Investigating the effect of tightening residential envelopes in the Mediterranean region

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Abstract: Nowadays, buildings are responsible for the 40% of energy consumption (36% of greenhouse gas emissions) in the European Union. The European Council pointed out the need to refurbish a large amount of the existing building inventory, as new buildings are related to the 1-2% of the total energy consumption. Air-infiltration and tightness of buildings are usually neglected parameters during retrofitting or building design, especially in the Southern European counterparts, where air-tightness standards are absent from the national building regulations. To this effect, this study investigates the impact of tightening existing residential envelopes, focusing on the impact to the default construction and synergies arisen between air-tightness and other interventions (i.e. thermal insulation). The study was undertaken in the Mediterranean climate conditions, examining detached houses located in Cyprus. This is the first study in national level, presenting the air-tightness characteristics of buildings as these were collected by a blower door test. In general, the outcome shows that the improvement of air-tightness primarily reduces the energy associated with winter thermal loads. Apart from that the tightness of building envelopes beneficially contributes on the performance of other energy saving measures. In particular, the reduction by thermal insulation can be enhanced up to 12%, while the synergy with a glazing system may reduce heating demand up to 7%.

Keywords: Air-tightness, Infiltration, Residential envelopes, Mediterranean region, Cyprus

1. INTRODUCTION

In the European Union, buildings are responsible for nearly 40% (22% dwellings and 18% commercial buildings) of energy consumption (and 36% of GHG emissions) (EUC, 2012). The Europe-wide initiatives on transforming the energy system for a decarbonized future recognize the importance of buildings in reducing carbon emissions (EUC, 2011). Due to the evolution of technology and industrialization, houses relied on artificial systems, ignoring the adaptive ability of the human body (Clements-Croome, 2000; Roaf et al., 2010). Evidently, householders consume most of their energy to maintain comfortable conditions, due to a poor building design and operation. Lapillone and Wolfgang (2009) presented a breakdown of the residential energy use, claiming that space conditioning contributes heavily up to 68%.

There seems to be two lines of thought with regards to the strategies on existing buildings; demolition or retrofitting. Undoubtedly, demolition and new buildings may be defined as better solutions. Though, an enormous amount of the European housing inventory will need refurbishment that will substantially result in energy reduction and its associated CO_2 emissions (Burton, 2012). Borgeson and Brager (2011) pointed that the achievement of energy targets must not lead to scarification of thermal comfort and indoor air-quality.

Dokka and Rodsjo (2005) developed the Kyoto pyramid, categorizing the actions that must be considered during the "passive" design of commercial or private buildings (see Figure 1). The Kyoto pyramid classifies the reduction of heat losses as the primary measure towards passive design, followed by the reduction of electricity use, utilization of solar energy, regulation of energy and selection of local energy source (Dokka and Rodsjo, 2005).

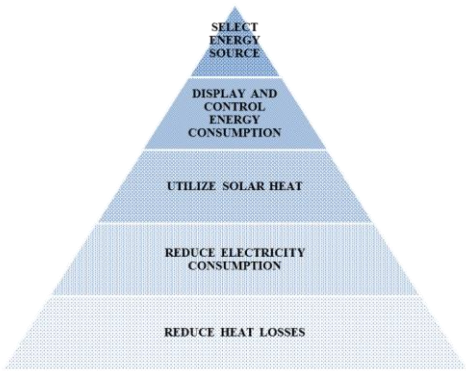

Figure 1 The Kyoto pyramid (Dokka and Rodsjo, 2005)

The tier referring to heat losses is coherent with the external envelope which determines the physical boundaries between the indoor and outdoor environments. Regulating the impact of heat transfer mechanisms, results on a stable indoor environment and lower energy consumption for maintaining thermal comfortable environment.

A neglected parameter, especially in southern European counterparts, is the air-tightness of the building. In spite the implementation of EPBD, only Spain is regulated by partially requirements, concentrating on the windows' performance (Erhorn-Kluttig et al., 2009). The air-tightness of the building determines the resistance on the unintended flow of air through the building envelope (CIBSE, 2000).The excess air infiltration is usually inherent with the irrational energy consumption and indoor thermal comfort. For instance, the warm air is leaking through the gaps and cracks, enhancing the heat losses of the envelope. As a result, an amount of energy is wasted to condition air which escapes from the building (EST, 2005). In a study by Chen et al. (2012), it was concluded that a reduction of 12.6% was achieved when the permeability was reduced from 0.98-0.5 ACH. Additionally, in an investigation of different air-tightness scenarios, Logue et al. (2013) observed a reduction of residential energy demand when the houses' leakage was decreased.

