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Analysis of the impact of door and window replacement and shading installation

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ABSTRACT

In the case of an out-dated building, replacing poorly sealed windows and doors results in significant energy savings, but it is essential to consider the building's structural principles during the modernization process.

This study underscores the critical importance of both high-performance window systems and high-quality installation practices in achieving optimal energy performance in residential building renovations. Proper air sealing and the integration of effective shading devices, including roller shutter systems, have been shown to significantly reduce both heating and cooling energy demands, leading to substantial energy savings. These findings emphasize that both material selection and precise installation are essential for maximizing energy efficiency in residential retrofits.

KEYWORDS

window modernization, building energy, window characteristics, air sealing, energy code compliance

1. INTRODUCTION

To increase the energy efficiency of buildings, the EU has established a legislative framework. The directives 2010/31/EU [1] on the energy performance of buildings and 2012/27/EU [2] on energy efficiency, amending directive 2018/844/EU [3] together support policies that aim to make the building stock as energy-efficient and low-carbon as possible by 2050. EU countries must develop clear, long-term renovation strategies to achieve carbon neutrality in their national building stock by 2050, with indicative milestones for 2030, 2040, and 2050. Member states must update their national calculation methods based on the annexes of the standards developed by the European Committee for Standardization (CEN) under mandate M/480, specifically ISO 52000-1:2017 [4], ISO 52003-1:2017 [5], ISO 52010-1:2017 [6], ISO 52016-1:2017 [7], and ISO 52018-1:2017 [8]. The previously listed Energy Performance of Buildings (EPB) standards play a key role in supporting the energy efficiency directives.

EU regulations have necessitated a review of Hungarian legislation, leading to the adoption of Decree 9/2023 (V. 25.) of the Ministry of Construction and Transport [9]. The energy performance of a building is still calculated based on the combined performance of the enclosing structures and building services, with windows and doors being essential components of the enclosing structure.

The primary function of openings installed in external enclosing walls is to separate the interior and exterior spaces while ensuring natural lighting and ventilation for the interior. The installation method and placement of these openings not only define the building's character and aesthetic appearance but also influence the comfort of the interior spaces, and the building's energy performance, and may have physical building-related consequences. In addition to the heat transfer coefficient, which depends on the characteristics of the glazing and the frame, three important factors are associated with these openings. The structure's airtightness and the installation method both affect filtration, which plays a role in heat loss

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calculations, similar to the coefficient mentioned earlier. The position of the opening within the wall structure typically influences the extent of thermal bridging; this phenomenon must always be considered, examined, and minimized. Shading can also significantly impact cooling energy demands. All three effects can be influenced through architectural tools, which must be defined during the design process.

Factory-produced insulating glass units consist of two or more layers of glass, with spacer bars ensuring the distance between the glass layers of varying thickness. The energy performance of the glazing depends on the quality of the glazing and coating layers, the quality of the spacers, and the quality of the gas fill between the glass layers.

From an architectural perspective, the most important properties to consider when selecting windows and doors are their size, color, and possibly the opening mechanism. Beyond the glazing, the type and material of the frame also significantly affect the energy performance. The frame and sash structures are mostly made of wood or plastic, but there are also metal, aluminum, steel, and mixed-material structures. Wooden windows are typically made from pine or redwood, while plastic windows are most often made from extruded, multi-chamber PolyVinyl Chloride (PVC) profiles, with mitered and welded joints. Aluminum windows are made from extruded elements, with most surfaces being powder-coated. Galvanized steel structures are made from rolled profiles.

2. STRUCTURAL ASPECTS OF WINDOW AND DOOR INSTALLATION

The classification, testing, and product standards for individual products are common within the European Union, but the specific requirements for each product are typically not centralized; these fall under the jurisdiction of the member states. Currently, there are nearly 120 standards in force related to windows and doors, with approximately 85% of them available in English. Some of these standards pertain to various tests, while others specify classification, which is particularly important for testing laboratories. However, as a designer, it is also advisable to be familiar with these standards when selecting a product. For windows and balcony doors, the most important functional requirements are airtightness, wind resistance, and water tightness. MSZ 9333:2011 [10], in line with European regulations, defines threshold values for these aspects depending on local weather conditions, geographic location, the building's façade height, and its position on the façade.

