Air tightness and its impact on energy consumption in multi-family residential buildings in Montenegro

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ABSTRACT

Airtightness is of key importance, both for indoor thermal comfort and for energy efficiency of buildings. Although formally regulated by the rulebook on minimum energy efficiency requirements for buildings, airtightness is not properly addressed in practice in Montenegro. Airtightness measurements are not mandatory, so there is no data in this regard for the building stock so far.

The paper presents the results of blower door measurements on a limited sample of apartments in multi-family residential buildings. Measurements were carried out in accordance with the ISO 9972:2015 standard. The aim of the measurements is to have an idea of the state of the buildings in Montenegro in terms of air permeability of their envelope, to determine which elements of the envelope contribute the most to infiltration and what is the potential of window replacement as an air tightening measure. The results of the measurements unequivocally showed that air tightness depends mostly on the type, quality of installation and maintenance of the windows. In one of the apartments, blower door measurements with wooden windows before and PVC windows after renovation showed that window replacement is an effective measure of increasing air tightness, which brought the number of air changes per hour at the reference pressure difference within the limits required by the rulebook.

In order to assess the energy impact of air tightness, energy consumption calculations were carried out for one of the apartments in accordance with the DIN 18599 standard, varying the climatic conditions, the U-value of the thermal envelope and the level of air tightness. The results of the calculations showed that the increase in air tightness is an effective energy efficiency measure, which achieves significant savings in energy consumption for heating, while savings for cooling are negligible. Furthermore, it is concluded that relative savings are significantly higher in buildings with an improved thermal envelope, located in a colder climate zone.

KEYWORDS

Air tightness, blower door, energy consumption, residential buildings, windows replacement

1 INTRODUCTION

At the local, regional and global level, various measures are being implemented to combat climate change. The European Union is leading the way in this, showing a strong determination to reduce greenhouse gas emissions. The well-known 2020 climate and energy package set by EU leaders in 2007 had three key targets: reducing GHG emissions by 20% compared to the 1990 level, increasing the share of energy from renewable sources to 20% and reducing energy consumption by 20% by applying energy efficiency measures. The European Green Deal, approved in 2020 is even more ambitious, setting an overarching aim of making the European Union climate neutral by 2050. It is clear that the building sector is crucial for reaching the mentioned energy and environmental goals, as it is responsible for 40% of EU energy consumption and 36% of energy-related GHG emissions.

Increasing attention is now being paid to the air-tightness of the building envelope, given that strict requirements for energy efficiency cannot be achieved just by increasing the thickness of the insulation and installing more efficient heating systems.

Much more attention is paid to air tightness in countries in colder regions. In the USA, for example, air tightness of buildings has been developed as an area of research for decades and there are databases with the results of thousands of fan pressurization tests (Sherman & Dickerhoff, 1998). Air tightness is also extensively regulated and researched in countries of Northern and Central Europe. Examples include studies conducted in Finland (Jokisalo, Kurnitski, Korpi, Kalamees, & Vinha, 2009), Ireland (Sinnot & Dyer, 2012) and the UK (Pan, 2010).

In countries with milder climate such as Montenegro, heat losses due to infiltration are relatively smaller, so the problem of air tightness is given significantly less attention. However, recently the results of several studies in the countries of Mediterranean Europe were published: Greece (Sfakianaki, et al., 2008), Italy (D'Ambrosio Alfano, Dell'Isola, Ficco, & Tassini, 2012), Spain (Feijó-Muñoz, et al., 2018) and Portugal (Pinto, Viegas, & de Freitas, 2011). Studies on the assessment of the impact of air tightness on energy consumption in countries with milder climate are even scarcer. One Spanish study (Poza-Casado, Meiss, Padilla-Marcos, & Feijó-Muñoz, 2021) report that in the Mediterranean provinces the energy impact of infiltration is in the range 8.61–16.44 kWh/m^{2}year for heating and significantly lower for cooling.

Although air-tightness in Montenegro is formally regulated by the rulebook on minimum energy efficiency requirements for buildings, measurements are not carried out and it is not known what the actual condition of building envelopes, whether old or new, is in this regard. The aims of the study, the results of which are presented in this paper, are: to get an idea of the state of the envelope of residential buildings in Montenegro in terms of air tightness, to determine which element of the envelope contributes the most to infiltration, to determine how much air tightness can be improved by replacing windows and finally, how different levels of air tightness affect energy consumption for heating and cooling.