Another common notion, referring to infiltration impacts, is the negative effect on the efficiency of thermal insulation due to deterioration of the insulation. Due to excessive leakage, the air may penetrate the structure and thus, the effectiveness of insulation is reduced (CIBSE, 2000). Moreover, USDOE (2010) exemplary states that infiltration is like an open window for 24 hours, annually. In essence, the addition of thermal insulation may reduce the transmission loses, however a convective link will still encounter between indoor environment and outdoors ("short-circuiting", (CIBSE, 2000)). Furthermore, in the context of thermal comfort, draughts arise, due to the unintended flow of air, causing discomfort and complaints to the occupants (EST, 2005).

The improvement of building permeability and thereby, the reduction of the unintended flow of air will enhance the indoor environment while the residential energy demands will be reduced. However, it is mandatory to mention and point out the cases where the ventilation of the whole building is reliant on infiltration. Due to the leakage areas on the existing envelope, the ventilation requirements may be occasionally satisfied, but the target rates are unreliable in the context of time and location (EST, 2006). By tightening the envelope, there is an indoor air quality risk because of the possible increased concentration of hazardous pollutants (VOCs, CO, CO_2, dust, moisture) generated by residential actions such as smoking, combustion, cooking or furniture. Thereby, it is indispensable to provide an alternative ventilation solution such as a mechanical ventilation system or a well-versed natural ventilation system.

This study investigates the impact of tightening existing residential envelopes, focusing on the impact to the default construction and synergies arisen between air-tightness and other interventions (i.e. thermal insulation). The study was undertaken in the Mediterranean climate conditions, examining detached houses located in Cyprus. This is the first study in national level, presenting the air-tightness characteristics of buildings as these were collected by a blower door test.

2. METHODOLOGY

As aforementioned, the study seeks to investigate the impact of reducing air infiltration by tightening building envelope of the default structure and also, to examine the synergies arisen by other energy saving measures (i.e. thermal insulation, glazing). In order to accomplish this study, a procedure was adopted, comprising a blower door test and a building simulation, utilizing data collected from actual residential buildings. Essentially, 3 air-tightness scenarios will be contacted, listed in Table 1.

Table 1: Air-tightness scenarios

Scenario	Air Permeability ($m^3/h.m^2$ @ 50Pa)	Details
Infiltration (1)	-	*Default building's air permeability*
Infiltration (2)	≈3	*This requirement is based on Energy Saving Trust best practise and Germany average of 2.8~3.0 $m^3/(h.m^2)$) @ 50 Pa*
Infiltration (3)	≈1	*Passivhaus Standard*

2.1. Case studies

Initially, 9 detached houses were selected for investigation. The dwellings are located at the south-west coast of Cyprus, in the urban area of Paphos town. In particular, 7 buildings were constructed prior 2007 (implementation of EPBD), which will be used during the building simulation. The remaining case studies were constructed in 2011, and their tightness will only be measured during blower door test, in order to examine the trend in the construction industry. Table 2 and Figure 2 present the selected houses for investigation and a short description of the construction year and floor area.

Figure 2 Exterior view of case studies

Table 2: Sample Characteristics

Index	Construction Year	Floor Area (m^2)
SD1	1995	290
SD2	1987	188
SD3	1996	384
SD4	1994	176
SD5	1987	117
SD6	2007	120
SD7	2006	208
SD A	2011	500
SD B	2011	450

2.2. Blower Door Test

A blower door test has been carried out, measuring the default air permeability of the building enclosure. The procedure was aligned with the EN 13829:2001 (CEN, 2001), with additional enhancements by (ATTMA, 2010). The guidelines were strictly followed, initially to avoid any damage on the envelope of the private properties during the depressurization of the building and also, to ensure the quality of the results. The results from the blower door test will be used on the generation of building models, in order to examine in depth the impact of reducing air infiltration.

