Long Paper

The Eyes of the City as a Threatened Asset of Cultural Heritage

Improvement of Historic Casement Windows with Vacuum Glazing

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Abstract: Traditional casement windows are considered not only as aesthetically sophisticated window constructions, but also have been subjected to century-long optimization processes. Rough estimates state that there is a large number of these windows still to be found in the building stock of European cities, e.g., Vienna. However, the number is in constant decline, as casement windows often are considered expensive in maintenance and dissatisfactory in their thermal performance and fulfilment of current comfort desires of building occupants, and thus are often demolished and replaced by new windows. Moreover, many building retrofit subsidy programmes do not consider the restoration of windows as a feasible measure and only window replacement is subsidized. Needless to say, the replacement of casement windows with modern-day single layer multi-pane windows in historic facades is often a fundamental distortion in the corresponding façade appearance and thus a threat to the built cultural heritage of cities. One option to satisfy both the performance expectations of occupants and the appearance upkeep required for cultural heritage protection is employing vacuum glass as replacement for float glass. The implementation of vacuum glass products in existing window constructions – however – brings up a set of questions, such as the possible thermal performance improvement of the window, thermal bridge effects in the glass/frame/Wall joints, and constructive integration possibilities. A collaborative R&D project started in 2019 (VAMOS – *Vakuumglas-Kastenfenster: Performance – Monitoring in Sanierungsprojekten*) focussed onto the construction implementation of vacuum glass in demonstration windows, which was accompanied by comprehensive simulation and monitoring of the demo site windows.

***Keywords**: Casement Windows—Thermal Retrofit—Vacuum Glazing Products—Built Environment—Thermal Improvement.*

CHNT Reference: Pont, U., Schober P., Wölzl, M., Schuss, M., Haberl, J. and Hauer, K. (2025). 'The Eyes of the City as a Threatened Asset of Cultural Heritage: Improvement of Historic Casement Windows with Vacuum Glazing', *Proceedings of the 26th International Conference on Cultural Heritage and New Technologies*, Vienna and online, November 2021. Heidelberg: Propylaeum.
doi: 10.11588/propylaeum.1449.c20784.

Introduction

This contribution focusses on the presentation of approach, method, and results of two Research and Development projects pertaining to the thermal improvement of traditional casement window constructions via implementation of novel vacuum glazing products. Casement windows are window constructions constituted by two sequential single glazed window sashes and specific boundary constructions to the surrounding walls (known as casement or box). As a first step, an exploratory research project (VIG SYS RENO, see Pont et al., 2018a) has been carried out some years ago (2014–2015) to investigate the principal suitability and feasibility of casement window retrofit via vacuum glazing products. In this first approach, vacuum glazing products were rigorously tested toward their thermal, acoustical and mechanical properties. Moreover, simulation-based performance inquiries were conducted and rough estimates of the overall performance impact of a window retrofit with vacuum glazing products were done. The results of these efforts, as illustrated in the publicly available report about this project (Pont et al., 2018a) as well as in pertinent publications (Pont et al., 2016; Proskurnina et al., 2016) illustrated a high potential for vacuum glass implementation regarding thermal performance improvement. Indeed, a ten percent heating demand reduction was found in calculations of typical *Gründerzeit* buildings (*Gründerzeit* refers to the late Austro-Hungarian Dual Monarchy of 1850 to 1918), if their casement windows would be improved with vacuum glass. However, these estimates originated from normative calculation, thermal bridge simulation and lab-testing of technology demonstrators only, and not from performance monitoring of real projects, and thus could be considered as yet-to-be-proven in real projects. Based on the described preliminary efforts, a full-fledge collaborative research & development has been setup and conducted from 2019 to 2021. This project (VAMOS) was conducted together with small-scale companies of the domain carpentry and window building as well as with a large scale glass producer, who recently set up a production line for vacuum glass in Europe. The carpentry people delivered their daily practical experience in retrofitting, renovating, or reconstructing of casement windows, and provided demonstration sites for vacuum-glass enabled windows. Based on comprehensive construction evaluation and results of numeric thermal bridge simulation of these windows, six different sites were identified for demonstration implementation of vacuum glazing into existing windows there. These windows were equipped with extensive monitoring equipment to determine their real-life performance. Moreover, during one year of monitoring period (including a cold and a hot season), also user comfort and visible effects (such as condensation on the window glass and frame constructions) were monitored. These efforts were conducted (i) to deliver a real-life-project-based proof of concept that casement windows equipped with vacuum glass may deliver a significant contribution to reduce building-related energy consumption in the historic building stock at little to no negative impact on the building's aesthetic. (ii) to gain long-term performance data of the vacuum glass windows both on building component (U_{Win}-value) and building construction detailing level (f_{Rsi}-value, minimum surface temperature) and (iii) to answer relevant questions, such as if the implementation of vacuum glass should be conducted in the inner window sash or in the outer window sash. While some of these questions have been preliminarily discussed in previous and up-coming publications (e.g. Schuss et al., 2021 and Pont et al., 2022), this contribution is utilized to provide a general overview on the one hand, and to discuss the vacuum glass implementation in view of pertinent guidelines issued by the Austrian Monuments. Thereby, the potential of such performance improvements, connected challenges, and potential conflicts with heritage protection will be addressed as well. Note that other publications focus on technical details such as Key Performance Indicators, Monitoring Setup and results, and simulation efforts, which – due to spatial restrictions – cannot be addressed in detail in this contribution (see Pont et al., 2022).