2.1. Airtightness

The airtightness of windows and doors is divided into four categories:

- *Poor airtightness*: This is the case when the structure is warped, poorly fitted, or has an un-insulated, unsealed installation gap;
- *Medium airtightness*: Windows and doors with a double structure, well-fitted but unsealed, or single-structure windows with well-fitted self-adhesive frame and sash seals; or windows with only thermal insulation sealing in the installation gap are categorized here;
- *Good airtightness*: Windows and doors with continuous factory-installed, shaped frame-sash seals, sealing at least at one point on each side; or those classified in the certification document as Class 4 following EN 12207:2016, [11] for airtightness, and in all cases, the installation gap is sealed airtight;
- *Excellent airtightness*: This classification is only applicable when the air tightness measurement results according to the ISO 9972:2015 [12] standard are available.

In the case of outdated windows and doors, the increase in air exchange due to airtightness issues requires accounting for additional ventilation, which can sometimes lead to significant heat loss, thus affecting the building's energy performance. This is influenced not only by the design and condition of the window and door structure itself but also by the tightness of the installation gap, which is often not done according to specifications even in the case of new windows and doors.

The external seal of the installation gap is responsible not only for air and wind tightness but also for water tightness. Without it, the wind pressure can force rainwater through these gaps into the structure.

2.2. Water tightness

Water tightness is also a requirement for the window and door structure itself. The Hungarian regulations are among the strictest - starting with the V1 category (exceptionally water-tight) and moving towards less stringent requirements for large, medium, and small water tightness. However, while maintaining operability, perfect water tightness is usually not achievable, and the openings designed to drain moisture and condensate from the air chambers must allow for moisture to exit the structure towards the outside, protecting the interior. Special attention must be given to keeping these drainage openings clear during the installation of the sill.

Due to the complex issues, the installation of windows and doors is regulated by official documents in several countries: RAL Montage [13], EnEV [14], ÖNORM B5320:2024 [15]. In addition to the external air- and water-tight sealing, proper sealing must also be provided on the internal side of the installation gap, which serves as a vapor barrier for the interior. If moisture were to enter the gap unhindered and be blocked by the external seal, already in a colder environment, condensation within the structure could damage both the window and the masonry.

The external and internal gap seals can also be achieved using membranes with variable water vapor diffusion resistance values (*sd*), which result in an "outward-opening" structure depending on the vapor pressure, ensuring the correct direction for vapor migration.

It is important to note that with the proper installation of modern, sealed structures, the air exchange through windows and doors is reduced to an extent that, to maintain suitable indoor air conditions - primarily to ensure a fresh air supply and indoor moisture removal - the appropriate ventilation must be provided. This can be achieved through conscious choices in the way the building is used, for example, regular, short-duration cross-ventilation, or using built-in ventilation systems.

2.3. Impacts of window position

Previous studies conducted by Decheva [16], Misiopecki et al. [17] were focused on determining for various window-to-wall connection cases. The optimal position of a single-shell window or door in a silicate-structured, thermally insulated layered wall is close to the thermal insulation line, aligned with the central axis of the wall structure's isotherms. If the window or door is shifted inward from this plane, which is considered ideal from an energy efficiency perspective, the thermal insulation must also be extended into the reveal. The insulation must be applied uniformly along the entire perimeter of the window or door. By placing a window in the optimal positions, the thermal bridge losses could be reduced by more than 50%. Thus, it is important to design window-to-wall connections carefully.

The findings of the study on the optimization of energy performance and thermal comfort in a typical residential building indicate that the most pronounced improvements were achieved through the enhancement of thermal insulation and the implementation of multi-pane glazing systems. Additionally, the building's performance was further optimized by adopting a more compact architectural form and by reducing the window-to-wall ratio, both of which contributed to minimizing energy losses and improving overall thermal efficiency [18].