2 BACKGROUND

Air tightness as the main envelope property impacting infiltration is usually defined as the flow of air that infiltrates the building at certain pressure difference, usually 50 Pa. The standard procedure for determining the airtightness of building envelope is the fan pressurization method. The procedure commonly known as the blower door test is explained in detail in the standard ISO 9972:2015 (International Organization for Standardization, 2015). It consists in placing a fan on the door which generates pressure difference across the envelope. The more leaky the building envelope, the more flow will be required to achieve the given pressure difference. The speed of the fan is varied so that pressure differences in the range of 10 to 75 Pa are generated, and the relationship between pressure difference Δp and air flowrate $\dot{V}$ can be represented by a power law as:

$$\dot{V} = c_L \Delta p^n, \tag{1}$$

where c_L is the air leakage coefficient and n is the air flow exponent.

The generally adopted reference pressure difference is 50 Pa, since it is large enough so that the measurement is not affected by the weather conditions and small enough to be achieved in most buildings using blower door fan. In order to be able to compare buildings with each other, metrics are defined that normalize air leakage at the reference pressure difference with something that scales with the size of the building. An overview of the metrics with their definitions is given in Table 1.

Table 1: Summary of air leakage metrics

Metric and definition	Equation	Unit
Air leakage rate at the reference pressure difference of 50 Pa, $\dot{V}_{50}$	$\dot{V}_{50} = C_L(50\ Pa)^n$	m^3/h
Air change rate at the reference pressure difference of 50 Pa, n_{50} The air change rate at the reference pressure difference of 50 Pa, n_{50}, is calculated by dividing the air leakage rate at the reference pressure difference of 50 Pa, $\dot{V}_{50}$, by the internal volume, V.	$n_{50} = \frac{\dot{V}_{50}}{V}$	h^{-1}
Air permeability at the reference pressure difference, q_{50} The air permeability at the reference pressure difference of 50 Pa is calculated by dividing the air leakage rate at 50 Pa, $\dot{V}_{50}$, by the envelope area A_E.	$q_{50} = \frac{\dot{V}_{50}}{A_E}$	$h^{-1}m^{-2}$
Specific leakage rate at the reference pressure difference, w_{50} The specific leakage rate at the reference pressure difference of 50 Pa is calculated by dividing the air leakage rate at 50 Pa by the net floor area A_F.	$w_{50} = \frac{\dot{V}_{50}}{A_F}$	$h^{-1}m^{-2}$
Effective leakage area, *ELA* Effective leakage area is the area of a fictitious orifice that allows the same air flow as the building envelope at the pressure difference of 4 Pa.	$ELA = c_L 4^{n-0.5}\sqrt{\frac{\rho}{2}}$	m^2

3 MEASUREMENT OF AIRTIGHTNES ON A LIMITED SAMPLE OF APARTMENT BUILDINGS IN MONTENEGRO

The blower door tests were performed using Minneapolis Blower Door Model 4.1, product of BlowerDoor GmbH which has a flow range from 25 to 7800 m^3/h at 50 Pa. The fan was mounted on the front door. The calibrated fan was connected to the speed controller which is connected to the digital pressure gauge DG700 and a computer. The test was fully automated by the accompanying TECTITE Express software installed on the computer. The software processed the data, fit the regression curve through a set of points $(\Delta p, \dot{V})$, plotted the charts and calculated the airtightness metrics. Blower door fan mounted on the front door of one of the tested apartments is shown in Figure 1.

Figure 1: Blower door fan mounted on the front door of the apartment

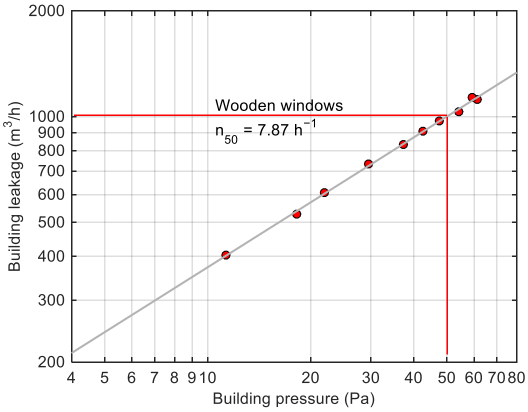
In all tested cases, the apartments were kept depressurized for a certain period of time, during which the envelope was inspected to determine the most contributing leakage points. During all measurements, the requirements of the ISO 9972:2015 standard were met: the wind speed was less than 6 m/s and the product of the building's height and the indoor outdoor temperature difference was less than 250 mK.
The results of all blower door tests with calculated airtightness metrics are given in Table 2, while air leakage curves are shown in Figure 2.

