_{mm} \le 3$ °C			littoral, $\Theta_{mm} > 3$ °C			kontinent. $\Theta_{mm} \le 3$ °C	primorje. $\Theta_{mm} > 3$ °C
	$f_0 \le 0.20$	$0.20 < f_0 < 1.05$	$f_0 \ge 1.05$	$f_0 \le 0.20$	$0.20 < f_0 < 1.05$	$f_0 \ge 1.05$		
Multi-family building	40.50	$32.39 + 40.58 \cdot f_0$	75.00	24.84	$19.86 + 24.89 \cdot f_0$	45.99	80	80
Family house	40.50	$32.39 + 40.58 \cdot f_0$	75.00	24.84	$17.16 + 38.42 \cdot f_0$	57.50	45	35
Office building	16.94	$8.82 + 40.58 \cdot f_0$	51.43	16.19	$11.21 + 24.89 \cdot f_0$	37.34	35	25
Educational building	11.98	$3.86 + 40.58 \cdot f_0$	46.48	9.95	$4.97 + 24.91 \cdot f_0$	31.13	55	55
Hospital	18.72	$10.61 + 40.58 \cdot f_0$	53.21	46.44	$41.46 + 24.89 \cdot f_0$	67.60	250	250
Hotel and restaurant	35.48	$27.37 + 40.58 \cdot f_0$	69.98	11.50	$6.52 + 24.89 \cdot f_0$	32.65	90	70
Sports hall	96.39	$88.28 + 40.58 \cdot f_0$	130.89	37.64	$32.66 + 24.91 \cdot f_0$	58.82	210	150
Store	48.91	$40.79 + 40.58 \cdot f_0$	83.40	13.90	$8.92 + 24.91 \cdot f_0$	35.08	170	150
Other non-residential buildings	40.50	$32.39 + 40.58 \cdot f_0$	75.00	24.84	$19.86 + 24.89 \cdot f_0$	45.99	/	/

Table 2. Technical systems defined for calculating delivered energy and primary energy [2]

Type of building	Heating system	Cooling system	System for preparation of domestic hot water	Mechanical ventilation and air-conditioning system	Lighting system
Family house	YES	NO	YES	It is taken into account if installation is foreseen	NO
Multi-family buildings	YES	NO	YES		NO
Office building	YES	YES	NO		YES
Educational buildings	YES	NO	NO		YES
Hospitals	YES	YES	YES		YES
Hotels and restaurants	YES	YES	YES		YES
Sports halls	YES	YES	YES		YES
Store buildings	YES	YES	NO		YES
Other non-residential buildings	YES	NO	NO		YES

- minimum share of energy delivered from renewable energy sources (min 30 % of annually delivered energy must be covered from renewable energy sources),
- fulfilment of airtightness requirements as proven by on-site testing prior to technical inspection of the building

Furthermore, it should be noted that not all technical systems are included in E_{prim} calculation in Croatia (Table 2).

In the light of the above presented definitions and national criteria for NZEBs, which are based on Technical Regulation [2] and are incorporated in the regulatory framework of the Republic of Croatia in accordance with the Directive [1], the Ministry of Construction and Physical Planning has prepared Guidelines for Nearly Zero Energy Buildings. These guidelines are destined for general public (Part 1 [4]) and for professionals (Part 2 [5]) concerned with this issue. It should be noted that hereinafter presented basic principles of NZEB design, and methods for quality control of construction works, which are crucial for the realization of NZEBs, stem from the authors' experience and knowledge that has been acquired on numerous scientific and professional projects.

2. Basic principles of NZEB design

Nearly zero-energy buildings should be designed in such a way that their energy needs are reduced as much as possible and, at that, there is no one single or uniform solution for achieving NZEB standard requirements.

Coordinated and comprehensive approach involving all professions included in building design (architecture designers, building physics designers, thermotechnical system designers, and electrical installations designers) is needed from the very first concept and conceptual design of the building, and all the way to the final implementation design, including also highly professional and carefully controlled construction works.

The energy concept of NZEBs should be considered already at the initial phase of design work, so as to successfully include in the design process the principles of sustainable, energy and environmentally conscious architecture. A high quality and optimal energy NZEB concept includes well balanced but not oversized thermal insulation thicknesses and thermotechnical systems, combined with obligatory use of renewable energy sources (RES). An optimised energy concept lowers the cost of investment, and results in an cost-optimal solution compliant with NZEB standard requirements.

NZEBs have to be designed with a favourable shape factor, in accordance with bioclimatic conditions, and by using optimal materials, elements and thermal insulation; details should be designed with minimum thermal bridges and to ensure low air permeability; solutions for controlling sun insolation should be provided, and use should be made of natural light; mechanical ventilation with heat recovery should be foreseen, and appropriate, available, feasible and highly efficient thermotechnical systems or systems with high proportion of renewable energy sources should be applied.

Price always has a great effect on the selection of products for the building envelope and technical system. Almost every building can be compliant with the NZEB standard, but the question is at what cost that could be realised. It is very easy to anticipate most modern, extremely expensive and highly efficient technologies, equipment and materials, and thus achieve the NZEB standard; this however is not the objective of the legislation defined in this field. The objective is to achieve the NZEB standard using cost-optimal solutions, favouring at that economically justified, technically feasible, sustainable and environmentally conscious solutions.

Yet another highly significant parameter that has to be achieved when designing NZEBs is an increased level of indoor comfort in NZEBs. At that it should be noted that an appropriate indoor air quality should be ensured (depending on the type of building use and/or space use), which can be achieved in case of an airtight building envelope of NZEBs only by using mechanical ventilation, preferably involving heat recovery of used indoor air. In addition, it is necessary to ensure a sufficiently high internal surface temperature of structural parts of the building (windows, walls, etc.) so as to avoid feeling cold or dew formation, and hence construction damage due to water vapour condensation.

Generally, five basic building design principles can be differentiated for NZEBs:

- thermal insulation – continuous thermal insulation of optimal thickness
- windows of appropriate thermal properties (U_w) and solar radiation transmittance properties ($g_\perp$)
- mechanical ventilation with heat recovery – to ensure an optimal indoor air quality (CO_2 concentration)
- airtightness of building envelope – to reduce heat losses, to reduce possibility of interstitial and surface construction damage, to reduce noise levels, and to ensure an efficient operation of mechanical ventilation
- minimisation of thermal bridges – to reduce heat losses and to reduce the risk of construction damage

Kyoto pyramid (Figure 1) shows a strategy for designing low energy buildings as developed in Norway. This strategy can by analogy also be used for the design of NZEBs.

First of all, it is necessary to reduce heat losses so as to reduce the heating and/or cooling energy needs. This can be achieved by optimizing building shape and zoning, by applying thermal insulation and by achieving airtight building envelope. Furthermore, by using efficient mechanical ventilation system with heat recovery (return), by designing ventilation channels with low pressure drop, etc. This also involves the use of advanced facade systems, optimal orientation of windows, use of daylight, proper use of heat mass for "storing" energy within the building envelope elements, etc.

The next step is to use energy efficient equipment and lighting.

The use of solar energy but also of geothermal energy or, in general, passive heating and cooling mechanisms, enable an optimal utilisation of passive solar heating, daylight, natural ventilation, night cooling, and using heat from the ground for pre-heating or cooling of air.

Monitoring and controlling the energy consumption has proven to be an efficient approach for reducing energy consumption in buildings: when users become aware of their consumption compared to immediate surroundings, they show the tendency to reduce energy consumption. In addition, if an intelligent control system is enabled, which incudes controlling energy consumption for heating, ventilation, lighting and domestic hot water, users generally tend to reduce energy consumption.

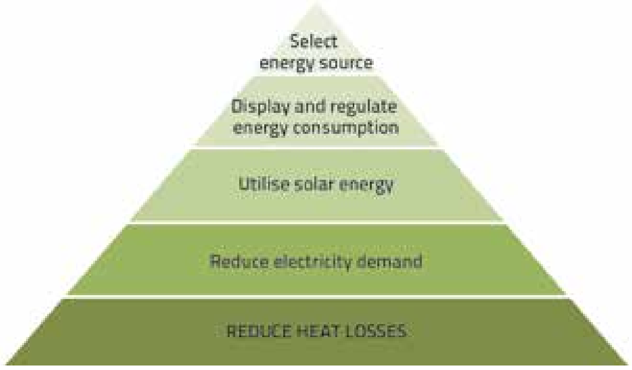


Figure 1. Kyoto pyramid – NZEB design strategies [6]

Selection of an appropriate energy source implies minimisation of the use of fossil fuels and encourages the use of renewable energy sources (RES), which includes using the solar collectors, photovoltaics, geothermal energy, ground water storage, biomass, etc. At that, RES can be considered as the "cherry on the cake".

The main advantage of the Kyoto pyramid lies in the fact that it places emphasis on the reduction of energy needed for heating, cooling, lighting, etc. before adding energy supply systems, and hence it promotes robust solutions involving the lowest possible environmental burden.