2.4. Shading elements

The solar gains received through glazed surfaces can reduce heating energy demand in winter, while in summer aim to minimize the amount of heat entering through these surfaces. This can be achieved with glass featuring low solar radiation transmittance and effective shading solutions [19]. Shading elements as architectural features casting shadows on windows, surrounding objects, neighboring buildings, and vegetation can also be considered. A simple method of shading involves using external or internal shading devices attached to the windows, whose efficiency depends on their color, density, and material. More effective external shading can be achieved with roller shutters, external blinds, or louvered shutters. The selection of shading products and the aesthetic requirements for their integration into the building have several structural implications. Hidden shading systems affect the installation the plane of the window or door, the size of the wall reveals, and raise requirements for the thermal insulation of the reveals [20].

The architectural and structural consequences of this design must be considered during the planning phase - this includes the appropriate size of the frame extension, the creation of a larger wall opening, and consideration of the placement and fixation of shading system rails concerning the remaining visible surface of the frame (Fig. 1). When using a frame extension made of a different material than the window or door frame, the airtightness, water tightness, and vapor barrier properties of the connection between the two structures must also be addressed. This can either be prefabricated with connections that meet these requirements or achieved on-site by properly placing membranes to seal the gap on both the exterior and interior sides. In the case of windows or doors extended into the plane of the thermal insulation, in addition to the more challenging fixation process, acoustic requirements must also be considered, as an open gap inevitably forms between the wall and the window or door, which is only covered by thermal insulation. A solution to this issue is an L-shaped steel profile running along the perimeter of the window or door, which completely seals the gap [21].

3. CASE STUDY ON THE IMPACT OF WINDOWS AND DOORS REPLACEMENT IN ENERGY EFFICIENCY

In the case of energy modernization needs for a family house built in the 1980s with silicate structures and without thermal insulation, a comprehensive renovation affecting the entire building and building systems represents a significant financial burden. The examined building has a gross floor area of 110 m^2 and a usable floor area of 92.7 m^2. As the first step of energy modernization, window and door replacement will be carried out. The calculations show that the quality of the construction and the installation of shading devices cause variations in the cooling and heating energy demand. The old windows have poor air sealing, with 70 mm wide wooden frame windows featuring double glazing, metal spacers between the glass layers, and presumably no gas filling. Heating is provided by a gas-powered boiler with a two-pipe system and a controlled-speed pump, while there is no cooling system in the building.

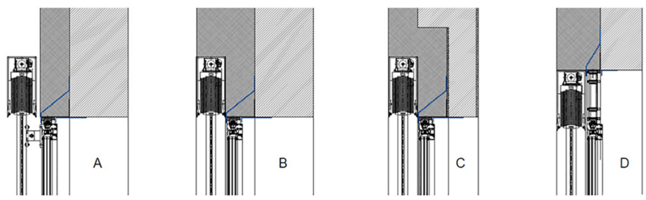

Fig. 1. Shading placement options in plane coordination, A: shading in front of the wall structure, B: shading within thermal insulation, C: shading within thermal insulation with a recessed wall reveal, D: shading in front of the window with a frame extension

The basic scenarios examined are:

1. state before the window replacement;
2. installation of new windows with good air sealing;
3. installation of new windows with moderate air-sealing.

As the next step, the effects of shading systems are examined. Without the installation of shading, the building does not meet the summer heat protection requirements. The examined basic scenarios are:

1. installation of new windows with good air sealing and roller shutter shading;
2. installation of new windows with good air sealing, shading, and split air conditioning for cooling;
3. installation of new windows with good air sealing, without shading, and split air conditioning for cooling.

4. CALCULATION OF HEAT LOSSES AND GAINS OF WINDOW AND DOOR STRUCTURES

The building's net thermal energy demand $Q_{F,net}$, (Fig. 2) is obtained by summing the heat losses and the heat gains corrected by a utilization factor,

$$Q_{F,net} = \left(Q_{veszt} - \eta_F Q_{nyer}\right), \quad (1)$$

where Q_{veszt} is the total heat loss during the heating period (kWh), η_F is the utilization factor of the gains, Q_{nyer} is the total heat gain during the heating period (kWh).