Table 2: Results of the blower door tests

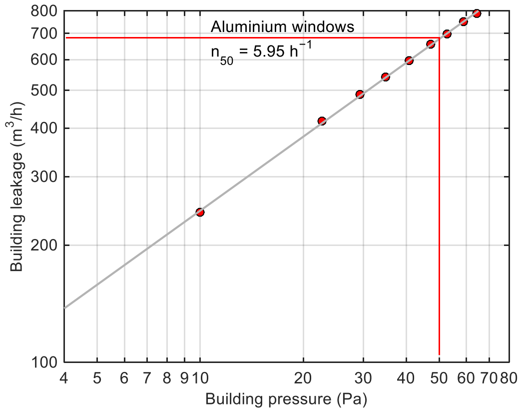
No.	Floor area A (m^2)	Volume V (m^3)	Year of construction	Air leakage rate $\dot{V}_{50}$ (m^3/h)	Air change rate n_{50} (h^{-1})	Specific leakage rate w_{50} (m^3/h/m^2)	Effective leakage area ELA (cm^2)	Building leakage curve: Air leakage coefficient c_L (m^3/h/Pa^n)	Building leakage curve: Air flow exponent n	Windows type
1	53	127	2006	1001	7.87	18.89	228.8	90.6	0.614	Wood
2	43	114	2011	679	5.95	15.78	148.5	57.4	0.631	Aluminium
3	58	162	2012	711	4.38	12.26	150.1	56.9	0.646	PVC
4	68	190	1963	1831	9.63	26.92	453.3	187.6	0.582	Wood
5	68	190	1963	1225	6.45	18.02	280.2	111.0	0.614	Wood/PVC
6	68	190	1963	305	1.60	4.48	63.1	23.6	0.654	PVC
7	85	227	1986	1418	6.25	16.69	334.5	134.8	0.602	Wood
8	85	227	1986	174	0.77	2.05	37.5	14.4	0.637	PVC

In all cases, most of the leaks were detected around the windows. The main air pathways were the gaps due to week abutment of the sash on the frame, as well as between the frame and carcass opening. In addition, significant leakages were recorded around the wooden shutter boxes of the windows that had them. The current Montenegrin rulebook on minimum energy efficiency requirements stipulates that n_{50} must not exceed 3.0 h^{-1} for buildings without mechanical ventilation and 1.5 h^{-1} for buildings with mechanical ventilation. The results in Table 1 show that this condition is met in only 2 out of 8 cases, and in both cases, these are apartments where PVC windows were subsequently installed (blower door tests 6 and 8). In general, all apartments with wooden windows (blower door tests 1, 4 and 7) turned out to be poorly sealed. The reasons are the poor quality of the old wooden windows themselves, as well as their installation, the fact that they do not have rubber seals, age and lack of proper maintenance. The only analysed building with aluminium windows also performed poorly in terms of air tightness. The reason was the sliding balcony doors where brush seals cannot sufficiently prevent air leakage.
The potential of window replacement as a measure to increase air tightness can best be seen by comparing the blower door tests 4, 5 and 6, as well as the blower door tests 7 and 8.
4, 5 and 6 are three completely identical two-bedroom apartments in the same building. In apartment 4, all windows are original, wooden. In apartment 5, windows on the east side are still wooden, while those on the west side have been replaced with PVC windows. In apartment 6, all wooden windows were replaced with PVC windows. By partially replacing wooden windows with PVC ones, the air change rate decreases from 9.63 h^{-1} to 6.45 h^{-1}, or by about 33%. By completely replacing the windows, the air change rate is reduced to 1.6 h^{-1}, that is, by 83%. In addition to the value of the number of air change rate, the replacement of the windows is reflected in the value of the air flow exponent, which indicates the size and shape of the dominant leaks. The value of the air flow exponent is 0.582 for wooden windows, 0.614 in the case when wooden windows are partially replaced with PVC ones and 0.654 in the case of PVC windows. Those values clearly indicate that by replacing the