2.1. Thermal envelope of NZEBs

Building envelope is a physical barrier between the internal conditioned space of the building and external environment, and the un-conditioned internal space of the building. It consists of opaque building elements (floor, walls, roof, etc.) and transparent building elements (windows, doors, etc.). The role of building envelope is to provide a healthy and comfortable indoor climate to occupants (indoor air quality, thermal comfort, acoustic protection, visual comfort).

Contrary to general perception, greater thickness of thermal insulation will not proportionally reduce U-value of individual building elements (Figure 2) nor will it reduce annual heat losses of the building or annual energy costs (Figure 3). Results shown in Figure 3 are related to a smaller single-family house with an external wall area of 100 m² located in Central Europe, with the climate typical for that zone (average outdoor air temperature in winter months is -12 °C while an average indoor air temperature is 21 °C).

It can generally be stated that the thickness of conventional thermal insulation products (EPS, mineral wool, etc.) of more than 20-25 cm does not have significant influence on heating energy savings. Various construction typologies and technologies are available on the market:

- wood (wooden frame, CLT, TJI/FJI, ...) + thermal insulation,
- foam concrete and cellular concrete + thermal insulation,
- steel structure + thermal insulation,
- masonry (or reinforced concrete) structure + ETICS,
- insulated concrete formwork (ICF), etc.

... but the question can be raised whether greater thickness of insulation is an appropriate solution?

Maximum allowable coefficients of heat transfer through individual buildings elements, in relation to reference climate conditions, are defined in Technical Regulation [2]. It should, however, be noted that – according to the above presented Kyoto pyramid – it is highly justified to reduce the heating and cooling energy needs in relation to E_{prim} reduction by using technical systems and energy sources only.

By respecting the allowable heat transfer coefficients it will not be guaranteed that the building will automatically meet the requirements of energy needed for heating or cooling. In the case of an unfavourable orientation, highly diverse disposition or the need for a greater number of air exchanges, it might be necessary to use greater insulation thicknesses so as to meet limit values of energy needed for heating. In climate conditions prevailing in the Republic of Croatia, even in the coldest regions, it would be very difficult to find good technical or economic justification or reason for increasing thickness of conventional thermal insulation products (EPS, mineral wool, etc.) beyond approximately 30 cm.

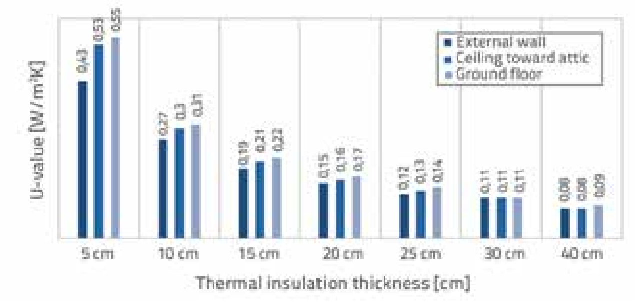


Figure 2. Influence of thermal insulation thickness on U-value of building elements

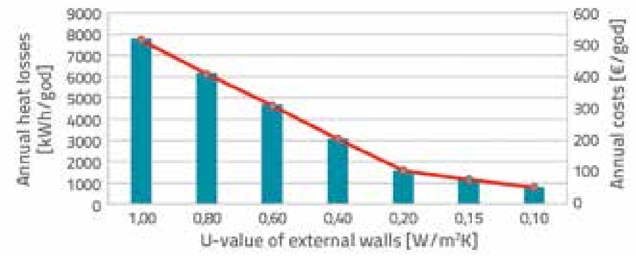


Figure 3. Influence of U-value of external walls on annual heat losses in case of a single-family house (external wall area: 100 m²) in Central European climate

Conversely, in warmer regions of Croatia, greater insulation thickness will result in significant increase in energy needed for cooling a building, so that it is really necessary to find an optimum that provides a minimum sum of the energy needed for heating and cooling of a particular building. That is why, in Mediterranean climate, approximately 15 cm would be the maximum thickness of thermal insulation that might be considered justified from the technical or economic standpoint.

In addition, manufacturers of various construction products have been developing over the last 10-15 years various new materials with the main aim to lower their thermal conductivity and hence their U-value. Some relatively newly-developed brick products filled with mineral wool (MW), EPS, and perlite, and a block made of expanded clay with integrated EPS core thermal insulation, are shown in Figure 4. These examples are certainly not the only advance, especially if developments in the field of thermal insulation are observed. Thermal conductivity (λ) is currently lower than 0,035 W/mK in case of EPS and MW, while the thermal conductivity of PUR or PIR and aerogels amounts to approximately 0,020 W/mK. As for the vacuum insulation panels the conductivity is approximately λ = 0,007 W/mK and, finally, advances have also been made with regard to reflecting foils and phase change materials (PCM) for the accumulation of energy in the case of lightweight construction, etc.

Although a wide array of thermal insulation materials and systems is currently available on the market, proper selection and installation will depend on requirements which vary on the case by case basis (external or internal insulation, fire protection requirements, and presence of moisture). Adequate selection of product to be used for particular layer of building components must satisfy thermal envelope requirements such as: fire protection, thermal bridge reduction, airtightness requirements, moisture control requirements (water vapour diffusion – vapour-impermeable or vapour-permeable solutions), requirements related to evacuation of liquid moisture, and other requirements including those relating to noise protection, structural requirements, environmental requirements, aesthetic requirements, cost-efficiency requirements, and requirements related to the speed and quality of construction.

Physical properties and physical behaviour of materials within the structure, and compatibility between several different materials, are not given adequate attention during the design and construction of buildings. This usually disrupts physical processes through building elements, i.e. transfer of heat and moisture, and thermal activity, occurring due to the difference between internal and external climate conditions, which causes construction damage.

Hygrothermal performance must be assessed during the design phase of NZEBs because the objective of NZEB construction is inter alia: to improve thermal comfort of occupants and users of such buildings, to provide them healthy indoor climate and, of course, to avoid construction damage that can be caused by humidity of indoor air in cases of an significantly airtight building envelope. It is especially important to estimate hygrothermal performance: for new materials and systems that are currently being developed, for existing building envelopes undergoing energy retrofitting because their existing dynamic hygrothermal balance is being changed, and also during design of new highly energy efficient building envelopes. Hygrothermal performance of building envelope elements can be estimated using the traditional method – Glaser method (stationary calculations), and/or using the dynamic method – HAM (Heat, Air and Moisture) models (transient calculations).

Figure 4. Some newly developed brick blocks with lower U-value compared to conventional products

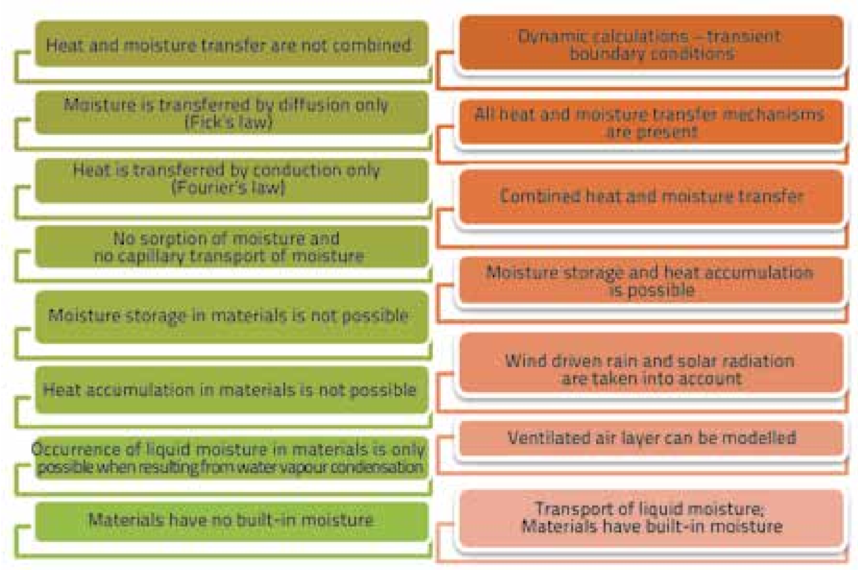


Figure 5. Glaser method limitations (left) and advantages of HAM calculation of hygrothermal performance of building elements (right)

Each calculation method has its limitations and the user (designer) has to be fully aware of the effects of such limitations. Glaser method limitations and HAM calculation advantages are presented in Figure 5.

Although dynamic hygrothermal simulations require a greater number of input data and higher knowledge and skill of users, they offer more possibilities for additional analysis of building elements (e.g. various aspects of durability and estimation of long-term performance).

If designed building is not moisture-safe, this can lead to the occurrence and spread of funghi and moulds, which is directly related to the humidity of indoor air and surface temperature of building elements (Figure 7). The lower the internal surface temperature of wall, the moister its surface is. As funghi and moulds are natural allergens, their growth and spreading can cause health problems (allergies) to persons exposed to their influence.

2.2. Airtightness of building envelope of NZEBs

The air permeability of building envelope is defined as resistance to the transfer of indoor warm air that leaves the building, or to the entry of cold external air in the building through cracks, voids and other openings created by accidental and unintentional flaws, but not through ventilation system. This transfer of air through building elements is called infiltration, and it is caused by the difference in pressure at both sides of the building envelope that occurs due to the difference in air temperature, wind pressure, and mechanical ventilation system (Figure 6).