2.3. Building Simulation

In order to examine the air tightness scenarios, mentioned earlier in this section, the building simulation will be applied. Through EPlus software, the models were generated, following the concept of model calibration. Data collected from actual buildings were used to build realistic simulation models. The whole procedure is extensively described in a previous study (Georgiou et al., 2014).

Following the successful validation of the models, a normalization was applied in order to globalize the outcome of the study. In particular, the models were normalized with regards to the weather conditions, occupancy patterns and HVAC operation. Referring to the outdoor climate, the simulation is based on two TMYs databases; coastal (Paphos Station) and low lands (Athalassa Station). The interventions will be examined during the heating and cooling periods, at any time of occupation, setting the HVAC set-point temperature according to EN 15251 (CEN, 2007), assuming a metabolic rate≈1.2 met and clothing value 1.0 and 0.5, for winter and summer, respectively. Table 3 presents the parameters related with the occupancy pattern and set-point temperatures of HVAC.

Table 3: Normalized occupancy pattern and set-point temperatures for HVAC systems

Space	Occupied Hours		Set-point temperature (^oC)	
	Weekdays	Weekends	Winter	Summer
Living Room	17:00-22:00	08:00-13:00 & 14:00-22:00	20	25
Kitchen	13:00-14:00 & 20:00-21:00	13:00-14:00 & 20:00-21:00		
Bed Room	22:00-07:00	22:00-07:00		

3. RESULTS

This section presents the results by the analysis of the findings of blower door test and building simulation. The study focuses on the performance of the houses constructed prior 2007. In general, a graphical approach was adopted for the presentation of results, applying box-whisker plots (mainly in the case of building simulation results).

3.1. Blower Door Test

The results from the blower door test are automatically produced by the TECTITE software. The Figure 3 presents the relation between air-tightness and construction year.

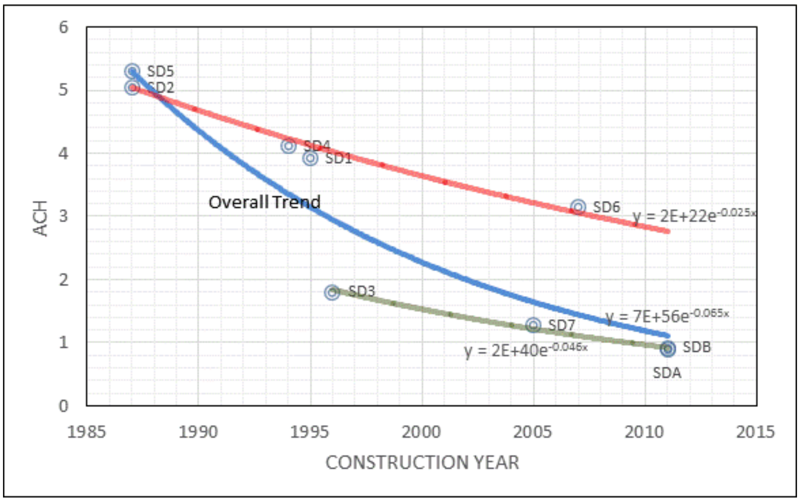

Figure 3 ACH against construction year

Overall, the trend declined dramatically through the years, due to tightened envelopes. As it can be noticed, two sub categories are presented in the Figure 3, with both having slight decrement. In spite the fact that local constructors are not obligated to any building regulations in terms of building air-tightness, air-tightness was improved since 1985. Possible facts for this trend are the high quality materials, the construction techniques or even the bearing structure of the buildings. The latter may be explained by the fact that the bearing structure of national stock is founded on concrete and bricks, eliminating the paths of air. In essence, the major infiltration sources of infiltration are the external openings. This is the main reason of the resultant sub categories, presented in the findings of blower door test. In particular, the houses comprising the lower region, have tighter door and window frames, as this was observed during the walk-trough visits. Consequently, in such buildings constructions, high levels of air-tightness can be achieved by sealing the frames of the openings, taking the exemplary performance of the newly constructed buildings (SDA and SDB).

3.2. Building Simulation

Effect on default construction

Tightening envelope seems to be more effective during the winter season, as lower impact was observed during summer period. Figure 4 presents the impact on annual heating and cooling load of the base construction, by tightening the building under two scenarios (intermediate-Infiltration 2 and strict-Infiltration 3).