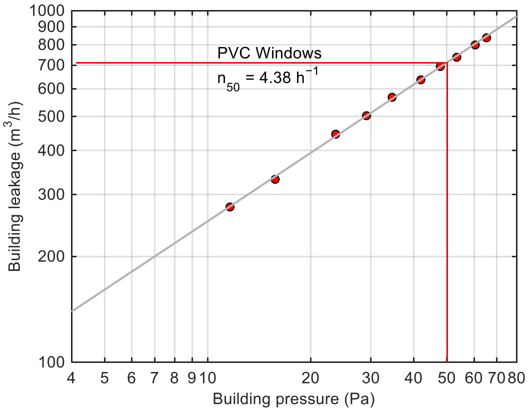
windows there is a transition from leakage through short and relatively large openings to leakage through long and relatively narrow ones.



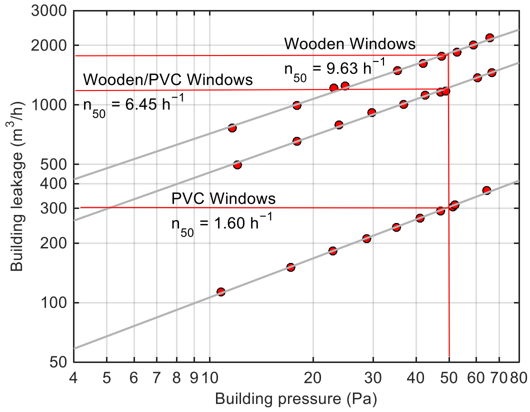
Blower door test No. 1



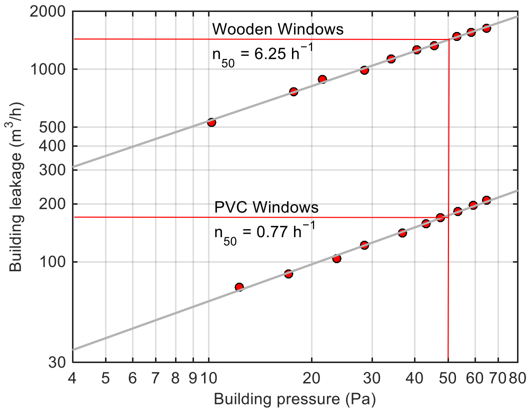
Blower door test No. 2



Blower door test No. 3



Blower door tests No. 4, 5 and 6



Blower door test No. 7 and 8

Figure 2: Air leakage curves (numbered in accordance with Table 2: Results of the blower door testsTable 2)

The most interesting blower door tests are those numbered 7 and 8. These are blower door tests conducted on the same three-bedroom apartment, before and after replacement of wooden windows with PVC windows. This apartment was convenient because the authors had the freedom to influence and interrupt the order and dynamics of the renovation works, to choose the windows to be installed and to supervise the quality of their installation. The building was materialized in the manner that was common for the last quarter of the 20th century. The external walls are uninsulated, mostly made of cast-in-place reinforced concrete. The former windows were wooden, casement type, double-glazed, where each pane was in its

own sash mounted on its own hinges and operated independently. Half of the windows and doors had roller shutters housed in wooden boxes. The windows did not have rubber seals. They were fully functional, although they lacked adequate maintenance. The new windows are made of Softline AD profile, a product of VEKA AG, Germany. These are five-chamber profiles, with a standard installation depth of 70 mm and with two seals. After the replacement, all windows were equipped with matching roller shutters of the same manufacturer. From the common diagram showing the leakage curves for blower door tests No. 7 and 8, it is clear that the air tightness was drastically improved by replacing the windows. The number of air changes at the reference pressure difference was reduced from 6.25 h^{-1} to 0.77 h^{-1}, i.e. by almost 90%, and now it not only meets the minimum requirement from the national regulation (3.0 h^{-1}), but also significantly approached the requirement for passive houses (0.6 h^{-1} in most countries).
Here, it is important to highlight that the objective was not to assess the complete building's airtightness or draw conclusions solely based on measuring the airtightness of a single apartment. When examining the airtightness of the entire building, several practical limitations arise. Often, the building's size makes it challenging to depressurize using a small blower door fan. Additionally, there may be numerous leaks in corridors, stairwells (such as elevator shafts, fire escape doors, basement, etc.) that are difficult to identify and control. Furthermore, accessing each individual apartment may be impractical if the building is already occupied. On the other hand, based on the measurement of airtightness of a single apartment, a general valid conclusion cannot be made about the airtightness of the entire building, because possible leaks that are not through the outer envelope but from the adjacent apartment or staircase would be taken into account even multiple times.