According to Technical Regulation [2], air permeability requirements must be fulfilled (maximum allowable values are defined in the same regulation), and fulfilment of these requirements must be proven by testing on a newly-constructed or renovated building in accordance with HRN EN ISO 9972:2015 and this prior to technical inspection of the building. This obligatory proof of fulfilling air permeability requirements by testing applies for NZEBs and buildings that have been designed to: $Q''_{H,nd} \leq 50$ kWh/(m^2 a) in continental climate, and to $Q''_{H,nd} \leq 25$ kWh/(m^2 a) in littoral climate. For the pressure difference of 50 Pa, the measured number of air exchanges must not exceed: $n_{50} = 3.0$ h^{-1} in case of buildings without mechanical ventilation systems, or $n_{50} = 1.5$ h^{-1} in case of buildings with mechanical ventilation systems. n_{50} is the number of air exchanges, during one hour at pressure difference of 50 Pa, in relation to the volume of indoor air. In addition, it is important to note that these requirements must be met for each apartment individually in case of multi-residential buildings with more than one housing unit, while in case of non-residential buildings these requirements refer to the envelope of the heated part of the building.

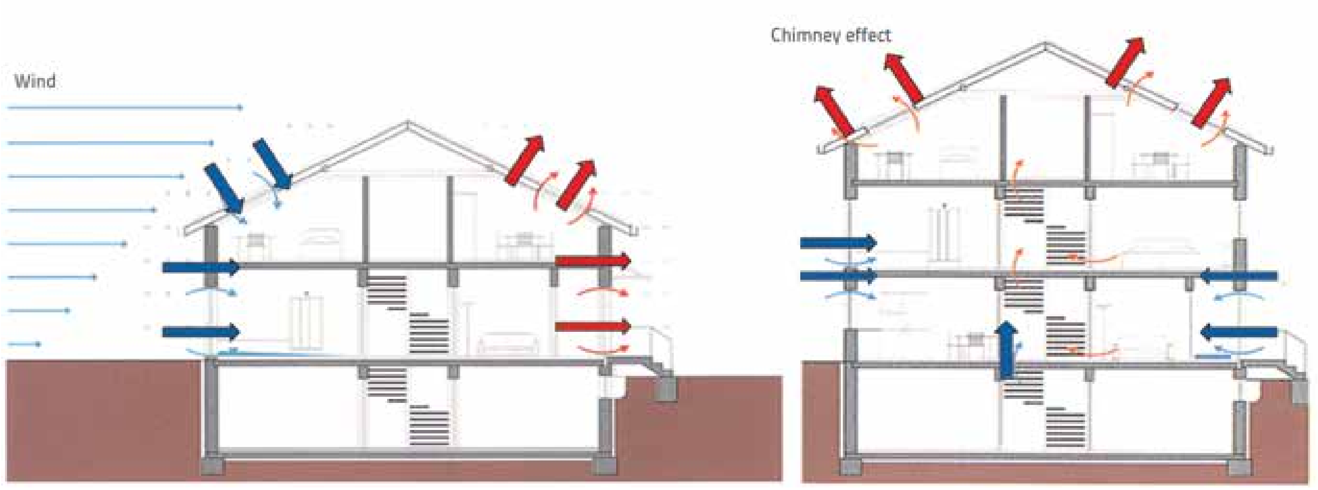


Figure 6. Schematic representation of air infiltration and exfiltration through building elements

Figure 7. Funghi and mould growth on the surface (left) and within building elements (centre and right)

Although the recommendation involving airtight building envelope may seem counterintuitive to laymen because such measure is not thought to ensure sufficient quantity of fresh air in buildings, it must be emphasized that airtightness of building envelope is crucial not so much because of heat losses (although these losses might be significantly reduced) but precisely because of reduced possibility of water vapour condensation in building elements. Fresh air in NZEBs is provided through mechanical ventilation with recuperation (heat recovery).

Infiltration of air into building envelope layers by leakage (which also allows entry of water vapour) is approximately 30 times greater for 1 mm width crack compared to transfer by diffusion per one square meter of surface. The described issue can be supported by previous research [7] demonstrating that 360 g/m^2 of water vapour is transported each day through air permeable building envelope by diffusion (n_{50} = 3.5 h^{-1}), while up to 2.5 l of water is transported via air infiltration through joint with dimensions of 1 m in length and 1 mm in width at pressure difference of 2 Pa. On the other hand, if an airtight building envelope is observed (n_{50} = 0.6 1/h), with the resistance to water vapour diffusion of building element equal to s_d = 10 m, then it can be seen that 1 g/day/m^2 of water vapour is transported by diffusion.

Air leakage (and hence leakage of water vapour) does not necessarily lead in all cases to construction damage due to moisture. However, caution is still needed and therefore all cracks and leakage points at building envelope must be sealed. The cases of leakage that WILL NOT lead to construction damage due to moisture are:

- When the air flows from the exterior toward the interior of the building (in colder regions) – small absolute moisture of air.
- When the air flow speed is high.
- When the path of air flow from the interior toward the exterior is short.

On the other hand, the cases of leakage that WILL almost certainly lead to construction damage caused by moisture are:

- When the air flows from the interior toward the exterior (always at the top of the building due to natural pressure difference) – considerable absolute moisture of air.
- When the air flow speed is small (at small pressure differences – cases with little wind).
- When the path of air flow from the interior toward the exterior is long (greater thickness of building elements).

As already emphasized, the consequences (risks) of air permeable buildings are:

- Higher thermal losses.
- Water vapour condensation.
- Lower efficiency of mechanical ventilation systems (in relation to heat recovery).
- Reduced sound insulation of building envelope.
- Reduced indoor air quality.

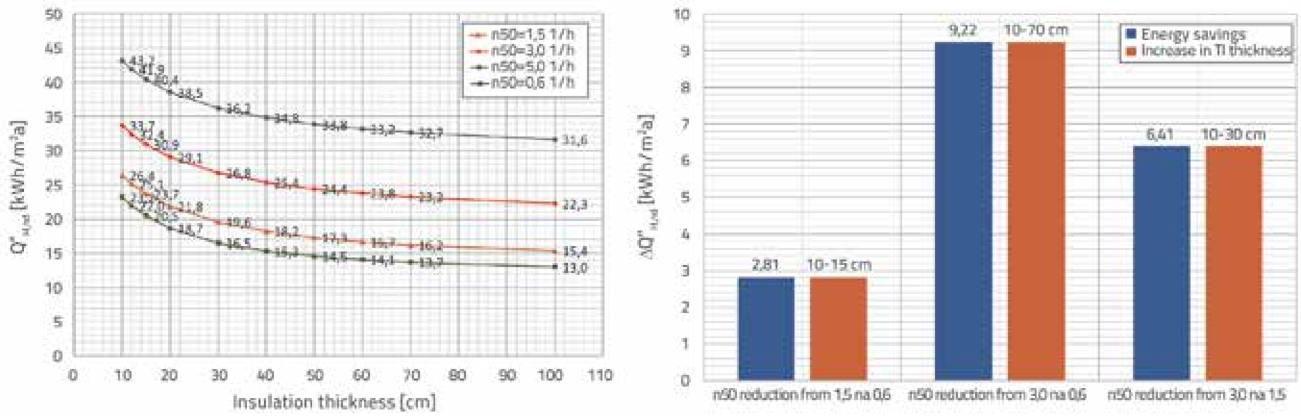


Figure 8. The influence of air permeability on heating energy needs (left) and comparison with energy savings in case of an increase in thermal insulation thickness (right)

The problem of construction damage due to water vapour condensation in layers of building elements has already been discussed. It is also related to the problem of poor indoor air quality due to funghi and mould growth, while the system of mechanical ventilation with heat recovery has a reduced efficiency due to lower temperature of air leaving the building which is caused by infiltration. The influence of cracks and gaps on sound insulation of building elements is also known.

The influence of air permeability on heat losses of NZEB will be analysed in this paper using as an example a family house with the useful floor area of A_k = 175.34 m², and situated in reference climate Zagreb Maksimir. The house was designed for the NZEB level, and the objective was to achieve $Q''_{H,nd}$ = 25 kWh/m²a. For the purpose of analysis, the values observed were the calculated specific energy needed for heating $Q''_{H,nd}$ (Figure 8, left) and savings $Q''_{H,nd}$ and $Q''_{C,nd}$ in case of lowering n_{50} and compared to the same saving levels in case of an increase in thermal insulation thickness of exterior walls (Figure 8, right). Figure 8 (right) shows that, for the analysed house, the reduction of n_{50} from 1.5 h^{-1} to 0.6 h^{-1} results in the calculated savings of the specific energy needed for heating and cooling of $\Delta Q''_{H,nd} + \Delta Q''_{C,nd}$ = 2.81 kWh/m²a, which is equivalent to the increase of thermal insulation thickness of external walls from 10 cm to 15 cm of mineral wool, i.e. to the savings of HRK 12.000 on the price of mineral wool. At the same time, the reduction of n_{50} from 3.0 h^{-1} to 1.5 h^{-1} results in calculated savings of specific energy for heating and cooling of $\Delta Q''_{H,nd} + \Delta Q''_{C,nd}$ = 6.41 kWh/m²a, which is equivalent to the increase of thermal insulation thickness of external walls from 10 cm to 30 cm of mineral wool, i.e. to the savings of HRK 45.000 on the price of mineral wool. Drastic case is if reduction of n_{50} from 3.0 h^{-1} to 0.6 h^{-1} is considered, when calculated savings result with $\Delta Q''_{H,nd} + \Delta Q''_{C,nd}$ = 9.22 kWh/m²a, which is equivalent to the increase of thermal insulation thickness of external walls from 10 cm to as much as 70 cm of mineral wool.