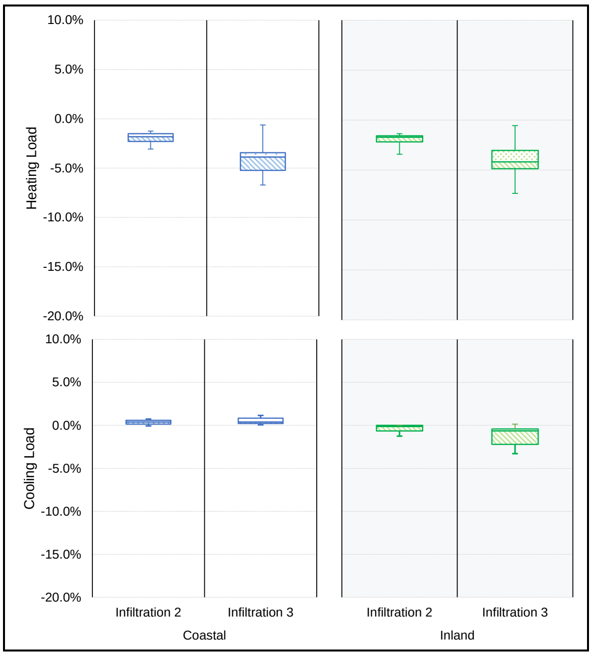

Figure 4 Impact on base loads by tightening building envelope

In particular, for both climates the median value of reduction during the winter season is 2% and 4% for Scenario (2) and Scenario (3), respectively. In some cases, the energy consumption may be reduced by up to 7%, with 75% of the samples found between 4-5% for coastal areas and 3-4% for inland areas.

Observing the impact on heating load, it can be noticed that the impact is lower during the summer season. During the cooling period, a converse relation is noticed between the two weather files. A negligible increment occurs at the coastal conditions, with the median equals to +0.4% (both Scenarios). On the contrary, at the inland conditions the houses presented an average reduction on thermal load by -0.4% and -1.2%, Scenario (2) and Scenario (3), respectively. In order to realize the difference between the weather conditions, Figure 5 illustrates the indoor conditions during summer.

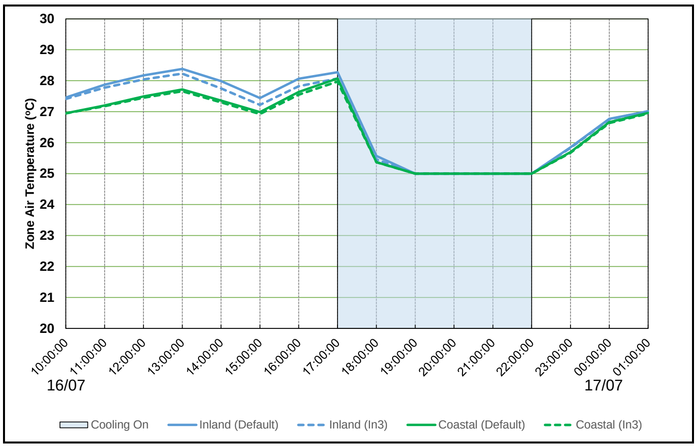

Figure 5 Difference of air temperature for coastal and inland-SD1

Due to the higher indoor temperature of the default state (case of inland weather), the Scenario (3) causes higher reduction of indoor temperature. As a result, the mechanical system operates in lower temperature difference, corresponding to higher energy reduction.

Now, in the perspective of thermal comfort, Figure 6 shows the effect of tightening on the seasonal thermal comfort score.