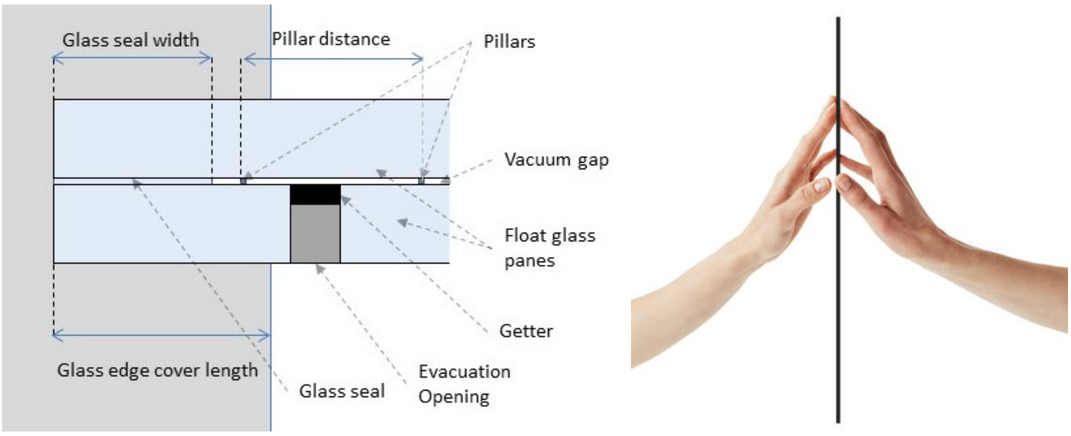


Fig 1. a) (left): Schematics of vacuum glazing product's terminology (Ilustration © Author U.Pont/M.Wölzl); b) (right): A vacuum glazing product photograph from side illustrating the small thickness of vacuum glass (courtesy of www.fineo-glass.eu / https://www.fineoglass.eu/wp-content/uploads/2021/04/fineo_product_header-460x460.jpg © Fineo Glass / AGC Interpane)).

What are Vacuum glazing products?