It can therefore be seen that significant reduction of ventilation heat losses can be obtained if greater attention is paid to airtightness of the building envelope, which also results in the lower NZEB cost. It is extremely important to point out that the airtightness criterion specified in the design (or by an appropriate regulation) can be met through proper realisation of details on the construction site, which implies changes to the way in which construction, installation, and finishing works are usually realised, as well as employment of competent workers. In this segment, the education of construction workers has already been initiated in Croatia through the Croskills project [8], and has continued through Horizon 2020 projects Fit-to-NZEB [9] and Net-UBIEP [10], further through Erasmus+ project BIMzeED [11], which were conducted or are still being conducted at the Faculty of Civil Engineering of the University of Zagreb. The airtightness of envelope of a Nearly zero-energy building (NZEB) can be achieved by proper realisation and sealing (Figure 9) using:

- specialized products such as specialized strips and foils (membranes),
- specialized liquid membranes, sealants, but also using
- plastered walls (without cracks in plaster and installation penetrations),
- reinforced concrete walls (without cracks and installation penetrations),
- some types of OSB boards if they have been tested and categorised as Class 3 or 4 (according to series of standard HRN EN 300) and if they are more than 18 mm thick, and
- specialized elements for the realisation of installation penetrations,
- installation of windows according to RAL guidelines, etc.

On the other hand, airtightness of building envelope can not be achieved by unplastered walls, using some types of OSB boards

Figure 9. Products that CAN BE USED for achieving airtightness of building envelopes

Figure 10. Products that CAN NOT be used to achieve airtightness of building envelope

or other fibreboards, thermal insulation plates (although they are connected via tongue and groove joints, or by overlapping), some types of sprayed insulation, gypsum boards, marking strips, universal / multipurpose / packaging adhesive strips and other general purpose strips, general purpose sealants and sealing substances (silicon sealant, PUR foam, etc.) (Figure 10):

Here it should be noted that designers need to differentiate vapour impermeable building envelope (that prevents water vapour diffusion) from air impermeable building envelope (that prevents air infiltration). The difference lies in the fact that air impermeable building envelope does not allow movement of air but not necessarily the diffusion of water vapour. In other words, it can also simultaneously be the vapour permeable envelope (an example is for instance the lime-cement plaster, etc.). On the other hand, the vapour impermeable envelope (vapour barrier) is at the same time vapour impermeable and air impermeable (such as aluminium foil).

2.3. Thermal bridges in NZEBs

Thermal bridge is a limited area in the building envelope that is characterized by an increased heat flow due to changes in material, building element thickness or its geometry.

Buildings must be designed and constructed in such a way that the influence of thermal bridges on annual energy needed for heating and cooling is as low as possible and that no damage occurs in form of interstitial or surface condensation under designed conditions of building use. The influence of thermal bridge is manifested as an increase or reduction of heat flow at certain detail under consideration. For linear thermal bridges it is marked as Ψ (psi), and the unit of measure is W/(m·K). For point thermal bridges it is marked as χ (hi), and the unit of measure is W/K.

Figure 11 (left) shows an increase in heat flow due to change in material and geometry of a building element (balcony). Here the U-value of the external wall is increased by Ψ×h so as to take into calculations the influence of thermal bridge caused by balcony on heat losses.

The trend of increase in thermal insulation thicknesses on building elements, with consequential reduction of transmission heat losses, has been observed from 2006 to the present day. The participation of thermal bridges in the total transmission heat losses has been relatively increasing over the same period. This trend has not been followed by solutions for the protection of thermal bridge zones, which is most often due to the lack of knowledge of designers, contractors and/or investors.

Yet another example of family house, showing influence of thermal bridges on energy consumption, will be presented in this paper. The analysed family house is located in city of Varaždin and its useful floor area is A_k = 182.40 m^2, while the

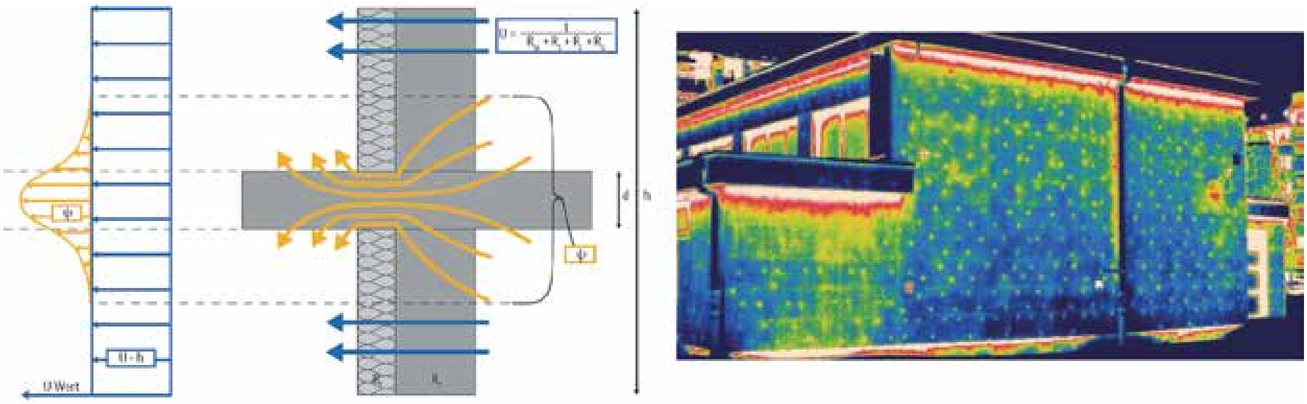


Figure 11. Increase in heat flow due to the change in material and geometry of building element (left) [12] and thermogram of building envelope with pronounced linear thermal bridges and point thermal bridges) [13]

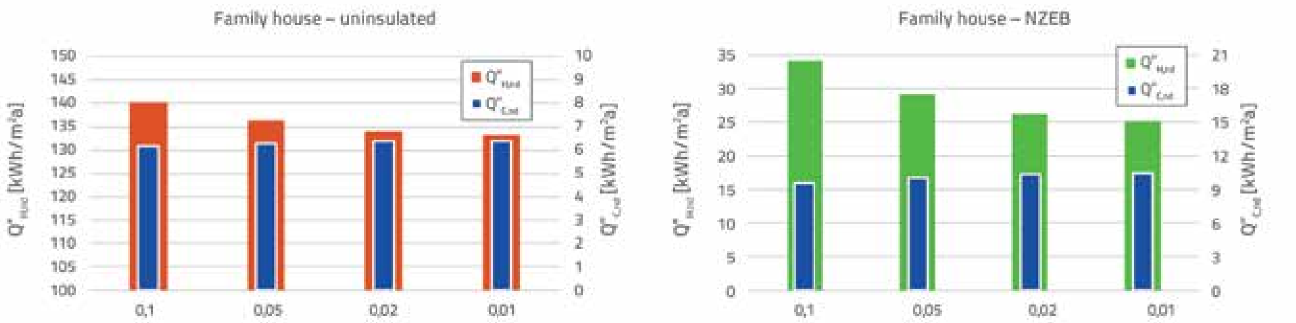


Figure 12. Influence of thermal bridges on $Q''_{H,nd}$ and $Q''_{C,nd}$ for a completely uninsulated family house (left) and for a family house insulated to the NZEB level (right)

surface area of the heated part of the building is A = 407.45 m², and the volume of the heated part of the building is V_e = 570 m³. The change of $Q''_{H,nd}$ and $Q''_{C,nd,}$ is analysed in this example. The influence of thermal bridges is modified by applying fixed increase values: ΔU_{TM} = 0.1 W/m²K; ΔU_{TM} = 0.05 W/m²K; ΔU_{TM} = 0.02 W/m²K; ΔU_{TM} = 0.01 W/m²K; while all other input parameters remain constant.

It can be seen that the relative influence of thermal bridges in case of an uninsulated house (ΔU_{TM} = 0.1 W/m²K is reduced to ΔU_{TM} = 0.01 W/m²K) is at the level of 5 % of $Q''_{H,nd}$ reduction, and 3 % of $Q''_{C,nd}$ increase on an annual basis (Figure 12, left). On the other hand, relative influence of thermal bridges for NZEB (when ΔU_{TM} = 0.1 W/m²K is reduced to ΔU_{TM} = 0.01 W/m²K) is at the level of 26 % of $Q''_{H,nd}$ reduction, and 10 % of $Q''_{C,nd}$ increase on an annual basis (Figure 12, right). This example clearly shows the influence of thermal bridges on the heating and cooling energy need, and demonstrates that thermal bridges have a significant influence that has to be taken into account.