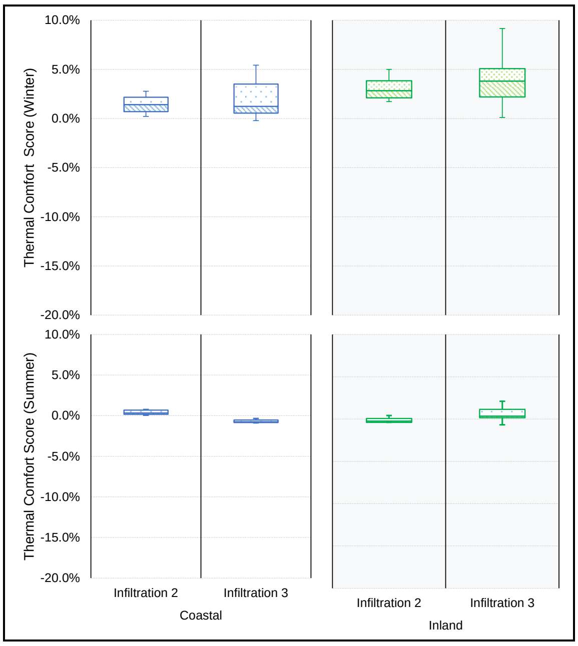

Figure 6 Impact on seasonal thermal comfort

As it can be noticed by Figure 6, the reduction of the air infiltration improves the indoor thermal conditions, especially during the heating period. In general, the indoor thermal conditions during winter can be improved up to 5% (coastal) and 9% (inland). Moreover, during the winter period, the results of the application of Passivhaus show a substantial variation. This is primarily based on the default properties of the building. Leaky houses (i.e. SD1, S2, and SD5) are associated with higher effect by tightening. For instance (see Figure 6, inland section), the 9% is presented in the case of SD1 dwelling, while for the SD4 (tighter building), the impact was estimated at ≈0.2%. Now, in the context of the cooling season, as in the case of energy performance the effect is not substantial, with median values close to 0%.

Effect on the performance of thermal insulation and glazing

The importance of air tightness is also revealed when comparing the performance of interventions with the permeability of base case. Figure 7 shows the comparison of the performance for the categories of thermal insulation and glazing systems, when tightening the building enclosure.

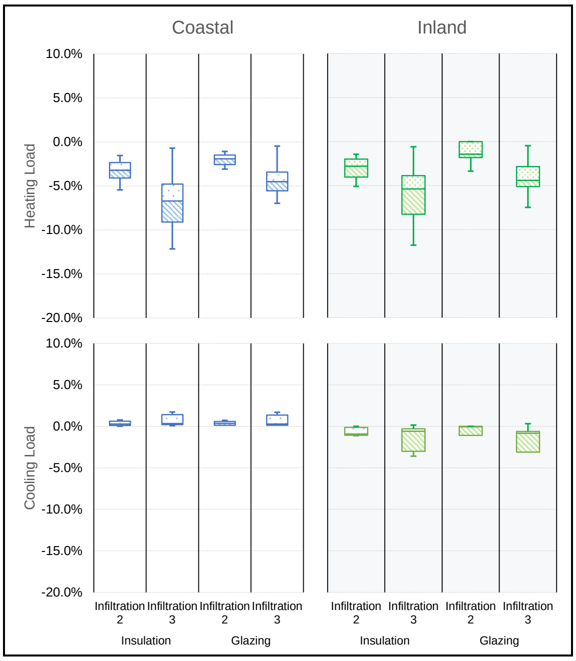

Figure 7 Impact on energy saving measures by tightening the envelope

During the winter season, the performance of thermal insulation (roof, external walls or floor) was dramatically improved when the Passivhaus standard was applied. In particular, 50% of the samples lie within the range of 5-9% (coastal) and 4-8% (inland) of heating reduction and can reach up to 12%, while Scenario (2) may reduce heating demand by 2-6% (coastal) and 2-5% (inland). In the same line, the impact of glazing performance ranges between -0.5% to -7% (both climates).

As in the case of base load performance, the impact of air tightness on the cooling performance is negative for the coastal areas and positive for inland weather conditions. Again, the effectiveness of tightening the building is lower for coastal areas with an increment for both thermal insulation and glazing that can reach up to 2%, while in the inland areas an improvement of approximately 4% is possible for both categories of interventions.

The same scene is also presented within the context of thermal comfort. Figure 8 shows the results on alternation of thermal environment by the synergies of air-tightness, thermal insulation and glazing system.