Vacuum glazing products are products of the glass industry that employ a vacuum gap as insulation layer. The vacuum gap is positioned between two glass panes and regularly less than a millimetre in thickness. To maintain both the vacuum and the form of the glass system, the system requires a set of additional components. First, a grid of small pillars is positioned within the interstitial space. These distance pillars are required to keep the parallelism of two glass panes against the air pressure. Without these pillars, the glass sheets would bow against each other. Moreover, a vacuum-tight glass edge seal is required around the perimeter of the gap along the glass edges. Different materials are employed for this vacuum-tight edge seal (glass or metal). Furthermore, vacuum glass products regularly feature an evacuation opening and a so-called getter point or line. The getter is endowed with a highly-reactive substance to chemically bind any remnants of air components within the vacuum gap. The overall system thickness of such vacuum glazing products currently starts at a bit over 6 mm (3 mm glass pane – 0.15 mm vacuum gap – 3 mm glass pane). Figure 1 illustrates a schematic section through a vacuum glass including relevant terminology as well the slim appearance in a side-view photograph (photo courtesy of the company AGC / Fineo).

The vacuum gap widely eliminates the heat transfer processes of conduction and convection, as such vacuum glazing products provide excellent thermal insulation key performance indicators. In contrast to regular insulation glazings, higher requirements toward the durability of the glass edge seal are required due to the necessity of the long-term upkeep of the vacuum, which ensures the insulation effect. As already indicated, vacuum glass products come at a very thin system thickness and excellent thermal insulation values, which predestines them as candidates to replace float glass panes in existing window systems from an energy saving point of view. Table 1 illustrates some key facts of currently available vacuum glass panes. Interestingly, the research and development efforts pertaining to the engineering of durable vacuum glass products date back over one century (Anton Zoller's german patent of a hollow glass pane (*hohle Scheibe*) dates back to 1913). Durable vacuum glass products as shown in Table 1 are available since about little longer than one decade. In this time, few efforts toward vacuum glass integration in window systems can be found amongst both producers and research institutions. Instead, the vacuum glass products have been used for fixed glazings of facades of new buildings (China) or as part of wine-chilling refrigerators requiring a transparent and highly-insulating door (United States).

R&D efforts onto vacuum glass integration in windows?

As already indicated, a set of projects has been conducted in the past years pertaining to integration of vacuum glass products into existing windows. In a parallel effort, two other research projects have been conducted that targeted the integration of vacuum glass into new windows. These projects were named MOTIVE (2016–2017, see Pont et al., 2020b) and FIVA (2018–2020, see Pont et al., 2020a and Pont et al. 2020b). Figure 2 illustrates the landscape of vacuum glass projects conducted by the authors. The fu,ndamental contrast between projects focussing on integration of vacuum glass into existing window constructions of historic meaningfulness (such as casement windows) and projects focussing on the integration of vacuum glass in new window constructions is highlighted in Table 2. The difference between these approaches is also underlined by the industry partners of the projects: While small scale carpentry companies that focus on construction of individual window solutions and maintenance of the building stock were the logical partners in the VAMOS project, large scale enterprises of the window industry were majorly interested in avant-gardist new vacuum glass window designs majorly intended for new buildings. Needless to say, both of the domains were fruitful playgrounds for generating highly-insulating windows, and do not compete with each other in principle, given that the upkeep of the historic building stock as cultural heritage is accepted as side goal in the general building-related energy consumption discourse.

Approaches to traditional casement windows

Rather conservative estimates judge the amount of casement windows in Austria to about 2.5 million (which all together hints onto about 15 Mio window sashes, compare Öttl, 2011). However, the number is in decline, as on a daily base casement windows are demolished and replaced by new windows with one insulating layer. Given the cultural meaningfulness of casement windows in the historic city centres of Central European cities, each lost casement window can be considered as a small decline of the beauty of these city centres. Figure 3 illustrates a series of casement windows, which impressively underline the importance of their upkeep for cultural heritage protection reasons. In the picture that compares the (not-well maintained) casement windows with some one-layer plastic insulation windows, it becomes clear that facades are disruptively changed in their appearance. Neither the slim timber profiles, not the 3D-effect of the façade appearance can be kept by such replacement windows. Moreover, the lifetime of the one-layer insulation glass windows is regularly limited by the glass product used. The exchange of the glass product regularly is not possible, leading to full replacement of such windows. Casement windows, equipped with float glass or equipped with vacuum glass can be maintained for a very long lifecycle, can be easily separated into components, and thus allow for a rather quick replacement of components, such as a broken glass.