Thermal bridges can not be eliminated from the building envelope and they will be present regardless of the thermal insulation thickness (Figure 13, left).

The following principle applies in the design and construction of NZEBs: thermal bridges must be avoided, i.e. their influence must be reduced as much as possible using all economically acceptable technical and technological possibilities.

This principle has to be applied because thermal bridges can result with following (Figure 13, centre and right): increased heat losses from building during winter; water vapour condensation on the surface; funghi / mould growth; destruction of building elements due to corrosion; increased accumulation of dust on moist surface; cracking due to difference in thermal behaviour; destruction of building elements due to freezing; detachment of plaster, paint and wallpaper; increase in thermal conductivity of insulation materials; and salt efflorescence.

A greater number of cases of construction damage due to surface condensation at thermal bridges have been registered in recently built buildings in comparison to earlier constructed buildings. This higher incidence of damage due to surface condensation at thermal bridges in modern buildings can be explained as follows:

- Buildings without thermal insulation - unfavourable influences of thermal bridges are not very pronounced because:
    - relative humidity (RH) of indoor air in such buildings is lower because the envelope is more air permeable – greater n_{50}
    - surface temperature is approximately uniform in the interior spaces and thus the condensate is evenly distributed, absorbed by substrate (building element), and dried without notable harmful consequences (the substrate absorbs the condensate without significant increase in relative moisture of material).
- Buildings with thick continuous thermal insulation – influence of thermal bridges is more pronounced because:
    - RH of indoor air is usually higher in interior spaces (if mechanical ventilation does not exist) because of better sealing of the building envelope – lower n_{50}

Figure 13. Thermogram of thermal bridge in the existing NZEB family house in Zagreb (left), consequences of thermal bridges (centre and right)

- most parts of internal surfaces are heated to the temperature close to the temperature of indoor air, which is certainly higher than the dew point temperature
    - except in local (and small) thermal bridge areas where the total amount of water vapour from the indoor air is condensed and surface material achieves very rapidly the critical moisture level at which the growth and propagation of funghi and mould is initiated.

Consequently, there is also an increased risk of surface condensation in NZEBs if thermal bridges are not adequately solved (internal surface temperature is too low) or if relative humidity of indoor air is high (which happens in NZEB buildings without mechanical ventilation).

2.4. Thermal mass of the building

When selecting an appropriate NZEB construction system, it is important not to forget the "thermal mass" (thermal inertia, heat accumulation) of the building. Heat accumulation is the property of building elements and materials to accept the supplied heat, to accumulate (preserve) this heat and transfer this heat to the surrounding area when the air temperature drops. This property is very important in buildings during winter periods in cases when heating is not operating continuously throughout the day, but is normally switched off during the night. In such cases, the accumulated heat prevents significant fall in air temperature in interior spaces during night time. The quantity of heat accumulated in building mostly depends on the difference in temperature between a building element and the surrounding air, on specific heat capacity, as well as on the mass of the element.

In multi-layered building elements, the materials with greater specific mass must be placed closer to the internal (warm) side in order to accumulate the greatest possible quantity of heat. In other words, to make good use of this effect, thermal insulation of building envelope must be placed from the external side.

Dynamic thermal inertia parameters of the building are: time lag and decrement factor. These parameters must be defined in order to estimate the heat storage capacity of individual building elements, which is related to the desired levels of indoor thermal comfort and decrease in energy consumption.

The influence of thermal mass on energy consumption will be shown on a multi-residential building constructed with prefabricated ventilated sandwich wall panels (ECO-SANDWICH system). ECO-SANDWICH system are concrete sandwich panels manufactured using recycled aggregate from construction and demolition waste. The building envelope made of these panels can be classified as a heavyweight envelope (surface mass = 458 kg/m^2).

Calculations were conducted according to the monthly calculation method described in HRN EN 13790. The method is based on the monthly balance of heat gains and heat losses determined in stationary state. The simulation was performed for the continuous mode of heating (heating, ventilation and air conditioning system (HVAC) is turned on every day and every hour) for structures varying from very lightweight to very heavyweight. Figure 14 (left) shows specific energy needs for heating and cooling depending on the specific surface mass of building envelope with constant U-value and relative change in heating and cooling needs in relation to heavyweight envelope. It has been demonstrated that very lightweight envelopes such as timber structures and lightweight metal sandwich panels consume 20 % more energy for heating and cooling in comparison to heavyweight envelopes.

Figure 14 (right) additionally shows the influence of effective thermal capacity on specific energy needs for heating and cooling of buildings in various climatic conditions in Croatia, ranging from the very cold climate in Gospić to the hot climate on the island of Hvar. It can be seen that the building with lightweight envelope consumes 33 % more energy in Gospić climate compared to the building with same architecture and orientation and equal U-values of building elements but with a heavyweight envelope. In Hvar such lightweight building envelope consumes 8 % more energy compared to heavyweight envelope with the same U-values.

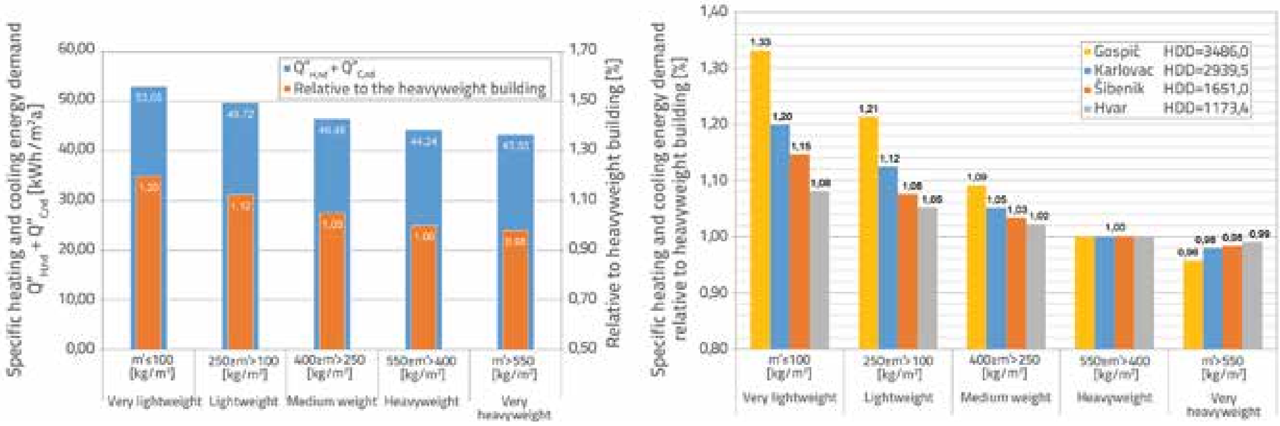


Figure 14. Specific energy needs for heating and cooling (left); Influence of effective thermal capacity on specific energy needs for heating and cooling of buildings in various climates (right) [14]

2.5. NZEB windows, optimal solar gains

Windows are widely accepted and highly desirable elements of every space that make our life more comfortable. They ensure fulfilment of significant factors influencing wellbeing of building users such as: sunlight, fresh air, noise protection, thermal protection, solar shading, protection against precipitation, and safety.

Windows generally have a more complex thermal function compared to insulated walls or roofs and are, already by this fact, highly significant in the energy balance of NZEBs.

Windows usually have a lower resistance to the heat flow (greater U_w-value) compared to other elements of the building envelope. The U_w-value of an excellent window that is recommended for NZEBs amounts to approximately U_w = 0.75 W/m²K, while the U-value of external walls that is recommended for NZEBs amounts to approximately U = 0.15 W/m²K, which is as much as five times less. In other words, heat transmission losses for walls are five times lower compared to such losses for windows.

As a result, they are mostly responsible for greater proportion in overall heat losses. At the same time, their transparency enables entry of solar heat and light into the building. Passive gains (solar gains) can positively contribute to the reduction of heating energy needs in winter but, on the other side, windows increase the energy needed for cooling in the summer. The energy needed for heating and cooling of buildings is greatly dependent on:

- type and size of glazing,
- orientation of windows,
- existence or absence of shading systems.

When designing new NZEBs it is important to properly evaluate solar heat gains and heat transmission losses through windows and other glazed parts of building envelope. Depending on the climate (location), orientation, size of windows, properties of windows (type of glass, frame, glass edge) and shading, it is necessary to find an optimum that provides energy balance in both winter and summer periods. There is no universal "recipe" for the design and selection of the window type, this is different for every building and for various locations (cold, moderate and hot climate). An optimal energy balance of windows is a fundamental requirement for NZEBs.

Balancing thermal losses and thermal gains through windows is achieved by considering U_w – value of windows (defines transmission heat losses) and $g_{\perp}$ - value of glass (defines solar heat gains). These two factors have the greatest influence on the annual energy needs for heating and cooling of buildings.