The net cooling energy demand $Q_{H,net}$ is calculated as follows:

$$Q_{H,net} = (Q_{terh} - \eta_H Q_{lead}), \quad (2)$$

where Q_{lead} is the total heat rejection (heat loss) during the cooling period (kWh), η_H the utilization factor, Q_{terh} is the total heat load (heat gain) during the cooling period (kWh).

The windows and doors influence the building's energy balance at several points, including the following: transmission heat losses corrected for thermal bridges through the structure (U-value), losses resulting from the airtightness of the building envelope, the increase in night-time ventilation, solar radiation gains through glazing, and the solar gains influenced by shading effects.

4.1. The thermal transmittance

The thermal transmittance (U-value) of windows and doors can be determined using:

- A numerical modeling based on the ISO 10077-2:2000 [22] standard;
- A simplified calculation method according to ISO 10077-1:2017 [23], with simplifications applied using the following relationships.

Glazing installed at an inclined angle has a higher Ug value than glazing installed vertically (this is why regulations permit a higher thermal transmittance value for roof windows or glass roofs). Therefore, it is crucial to consider the Ug value calculated in the planned or installed position for windows, doors, or other glazed structures. The thermal transmittance ($U_{ny,e}$-value) of single-shell windows and doors (windows, doors) can be calculated using the following Eq. (1) [5],

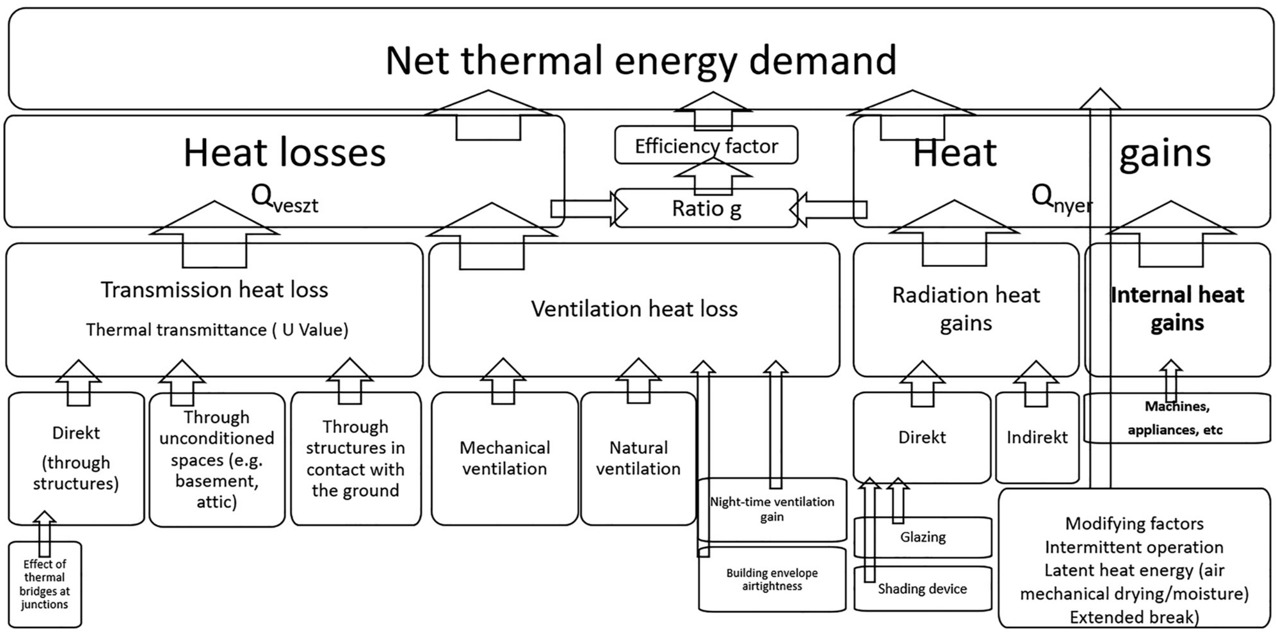

Fig. 2. Calculation method of the thermal energy demand

$$U_{ny,e} = \begin{cases} \dfrac{\sum i\ A_{ü} \cdot U_{ü} + \sum A_p \cdot U_p + \sum A_k \cdot U_k + \sum l_{k,ü} \cdot \Psi_{k,ü}}{\sum A_{ü} + \sum A_p + \sum A_k} \\ + \dfrac{\sum l_{k,p} \cdot \Psi_{k,p} + \sum l_{m,ü} \cdot \Psi_{m,ü}}{\sum A_{ü} + \sum A_p + \sum A_k}, \end{cases} \quad (3)$$