4 THE EFECT OF AIR TIGHTNESS ON ENERGY CONSUMPTION

Energy use for heating and cooling was calculated using the national MEEC software for calculating the energy performance of buildings, developed by the Fraunhofer Institute for Building Physics. Software is based on German methodology for calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting (German Institute for Standardization, 2018). The aim of energy calculations is to assess the effect of infiltration on energy consumption for heating and cooling, as well as the influence of the climate zone and the condition of the thermal envelope on the reduction of energy consumption due to the increase in air tightness. For this analysis, the usual systems used in Montenegro were adopted: biomass central heating system and multi-split cooling system.
The energy analysis was done for a three-room apartment (blower door test results 7 and 8 from Table 2). Calculations were made for both air tightness values. In order to analyse the influence of climatic conditions, calculations were made for all three climatic zones in Montenegro. Also, the calculations were made for the case when the building envelope is as it currently is and for the case when it is thermally improved so that it just meets the minimum requirements from the national regulation. The results of the calculations of delivered energy for heating and cooling before and after applications of measures to improve the thermal envelope and airtightness are given for all three climate zones in Table 3 and Figure 3.
For climate zone I (where the building is actually located), improving the air tightness by replacing the windows (reducing n_{50} from 6.25 h^{-1} to 0.77 h^{-1}) reduces the delivered energy for heating (including auxiliary energy) and cooling from 155.44 kWh/m^{2}year to 142.63 kWh/m^{2}year, or by about 8.2%. Interestingly, almost all of the reduction in energy consumption is due to a reduction for heating, while the reduction for cooling is almost negligible. Relative contribution of the increase in air tightness to the reduction of energy consumption is even greater in the case when the building envelope is thermally insulated, and in that case it amounts to about 15.6%.

Increasing air tightness as a measure of energy efficiency has an even greater effect in regions with a colder climate. If the same building were to be located in the north of Montenegro (climate zone III), the delivered energy for heating and cooling is reduced by replacing the windows from 258 kWh/m^{2}year to 233.26 kWh/m^{2}year or by about 9.6%. In the case when the building is thermally insulated, increasing the air tightness results in a reduction in the delivered energy of as much as 20.9%.

The effect of different degrees of air tightness on the delivered energy for heating and cooling was also investigated by varying the number of air changes at the reference pressure difference of 50 Pa in the range from n_{50}=1 h^{-1} to n_{50}=15 h^{-1}. It can be seen that with increasing air tightness, energy consumption for heating and cooling decreases linearly. By increasing n_{50} by a unit value, savings from 2.3 kWh/m^{2}year in climate zone I to 4.6 kWh/m^{2}year in climate zone III are achieved.

Table 3: Delivered energy for heating and cooling before and after the application of measures to improve the thermal envelope and air tightness

Climate zone	Building envelope	n_{50} (h^{-1})	Delivered energy (kWh/m^{2}year)			
			Heating	Cooling	Auxiliary	Total
I	Existing thermal envelope	6.25	129.84	21.78	3.82	155.44
		0.77	117.32	21.73	3.58	142.63
	Improved thermal envelope	6.25	63.60	12.67	2.68	78.95
		0.77	51.57	12.67	2.37	66.61
II	Existing thermal envelope	6.25	196.01	8.84	4.85	209.70
		0.77	176.70	9.06	4.61	190.37
	Improved thermal envelope	6.25	98.02	4.85	3.43	106.30
		0.77	79.28	5.13	3.11	87.52
III	Existing thermal envelope	6.25	248.67	3.50	6.04	258.21
		0.77	223.85	3.68	5.73	233.26
	Improved thermal envelope	6.25	112.25	1.49	3.92	117.66
		0.77	87.95	1.75	3.41	93.11