All details related to calculation of U_w-values for windows or doors are given in HRN EN ISO 10077-1; HRN EN ISO 10077-2. Calculation of U_w-value is based on four basic components of the total heat transfer coefficient (Figure 15):

- For elements containing glazing of surface A_g, i.e. windows, U_g – glazing values, i.e. glass or plastics; one or more glasses; with or without low-e coating, and with space between glasses filled with air or other gases.
- For elements containing opaque panels, e.g. doors: heat transfer through opaque panels
- U_f - value (heat transfer coefficient) for frame occupying an area of A_f, calculated according to HRN EN ISO 10077-2 or as specified in Annex D of HRN EN ISO 10077-1 for wooden, PVC or metal frame, with and without thermal bridge breaks, or in any combination of materials (wood-aluminium, wood-PVC, etc.).
- Linear heat transfer coefficient (ψ_g - value) for frame / glazing of length l_g, calculated according to HRN EN ISO 10077-2 or according to Annex E of HRN EN ISO 10077-1.

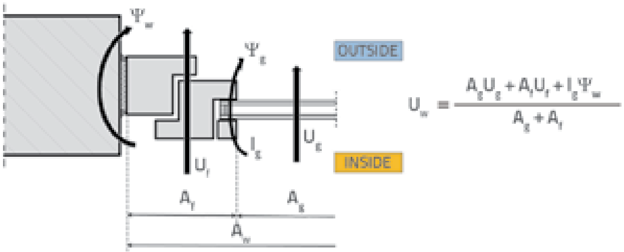


Figure 15. Schematic representation of parameters and expression for calculating U_w-value for windows

In addition, when needed, calculations given in HRN EN ISO 10077 also enable adding heat resistance for various types of shading devices (roller shutters, slatted shutters, etc.), depending on their air permeability values.

Figure 16. Condensation of water vapour at the glass edge (left), composite and aluminium glass edges (centre), thermogram of thermal bridge at glass edge (right)

Glass	Single pane	Double pane with air	Double glazing with low-e coating (pos. 3), with argon	Triple glazing with low-e coating (pos. 2 & 5), with argon	Quadruple glazing with low-e coating (pos. 3, 5 & 7), with argon
U-value of glass U_g [W/m²K]	5,8	2,7	1,1 - 1,3	0,53 - 0,75	0,36 - 0,44
Temperature at internal surface of the glass (outside temperature: -10 °C, inside temp.: 20°C)	-2,6 °C	9,5 °C - -2,6 °C	14,9 - 15,7 °C	17,1 - 17,9 °C	18,3 - 18,6 °C
Total solar radiation transmittance level, g-value	0,87	0,78	0,62 - 0,71	0,49 - 0,60	0,43 - 0,57

Figure 17. Temperatures at interior glass surface depending on U_g-values and the number and positions of low-e coatings

A small component, but highly important in the case of windows, is the edge of the glass. Its role is to keep a fixed spacing between two glasses and to regulate humidity in the space between the glasses. In combination with butyl seals it ensures sealing of the glass edge which prevents gas (argon, xenon, krypton) leakages from the space between the glasses. The role of these gases is inter alia to ensure low U_g-value of the glazing. The edge of the glass can additionally reduce energy losses along the perimeter of the double (triple or quadruple) glazing if it has low ψ_g values, and it can also reduce the possibility of local condensation of water vapour at the edge of the glass (Figure 16).

When glazing types are considered, it should be noted that double insulating glass (double glazing) is currently the most popular type of glazing in the existing buildings, although triple glazing is gaining in popularity in newer buildings, especially in NZEBs. Advantages / disadvantages of triple insulating glass (triple glazing) are:

- Better thermal insulation, e.g. lower U_g-value when using the same glass coating, spacing between glass panes, and fill (gas) between glass panes.
- Higher surface temperature at the internal surface of glass pane, which contributes to the feeling of higher comfort in the interior space (especially in NZEBs).
- Greater-mass glass units limit window opening possibilities (opening is possible, but a good quality solution must be provided).

People feel uncomfortable when objects and bodies that surround them simultaneously radiate with variable intensity in the direction of human body. The feeling of comfort is present only it the difference in body temperature is less than 4 K. Windows with $U_w \leq 0.8$ W/(m²K) have the surface temperature that is not significantly lower than the temperature of the surrounding walls, i.e. usually the temperature of windows is lower by < 3 K

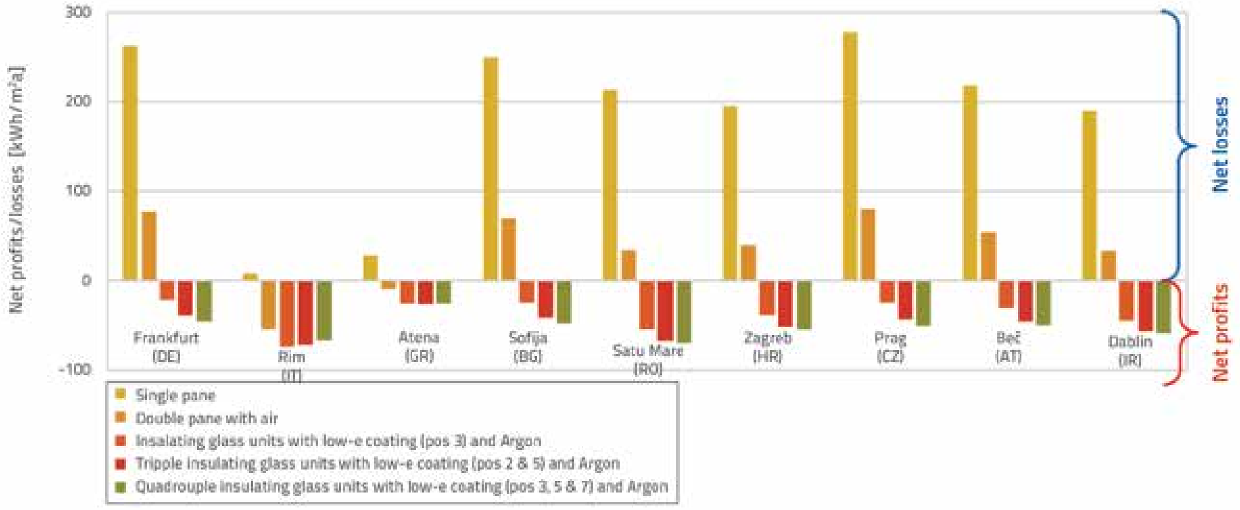


Figure 18. Net heat losses and heat gains for three different types of glass in different climate zones

compared to the temperature of walls (in weather conditions prevailing in Central Europe). Figure 17 shows different types of glass with the corresponding Ug – values and levels of total solar radiation transmittance ($g^{\perp}$ – values) depending on the number and position of low-e coatings, as well as the corresponding temperatures at the interior glass surface. It can easily be seen from this figure that only triple glazing with 2 low-e coatings and quadruple glazing with 3 low-e coatings meet requirements of surface temperature being lower less than 4 K than the temperature of air in the surrounding space.

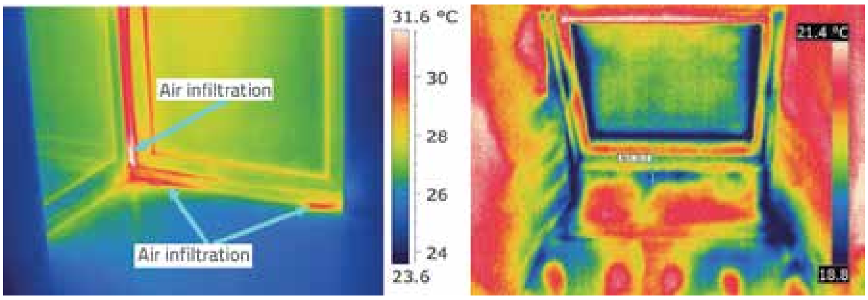


Figure 20. Thermograms with examples of poorly installed windows (not sealed according to RAL guidelines)

The following general strategy can be used for correct selection of glass for NZEBs:

- Cold climates: allow sunlight to enter the space (higher $g^{\perp}$value) and minimise transmission losses (minimum U_w)
- Hot climates: keep solar load away from the space (lowest possible $g^{\perp}$) while somewhat higher transmission losses (somewhat higher U_w) can be allowed.

Indicative values of net heat losses (positive values) and net heat gains (negative values) for various cities (climates) across Europe are shown in Figure 18. It can easily be seen from this figure that heat losses are much greater than heat gains for single pane and double pane with intermediate space filled with air and without low-e coating. On the other hand, heat gains are much greater than heat losses for double glazing with low-e coatings and with noble gases fill between individual glasses.

It can therefore be concluded that the use of low-e coatings slightly reduces solar heat gains, while greatly reducing heat losses, and that the replacement of air with argon (xenon, krypton) reduces heat losses but without reducing solar gains.

Optimization is clearly necessary! Heat gains must be assessed against heat losses, as well as the price of the window. Perhaps a double glazing in the south and triple insulating glass at north windows could be an optimal NZEB solution in certain cases, but here the thermal comfort and internal glass surface temperature must not be disregarded!

It is very important to note here that window installation is of crucial significance! Windows with very good characteristics can be good only if they are properly installed. Window installation involves finding solution to several key problems:

- loadbearing capacity,
- watertightness,
- airtightness,
- control of water vapour transfer,
- minimisation of thermal bridge effects.