where $U_{ü}$ is the thermal transmittance of the glazing, according [9]; U_p is the thermal transmittance of the opaque panel; U_k is the thermal transmittance of the frame [9]; $\Psi_{k,ü}$ is the linear thermal transmittance coefficient of the frame-glazing junction, according to [4]; $\Psi_{k,p}$ is the linear thermal transmittance coefficient of the frame-opaque panel junction; $\Psi_{m,ü}$ is the linear thermal transmittance coefficient of the stiffening profile-glazing junction; $A_{ü}$ is the surface area of the glazing; A_p is the surface area of the opaque panel (there is no opaque panel in the window); A_k is the surface area of the frame; $l_{k,ü}$ is the thermal bridge length of the frame-glazing junction; $l_{k,p}$ is the thermal bridge length of the frame-opaque panel junction; $l_{m,ü}$ is the thermal bridge length of the stiffening profile-glazing junction.

4.2. Consideration of shading structures

The additional thermal insulation effect provided by the thermal resistance of associated shading structures ($U_{ny,t}$) cannot be considered when verifying the elemental requirements. However, the thermal resistance of closed shading structures may be considered when calculating heating and cooling energy demand by adjusting the heat transfer coefficient of the window as follows [4]:

$$U_{ny,t} = 0.7 \cdot U_{ny} + 0.3 \cdot \frac{1}{\frac{1}{U_{ny}} - \Delta R}, \quad (4)$$

where $U_{ny,t}$ is the heat transfer coefficient of the window; U_{ny} is the thermal transmittance (U-value) of the window, ΔR is the additional thermal resistance, which includes the thermal resistance of the associated shading structure R and the thermal resistance of the air gap R_l between the shading structure and the window [4].

The summer thermal protection of the building, associated with shading structures, is verified, which sets requirements for the protection of glass surfaces against solar radiation. The methodology provides a shading correction factor based on the placement of shading elements and landscape features. By multiplying and weighting this factor with the combined total solar radiation transmission capacity of non-north-facing transparent structures and associated shading structures, and considering the gross surface area, the building's factor is obtained. The permissible limit value for this factor is 0.3 [4, 23, 24].

4.3. Consideration of the additional ventilation heat loss due to the airtightness of the building envelope

Ventilation heat losses are determined by the biologically required air exchange rate, but for windows and doors, the increase in air exchange due to airtightness deficiencies must also be taken into account. The ventilation heat transfer coefficient for a building with purely natural ventilation can be calculated as follows for both heating and cooling conditions:

$$H_{szell,F/H} = 0.35V \left(n_{szüks} \frac{\Delta t_{term}}{\Delta t} + n_{filt} \right) \quad (5)$$

where n_{filt} is the air exchange rate due to infiltration (1/h), Δt_{term} is the duration of the naturally ventilated period within the operating time (h), and Δt is the total period being analyzed (h). For windows with poor airtightness, the increase in air exchange due to infiltration is 0.2 1/h for wind-sheltered façades, 0.35 1/h for wind-exposed façades, 0.05 1/h and 0.1 1/h for moderately airtight windows, and 0.03 1/h for well-sealed windows.

4.4. Consideration of the solar radiation gains of glazing systems and the associated shading structures

$$Q_{sd,F/H} = \sum A_{ü,i} \cdot g_{\frac{F}{H},i} \cdot g_{árny,H,i} \cdot F_{árny,i} \cdot G_{s,i}, \quad (6)$$

where $A_{ü,i}$ is the area of glazing with orientation i and tilt angle (m^2), $g_{F/H,i}$ is the total solar transmittance of glazing with orientation i and tilt angle for heating/cooling conditions, $g_{árny,H,i}$ is the solar transmittance of the associated (sun-shading) structure for the window with orientation i and tilt angle, $F_{árny,i}$ is the total shading factor due to external obstructions (e.g., horizon, vertical and horizontal shading structures) for the window with orientation i and tilt angle, and $G_{s,i}$ is the solar radiation energy incident on the surface with orientation i and tilt angle for the given period (kWh m^{-2}).