Table 1. Key facts about some of the available vacuum glass panes, as of 2021/2022 (Images © Authors)

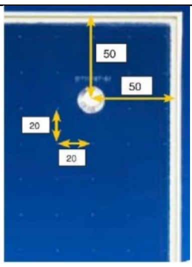
Illustration of the Product (Pictures: Pilkington, own Photographs by the authors)					
Producer and country	Pilkington (Japan)	Synergy (China)	Eagon (Korea)	Guardian (USA)	AGC Interpane (Belgium)
Product name (if available)	Spacia	-	-	-	Fineo
Pillar grid distance [mm]	20	40	40	40	20
Edge Seal thickness [mm]	Ca. 10	Ca. 10	Ca 10.	Ca. 10	Ca. 5
Getter	Getter in point shape (diameter 12 mm)	Getter in point shape (diameter 14 mm)	Getter in point shape (diameter 18 mm)	Getter in point shape (diameter 16 mm)	Getter in line shape (thickness 2 mm)
U_g-value [$W.m^{-2}.K^{-1}$]	0.9	0.58	0.48	0.47	0.7

Table 2. Goals and Construction paradigmae applicable in projects focussing on integration of vacuum glass in existing and new window constructions.

Scenario	**Vacuum glass integration in existing, historically meaningful windows**	**Vacuum glass integration into new windows.**
Major Goal	Improve the performance of the windows under upkeep of the appearance of the window	Generate attractive, new, highly-insulating windows under (optional) use of automated operation/
Construction paradigma	Integrate suitable vacuum glass panels into existing or rebuilt frame constructions minimal invasively (minimal adaptations on frame and glass edge cover length if applicable)	Construct the wing (profiles of the wing) based on the requirements of the vacuum glass (large glass edge cover length of 40 mm or more) Construction of the window frame based on the requirements of fittings, motors, and locking components.

There is a multitude of different casement window construction principles, illustrated in Table 3 as horizontal sections. These different construction principles also pose different thermal and construction behaviour properties. Given that these constructions majorly are used in the German-speaking D-A-CH-Region and there is no feasible translation to English for each of this window types, a short description is provided about each of the windows within the table. Note that the application of any insulating layer (might it be multi-layer insulation glass or vacuum glass) has to be carefully assessed by the position of both sashes in the window niche, the surrounding wall and panel materials, the integration of window seals, and the prevailing microclimates inside and outside of the window.

Case study buildings and performance monitoring

Figure 4 and Table 4 illustrate the case study buildings. In each of the case study buildings, three windows were subjected to rigorous monitoring via tailored sensors (temperatures and relative humidity at relevant points, such as inside, outside, in the interstitial space, and on both sashes' surfaces). Moreover, the heat flow through the window has been determined via a heat flow metering plate. The obtained data was structured and stored in a database and subjected to fundamental analysis. The three windows differed in the vacuum glass application (inside, outside, not at all = window kept in status quo), but were otherwise selected to face the same orientation and the same operation and occupancy profiles.