Installation ψ-values of 0.005 W/(mK) can be achieved if installation has been realised under optimal conditions. It is important for window to be installed in the thermal insulation layer and that the fixed frame of the window is, if possible, fully covered with thermal insulation. Generally, thermal insulation covering the frame should be approximately 6 cm thick. In that case, the value of $U_{w,\ installed}$ = 0.78 W/(m²K) can be achieved.

Consequences of applying conventional installation methods can be fatal. ψ-values of installation equal to 0.15 W/(mK) increase the $U_{w,\ installed}$ value to approximately 1,19 W/(m²K). It is interesting to note that similar value can be achieved with a cheaper conventional window if it has been installed under optimal conditions.

Moreover, proper installation of external windows and doors has one of the largest impacts on achieving the satisfactory

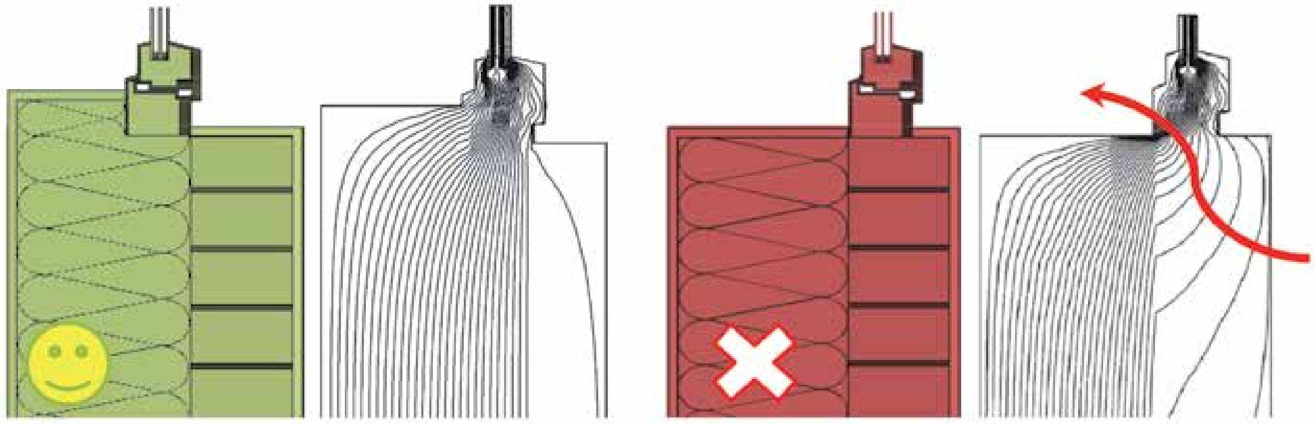


Figure 19. Installation of window in a thermal insulation layer (recommended installation method) and extremely inappropriate installation of window onto the loadbearing part of the wall without covering the frame

airtightness level of building envelope. Installation of external windows and doors according to RAL guidelines, better known as "RAL installation" [15], involves three sealing levels – internal vapour impermeable seal or vapour barrier, expanding strip or foam, and external seal or vapour permeable foil. Windows are exposed to thermal action and vibration, which is why cracks occur over time at the frame to wall interface. Vapour barrier and vapour permeable foil are elastic strips that prevent, at a long-term basis, the air from leaking through joints between the frame and wall. Window reveal onto which vapour barrier is glued must be plastered, and should be even and clean from impurities.

Improper installation of windows can result in higher heat losses (related to ventilation – airtightness and transmission – thermal bridges) but also in construction damage and feeling of discomfort (infiltration of cold air through frame to wall connections, appearance of funghi and mould that are harmful to human health) (Figure 20).

3. Quality control of construction works (Blower door + thermography)

There are many examples of poorly realized construction works in Croatia, which is mostly due to the lack of required knowledge and skill, tight construction deadlines, attempts to make savings, etc. Building envelopes of NZEBs have not been spared from this practice. In fact, many examples can be cited of construction damage caused by installation of inadequate materials and failure to apply recommended construction technologies and rules of professional practice.

As to energy efficiency, the building envelope has the highest influence on the quality of the building not only because of materials used and systems applied but also because of realisation of details [16]. It is considered that workers have to have appropriate qualification (knowledge and skills) and adequate equipment to be able to properly realise the work entrusted to them. In addition, they have to be properly motivated to perform work to good quality standards, and so good communication and information transfer between all participants in construction work has to be ensured.

3.1. Air permeability testing method – Blower door

Air permeability testing by means of Blower door test is obligatory for NZEBs. This test is conducted prior to technical inspection of the building in accordance with relevant standard. In the case of multi-residential buildings (more than one apartment), air permeability requirements have to be met for each apartment.

From the measurement point of view, air permeability is determined by measuring air flow through building envelope as a function of difference in pressures between two sides of the envelope. At that, the Blower door device (Figure 21) is used to create forced difference in pressure between the interior and exterior environment.

Standard pressure difference of 50 Pa (overpressure or underpressure) is used for estimating air permeability of buildings. This difference is equivalent to the wind blowing at 35 km/h from all sides of the building at the same time. Such pressure difference of 50 Pa is necessary and sufficient to overcome measurement noise and other influences affecting accuracy of measurement, which occur either due to change in air temperature during the measurement, or due to weak wind action. All this makes this method relatively accurate and repeatable.

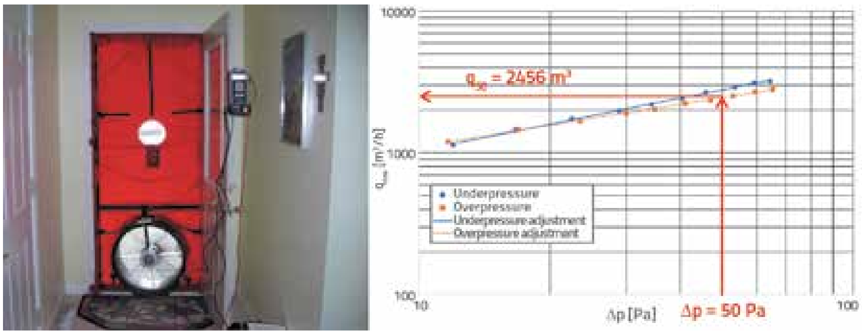


Figure 21. Blower door device and measurement results

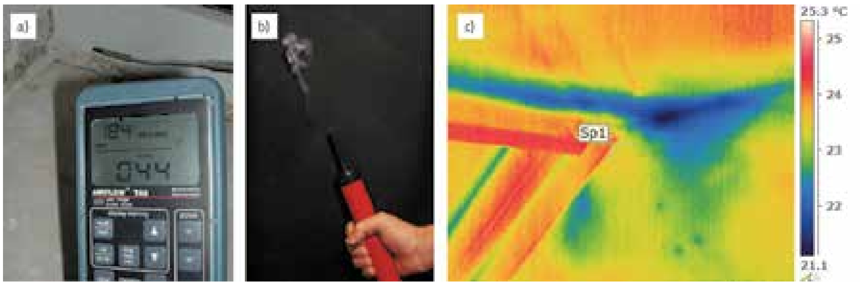


Figure 22. Detection of infiltration points using: a) anemometer, b) cold smoke, c) IR thermography

It is recommended to conduct the building envelope air permeability testing prior to the finishing works, i.e. prior to the end of works on the building. The aim of this recommendation is to increase the quality of works on building envelope airtightness and to correct any errors that inevitably occur during realisation of work. In this phase (before finishing works are done), correction of detected errors is faster, less complex and cheaper. The realisation of airtightness after the completion of works would greatly increase the cost and would in addition complicate the deficiency elimination procedure.

The use of anemometer, cold smoke or infrared thermography enables detecting the points of air infiltration into building elements during the Blower door testing, Figure 22.