The glazing area can be determined based on the geometric data of the window or the average frame-to-glass ratio: $A_{ü} = A_{nyz} - F_{keret}$, where $A_{ü}$ is the area of the glazing with orientation i and a specific tilt angle, A_{nyz} is the window area (m^2), F_{keret} is the frame ratio of the window/door, and the frame-to-glass ratio can be obtained based on the geometry of the specific window. In the absence of more accurate data, the frame-to-glass ratio is generally assumed to be 30%, 10% for skylights and thin conservatories, and 50% for small windows (<0.5 m^2). The total solar transmittance of the glazing (considering the incident angle) is given by $g_{F/H} = F_{ü} \cdot g_n$, where $F_{ü}$ is the glazing correction factor based on the incident angle, with a default value of 0.9, and g_n is the solar transmittance of the glass for perpendicular solar radiation.

5. RESULTS AND DISCUSSION OF THE CASE STUDY

The verification of the thermal transmittance coefficients of the windows and the changes in the building's cooling and heating energy demand were performed using the Auricon Energetic software.

Based on calculations, the thermal transmittance coefficient (U_{ny}) of the existing window structures ranges from 2.79 to 3.12 W/m^{2}K. The thermal transmittance coefficient of the double glazing is 2.75 W/m^{2}K, the thermal transmittance coefficient of the 70 mm wide wooden frame is $U_k = 2.2$ W mK^{-1}, and the linear thermal transmittance coefficient of the connection thermal bridge is $\Psi_{k,ü} = 0.08$, $g_n = 0.68$.

During the renovation, modern, high air-sealing, triple-glazed, low-E coated windows and balcony doors with argon gas filling will be installed, featuring five-chamber plastic frame structures. The internal reinforcement profile of the glass structure is made of plastic. Due to the requirement for roller shutter shading, the installation of the windows and doors will be in the middle zone of the wall structure. The thermal transmittance coefficient of the glazing is $U_ü = 1.2$ W/m^{2}K, the radiation thermal transmittance coefficient is $g_n = 0.56$, the frame thermal transmittance coefficient is $U_k = 1.0$ W/m^{2}K, and the linear thermal transmittance coefficient of the connection thermal bridge is $\Psi_{k,ü} = 0.02$. All the planned windows meet the 1.1 W/m^{2}K requirement, and according to software calculations, the thermal transmittance coefficient (U_{ny}) ranges from 1.08 to 1.10 W/m^{2}K.

The impact of window and door replacement: Based on the calculations, after replacing the windows with good air sealing, a 55.17% reduction in cooling energy demand ($Q_{H,net}$) can be observed, along with a 26.44% decrease in heating energy demand ($Q_{F,net}$). The overall energy performance shows an improvement of 22.5% in this case. If the air sealing is of medium quality, meaning the windows are of high quality but only thermal insulation is added to the wall gap without sealing, a 55.23% reduction in cooling energy demand ($Q_{H,net}$) is observed, with a 24.66% decrease in heating energy demand ($Q_{F,net}$). The overall energy performance improves by 21.06% compared to the original state. The detrimental effect of filtration through the installation gaps can be detected. The change in energy demand between medium and good air sealing installations can be observed. When comparing the impact of medium and good air-sealing window installations on energy demand, it is clear that medium-quality installations result in an increase in heating energy demand, a slight decrease in cooling energy demand, and a 1.5% increase in overall energy consumption (Table 1).

The impact of shading systems: In the case of installing new, well-sealed windows with roller shutter shading, the cooling energy demand ($Q_{H,net}$) decreased by 100% compared to the original state, while the heating energy demand remained unchanged. The beneficial effect of roller shutters can be quantified - with the installation of shading, the cooling energy demand can be reduced to zero (Table 2).