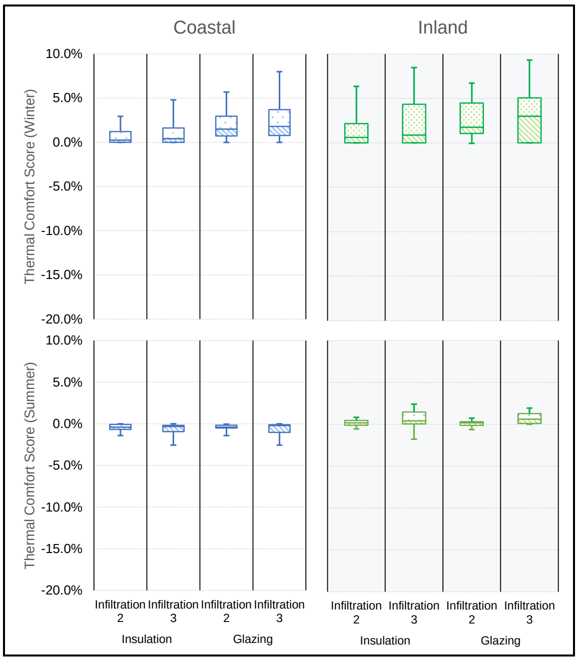

Figure 8 Impact of envelope tightening on the thermal comfort of thermal insulation and glazing measures

Again, the effect on winter season is higher for both climates. Comparing with thermal loads, the air-tightness shows greater impact on the glazing system, especially during the winter period. The median values, for glazing systems, are slightly higher than those of thermal insulation. The thermal comfort score is compromised (not substantially) during cooling season, as at the case of energy performance.

Air-tightening and Indoor Air Quality (IAQ)

Evidently, tightening building envelope may reduce the air infiltration, however this has an impact on the indoor pollutant's concentration. In general, leaky dwellings rely on the mechanism of the uncontrolled ventilation (infiltration) to provide occupants with fresh air and dilute pollutants. This effect is outside the context of this study, but it was considered critical to present the impact of tightening the envelope on the concentration of indoor pollutants. Due to the amount of data, only an example is depicted in the Figure 9, for the case of living room of a leaky house (SD4). In particular, the CO_2 concentration (left y-axis) of the space is plotted with the air temperature (right y-axis) for a day period, under the 3 scenarios of air tightness. The blue region on the graph indicates the period when the heating system is switched on.

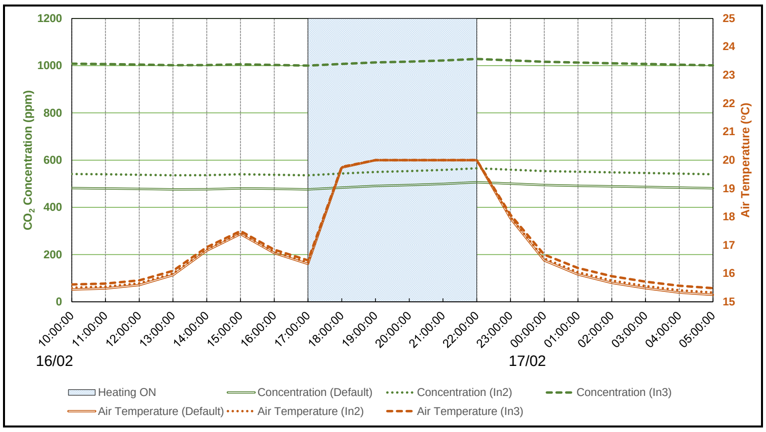

Figure 9 Living room CO_2 concentration-SD4

It can be clearly noticed that the CO_2 concentration is dramatically increased under the Scenario (3), while an increment is presented on the air temperature. The CO_2 levels are daily accumulated within the space, resulting on high levels of concentration.

4. CONCLUSIONS

The study presented the investigation of air infiltration in residential envelopes at the Mediterranean region. The results comprises by the findings of a blower door test and the analysis of building simulation. The study examined 9 single detached houses, located in Cyprus.

The blower door test results revealed a decreasing trend on envelope air-tightness in the last decades. Newly constructed buildings showed exemplary levels of air-tightness (Passivhaus Standard), under no obligation on energy efficiency building regulations. Due to the concrete structure and the location of air paths, these examples may motivate the tightening of building envelopes during retrofitting, as the majority of national housing inventory is founded on the particular building structure.

The building simulation results showed that air penetration seems to affect positively the winter performance of the envelope, with the Scenario 3 (Passivhaus Standard) having higher impact. Meanwhile, during the winter season the thermal comfort is enhanced, on the contrary with the summer season, where tightness may slightly compromise the overall scene. In addition, it can be concluded that tightening can beneficially contribute on the performance of the other measures, especially during heating period. Particularly, the improvement of air-tightness under the scenario of Passivhaus standard can improve the winter performance of thermal insulation up to 12%, while the synergy with a glazing system may reduce the heating demand up to 7%.

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