The Equivalent Leakage Area (ELA) has to be calculated to make the Blower door test

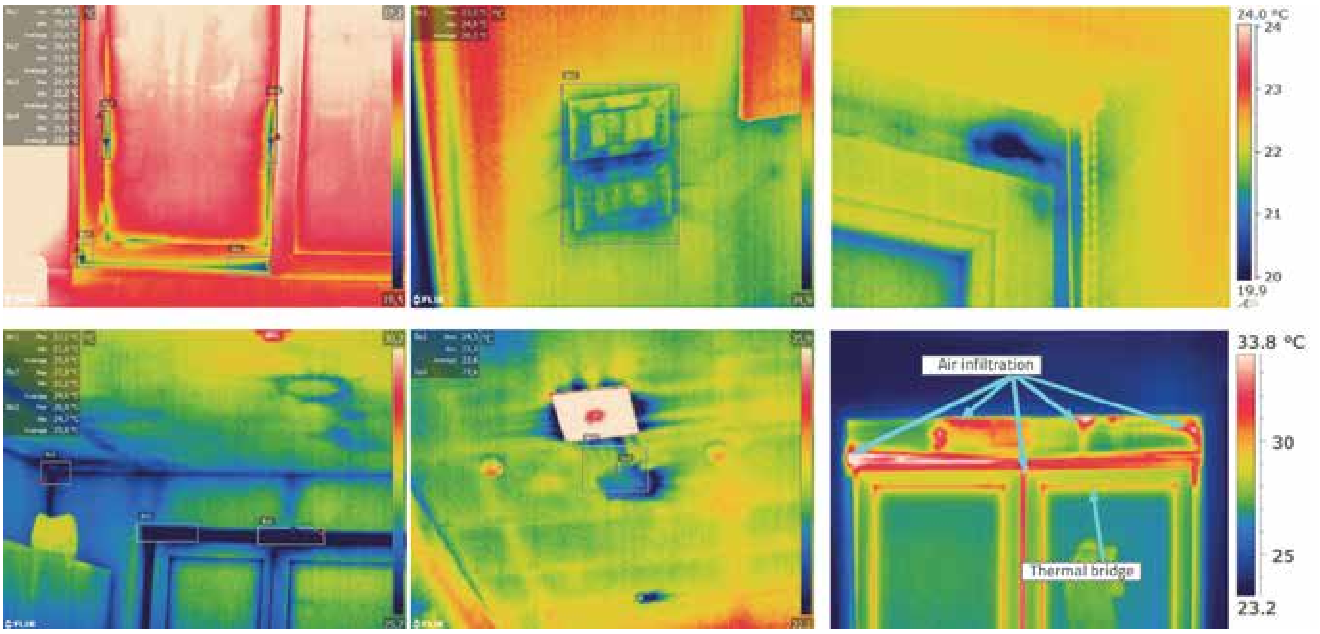


Figure 23. Thermograms of poorly realized details causing air infiltration into building elements

results more understandable to general public and to show how small details are important for the quality of construction works. The ELA is the opening area with sharp edges through which laminar air flow is present, and this flow is equivalent to air flow through the sum of areas of all deficiencies on the building envelope that has occurred due to equal conditions of pressure difference at both sides of the building elements [17]. As it is only an aerodynamically equivalent area obtained on the basis of many assumptions, ELA can be regarded only as a useful orientation value and nothing more.

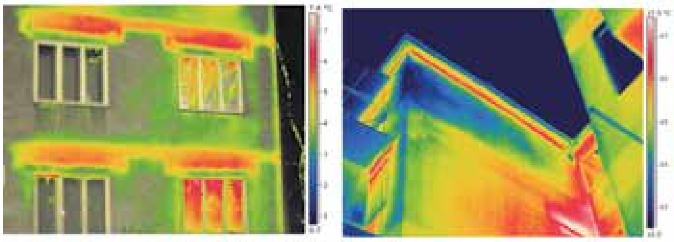
The example of a family house with the useful floor area of A_k = 173.63 m^2, indoor air volume of V = 420 m^3, and the building envelope area of 342.66 m^2, is considered. The air flow of 1259 m^3/h was measured at pressure difference of 50 Pa, which resulted in n_{50} = 3.00. The Equivalent Leakage Area was also calculated and it amounted to ELA = 628 cm^2, which corresponds to 0.018 % of the area of the building envelope.

The ELA value of 628 cm^2 (0.018 % of the building envelope area) points to the need for a detailed and high quality realisation of all and even the smallest details, and also to the need for strict quality control of realisation of airtight building envelopes, for NZEBs in particular, by in-situ testing only.

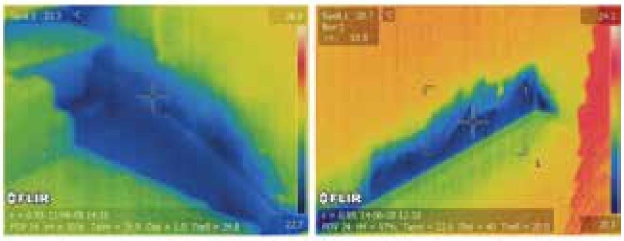
Most frequent errors in the realisation of airtight building envelopes include deficiencies at joints, deficiencies around penetrations and damage of airtight envelope, use of inappropriate products (distribution boards, cable ducts, etc.), installation of external windows and doors not compliant with RAL guidelines, and similar deficiencies (Figure 23).

If the above described errors that occur during realisation of works are not rectified, building elements will eventually suffer construction damage. This is especially pronounced in the case of NZEBs, which are perceived by general public as unconditionally high-quality buildings.

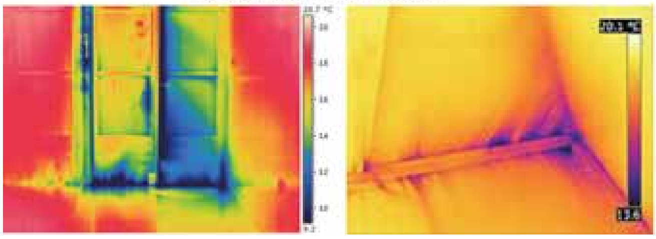
Detection of heat losses (caused by thermal bridges)



Detection of increased moisture



Detection of cold air infiltration



HVAC system control

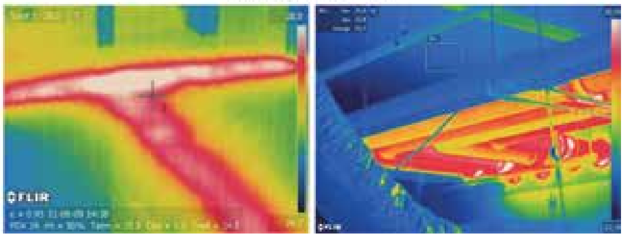


Figure 24. Several thermograms showing most frequent uses of IR thermography in buildings

3.2. Infrared thermography method

Infrared (IR) thermography is a contactless method for measuring temperature and its distribution across the surface of a body under consideration. In IR thermography, the energy radiated from the surface of a body is converted via sensor into a part of the electromagnetic spectrum that is visible to human eye (0.4 to 0.7 µm).

After installing thermal insulation to the building envelope, the IR thermography is used to check its quality and confirm efficiency of the solution applied to reduce thermal bridge effects, to identify possible areas of smaller thickness in the insulation layer, and to check for possiblly moist areas (Figure 24)

Over the past five to ten years, the price of thermographic measurement devices has become more acceptable (due to novel technological solutions and more widespread use), which has inter alia resulted in an increasing use of thermographic devices by insufficiently educated persons. This has on many occasions resulted in inadequate processing and inaccurate interpretation of thermographic measurement results.

4. Conclusion

Higher quality can be achieved if several simple rules are applied and, in this respect, the holistic approach becomes the design standard, and is in fact inevitable in the design of Nearly zero-energy buildings (NZEB). In other words, a coordinated activity of all professions whose design solutions influence realisation of buildings (architects, building physics designers, thermotechnical systems and electrical installations designers) is needed in order to achieve the above mentioned objectives regarding design of NZEBs. An integrated and well-coordinated approach is needed, starting from the conceptual design and creation of energy concepts, and all the way to the final definition of construction-stage details and supervision of construction work. It is necessary to analyse and define building details well in advance so as to avoid problems and improvisations during realization of NZEBs, as it has much too frequently been demonstrated that improvisation in many cases results in problems.

The entire building concept, or an integrated concept and approach in designing NZEBs, includes all aspects of building construction (architecture, facade, structure, function, fire, acoustics, materials, use of energy, quality of environment in enclosed spaces, etc.).

It can generally be concluded that the importance of design and realisation of details increases with the level of thermal protection. If such building details are realised carelessly, damage can occur in building elements, often in form of mould or corrosion (deterioration) of material.

When attempts are made to provide an overall summary of various aspects of NZEB, the question can be raised, how to control the various aspects of NZEBs, i.e. who should be responsible for the achievement of truly high quality and really efficient NZEB?

Each participant in construction works, regardless of his role in the design, construction, use and maintenance of NZEBs, is responsible for respecting the rules and guidelines provided by the manufacturers of materials and systems that are incorporated in building. The realization of works on NZEB projects should be entrusted to highly experienced and competent workers who are well aware of the consequences of negligent or poor construction practices and, at that, it is important to apply good quality products appropriate for their intended use. Measurements prescribed by relevant regulations must be conducted after realization of the work.

With regard to realisation of building envelopes, and for NZEB projects in particular, it should be noted that all participants in construction should be adequately qualified (and even certified) for the realization of NZEBs, as that would prove their knowledge of construction practices (best examples), and familiarity with adequate construction technologies. The workers involved in the process must have appropriate specialized qualifications. At that, it is necessary to put in place the system in which they are responsible for the final product, which is a good quality building, both with their reputation and material resources.

Education of construction workers was initiated in this respect in Croatia through the Croskills project (certification system for construction workers was defined and it is regulated through an appropriate ordinance and by Ministry of Construction and Physical Planning), and this activity was continued through Horizon 2020 projects Fit-to-NZEB, Net-UBIEP and nZEB Roadshow, and through the Erasmus+ project BIMzeED, which were conducted or are still being conducted at the Faculty of Civil Engineering of the University of Zagreb.

Lifelong learning and keeping up with developments in construction sector, with a particular emphasis on NZEBs, is an obligatory precondition for increasing competencies of all stakeholders involved in NZEB projects.

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