Table 1. Building renovation options, changes in total cooling and heating energy demand

	Cooling energy demand $Q_{H,net}$ (kWh/year)	Change in cooling energy demand (%)	Heating energy demand $Q_{F,net}$ (kWh/year)	Change in heating energy demand (%)	Overall energy performance characteristic (kWh/m^{2}year)	Change in overall energy performance characteristic (%)
Existing window/ door with poor air tightness	665.01	reference	15733.81	reference	517.37	reference
New window/ door with good air tightness	310.79	−55.17	11573.74	−26.44	400.88	−22.52
New window/ door with medium air tightness	310.35	−55.23	11853.89	−24.66	408.43	−21.06

Table 2. Building renovation options, changes in total cooling and heating energy demand

	Cooling energy demand $Q_{H,net}$ (kWh/year)	Change in cooling energy demand (%)	Heating energy demand $Q_{F,net}$ (kWh/year)	Change in heating energy demand (%)	Overall energy performance characteristic (kWh/m^{2}year)	Change in overall energy performance characteristic (%)
New windows and doors, with good airtightness, with roller shutter shading	0.00	−100.00	11573.74	−26.44	400.85	−22.52

It can also be confirmed by calculations that the incorrect installation of window structures with medium air sealing has the greatest impact on heating energy demand. Due to filtration, the heating energy demand is higher, while the cooling energy demand decreases due to heat dissipation through ventilation. Roller shutter shading reduces the cooling energy demand by 100% in the examined building (Table 2).

Due to the space requirements for the roller shutter box, the window structures are placed in the middle plane of the wall. The frame structure is created with frame extensions, and self-adhesive sealing strips are used on both sides to ensure protection against rain, air, and vapor. This ensures high-quality installation and the creation of the most favorable technical solution.

6. CONCLUSION

The analysis demonstrates that, in outdated residential buildings, the replacement of poorly sealed windows and doors substantially reduces transmission heat losses, thereby achieving considerable energy savings and improving both heating and cooling energy performance. Solar heat gains through glazed surfaces contribute beneficially to reducing heating demand during the winter season, while, in summer, the application of shutter boxes effectively mitigates internal heat loads, leading to a reduction in cooling demand. The positioning of windows and shutter boxes emerged as a critical factor influencing thermal performance. Computational assessments revealed that suboptimal or unprofessional installation practices can significantly compromise the intended energy efficiency benefits. Even in cases where modern, high-performance window units are employed, insufficient air sealing of installation joints degrades the overall performance of the building envelope.

Simulation results indicated that the installation of high air-tightness window systems in typical residential building retrofits leads to substantial reductions in both cooling and heating energy demand. Specifically, the replacement of outdated windows with modern, well-sealed alternatives resulted in a 55.17% decrease in cooling energy demand ($Q_{H,net}$) and a 26.44% reduction in heating energy demand ($Q_{F,net}$). Conversely, where installation inaccuracies led to only medium-quality air sealing -despite the use of high-performance fenestration - the cooling energy demand still decreased considerably; however, the reduction in heating energy demand was markedly less significant. Consequently, the overall energy savings potential diminished. The deterioration in air-tightness due to inadequate sealing of installation gaps caused elevated infiltration heat losses, particularly exerting a negative effect on heating performance.

Furthermore, the influence of external shading systems was identified as highly significant. The integration of roller shutter shading in conjunction with new, well-sealed windows completely eliminated the building's cooling energy demand, achieving a 100% reduction in $Q_{H,net}$. The implementation of external shading systems enables the cooling energy demand to be reduced to zero, translating into notable energy savings and a significant enhancement in overall building energy efficiency.

These results highlight the dual importance of selecting high-performance fenestration components and ensuring precise, high-quality installation practices, including thorough air sealing and the incorporation of effective shading devices. Neglecting these aspects undermines the achievable improvements in energy performance and diminishes the effectiveness of the renovation strategy.

REFERENCES

[1] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, Document 32010L0031, European Union.

[2] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC text with EEA relevance, Document 32012L0027, European Union.