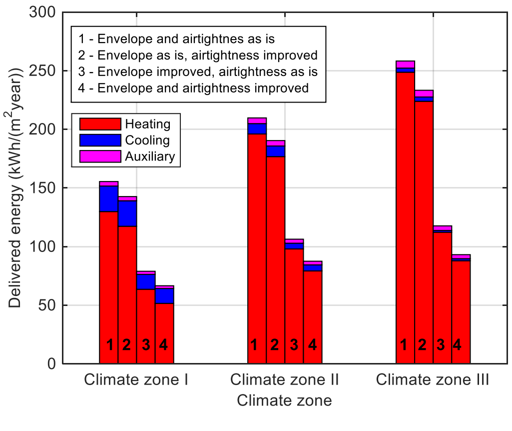


Figure 3: Delivered energy for heating and cooling

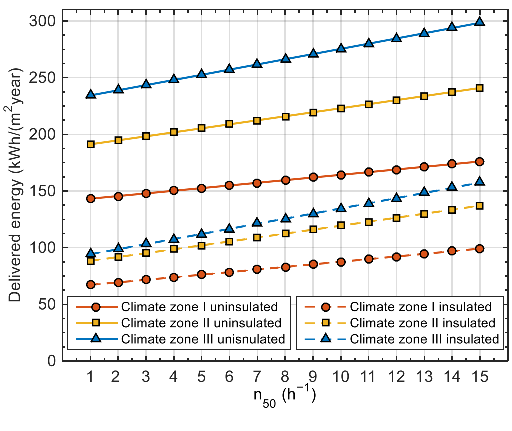


Figure 4: Delivered energy for heating and cooling as a function of n_{50}

It is important to acknowledge that when measuring the leakage of a single apartment's envelope using a blower door fan, the recorded results includes potential leaks that originate not only through the outer envelope, but also from the neighbouring apartments that are thermally conditioned. Consequently, there is a possibility that infiltration and the associated energy consumption might be slightly overestimated. However, the authors are convinced that these contributions are negligible considering the construction method and the fact that hand and smoke pen inspection during the depressurization did not indicate internal leakages.

Improving airtightness while neglecting adequate air exchange can result in poor indoor air quality. Among other things, there may be increased relative humidity; potentially leading to the formation of condensation and mould on interior walls if their temperatures fall below the dew point (the problem is more prominent when the envelope is not thermally insulated). In old buildings such as the one considered, there is often no ventilation system, except possibly extraction ventilation in kitchens and toilers, which is ineffective when, due to good airtightness, there is no possibility of sufficient air suction through the envelope. To mitigate these issues, regular window airing of the apartment becomes essential. However, experience from renovating existing buildings has shown that occupants often fail to modify their habits after airtightness improvements. It is worth emphasizing that when calculating energy consumption, the software adjusts the air change rate due to window airing as a function of infiltration and does not allow the total air change rate (infiltration plus window airing) to go below the value of 0.5 h^{-1}, which is widely accepted as a threshold value bellow which the perception of poor indoor air quality can occur.
The idea for future research is the use of whole-building energy simulation software such as EnergyPlus, which would enable the analysis of the impact of air tightness on infiltration and indoor air quality, above all on relative humidity.

5 CONCLUSIONS

The results of blower door tests on a limited sample of multi-family residential buildings in Montenegro indicate the poor performance of building envelopes in terms of airtightness and that this problem should be addressed in a way that it deserves. Examining the building envelope during the fan depressurization determined that windows are by far the most contributing cause of air leakage. In this respect, old wooden windows without rubber seals performed the worst. The replacement of windows proved to be an effective measure for increasing air tightness, which improves n_{50} almost to the standard applicable to passive houses.
The analysis of energy consumption at different levels of air tightness showed that with a decrease in air changes rate, energy consumption for heating is significantly reduced, while the reduction in energy consumption for cooling is practically negligible. Furthermore, in relative terms, the reduction of energy consumption due to the increase in air tightness is more pronounced in colder climate zone and when the thermal envelope of the building is improved by reducing its U-value. For the observed case study, with a reduction of n_{50} by a unit value, energy savings of 2.3 kWh/m^2year are achieved when the apartment is located in climate zone I to 4.6 kWh/m^2year when it is located in climate zone III.
The generality of the conclusions of this study is limited due to the fact that a relatively small sample of buildings was analysed. The idea for future research in this area is to consider a larger sample in order to obtain statistically credible results.

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