[3] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (text with EEA relevance), Document 32018L0844, European Union.

[4] *ISO 52000-1:2017*, Energy Performance of Buildings - Overarching EPB Assessment, Part 1: General Framework and Procedures, CEN, 2017.

[5] *ISO 52003-1:2017*, Energy Performance of Buildings - Indicators, Requirements, Ratings and Certificates, Part 1: General Aspects and Application to the Overall Energy Performance, CEN, 2017.

[6] *ISO 52010-1:2017*, Energy Performance of Buildings - External Climatic Conditions, Part 1: Conversion of Climatic Data for Energy Calculations, CEN, 2017.

[7] *ISO 52016-1:2017*, Energy Performance of Buildings - Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads, Part 1: Calculation Procedures, CEN, 2017.

[8] *ISO 52018-1:2017,* Energy Performance of Buildings - Indicators for Partial EPB Requirements Related to Thermal Energy Balance and Fabric Features, Part 1: Overview of Options, CEN, 2017.

[9] *9/2023, (V. 25.) ÉKM*, Decree on the determination of the energy performance of buildings (in Humgarian), Construction Government Decree, 2023.

[10] *MSZ 9333:2011*, Application Requirements for Windows and External Entrance Doors (in Hungarian), Hungarian Standard Office, 2011.

[11] *EN 12207:2016*, Windows and Doors - Air Permeability – Classification, CEN, 2016.

[12] *ISO 9972:2015*, Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method, CEN, 2015.

[13] Guideline for the planning and installation of windows and exterior doors for new buildings and renovations, RAL Quality Association for Windows and Doors, Bonn, 2020.

[14] Energy Saving Ordinance (in German), Federal Ministry of Economics and Energy, 2014, Germany.

[15] *ÖNORM B5320:2024*, Installation of Wwindows and Doors in Walls - Design and Execution of the Construction and Window/ Door Connection, Vienna: Austrian Standards Institute, 2024.

[16] L. M. Decheva, "Windows for energy effective buildings – Thermal bridges by window insertion" (in Norvwegien), MSc Thesis, Norwegian University of Science and Technology, Trondheim, Norway, 2012.

[17] C. Misiopecki, M. Bouquin, A. Gustavsen, and B. P. Jelle, "Thermal modeling and investigation of the most energy-efficient window position," *Energy Build.*, vol. 158, pp. 1079–1086, 2018.

[18] C. H. Radha, "Traditional houses energy optimization using passive strategies," *Pollack Period.*, vol. 13, no. 2, pp. 185–194, 2018.

[19] R. R. Ördög, Zs. Szűrös, and T. Horváth, "Energy analysis of buildings with large glazed surfaces," in *9th International Conference on New Energy and Future Energy Systems*, Győr, Hungary, July 29–30, 2024, pp. 58–64.

[20] M. Rais, S. Elhadad, A. Boumerzoug, and B. Baranyai, "Optimum window position in the building façade for high day-light performance: empirical study in hot and dry climate," *Pollack Period.*, vol. 15, no. 2, pp. 211–220, 2020.

[21] J. Šadauskienė, J. Ramanauskas, D. A. Krawczyk, E. Klumbytė, and P. A. Fokaides, "Investigation of thermal bridges of a new high-performance window installation using 2-D and 3-D methodology," *Buildings*, vol. 12, no. 5, 2022, Art no. 572.

[22] *ISO 10077-2:2000*, Thermal Performance of Windows, Doors and Shutters - Calculation of Thermal Transmittance, Part 2: Numerical Method for Frames, CEN, 2000.

[23] *ISO 10077-1:2017*, Thermal Performance of Windows, Doors and Shutters - Calculation of Thermal Transmittance, Part 1: General, CEN, 2017.

[24] T. Csoknyai, Zs. Szalay, B. Nagy, and M. Horváth, "Applied building energy engineering" (in Hungarian), 2024. [Online]. Available: https://mernokvagyok.hu/epitesi/wp-content/uploads/sites/13/2024/01/Alkalmazott_Epuletenergetika-segedlet.pdf. Accessed: July 10, 2025.