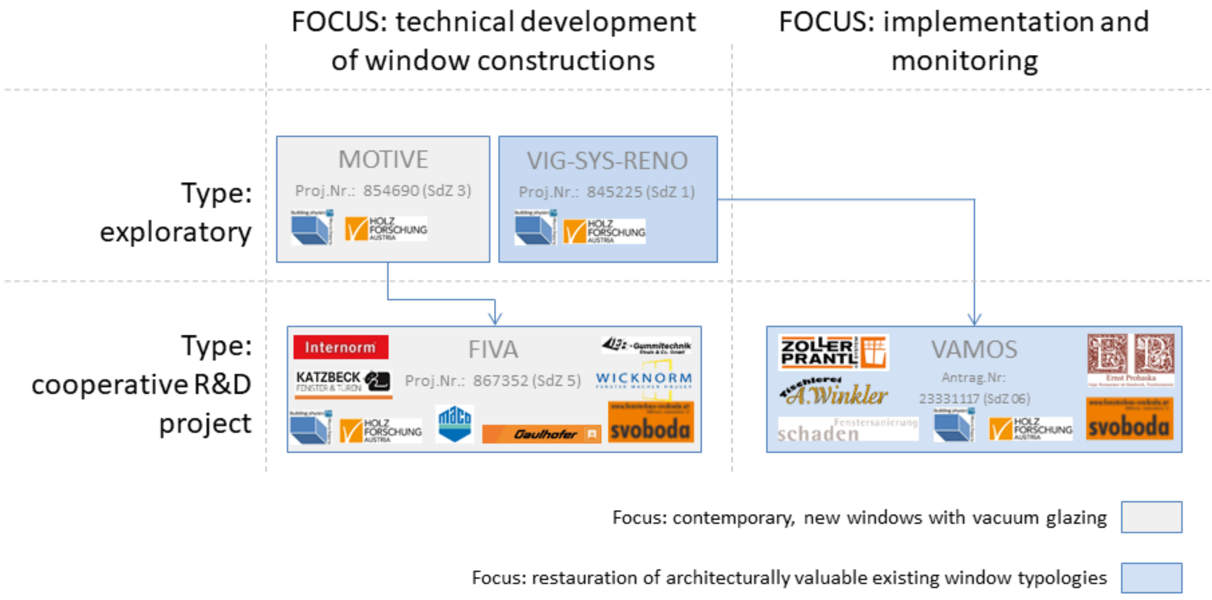
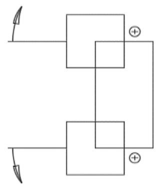
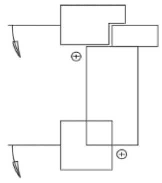
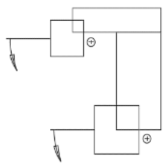
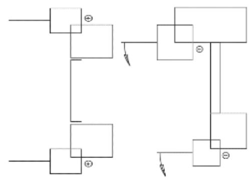


Fig 2. Landscape of R&D projects pertaining to vacuum glass integration into (existing and new) windows (© Authors).

Fig 3. Beautiful casement windows (upper row) versus inconsistent appearance of a façade with casement windows of little maintenance and incongruous replacements by multi-layer insulation-glass windows made of plastic (© P. Schober).

Table 3. Horizontal sections of different casement window types (drawings © Holzforschung Austria).

			
Pfostenstockfenster (Window with outer sash in the façade plane and turning to the outside; inner sash turning to the inside; Known as “Alt-Wiener-Katenfenster” and “Grazer Kastenfenster”)	Leistenstockfenster (Window that turns both sashes to the inside, including a hidden supporting wooden beam frame around the outer sash, “Wiener Kastenfenster”)	Rahmenpfostenstockfenster (Window that turns both sashes to the inside, including a visible supporting beam frame around the outer sash, “Wiener Kastenfenster”)	Doppelrahmenstock-Fenster.(Window that turns both sashes to the inside, and features supporting frames around both sashes, “Wiener Kastenfenster”)

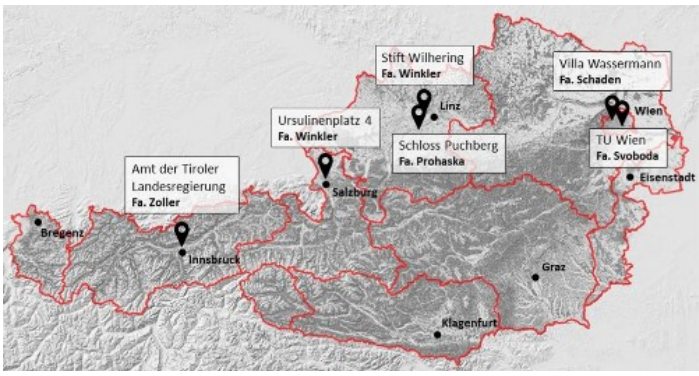


Fig 4. Distribution of the six case study objects in Austria (the responsible carpenter is written in bold letters) (© Authors).

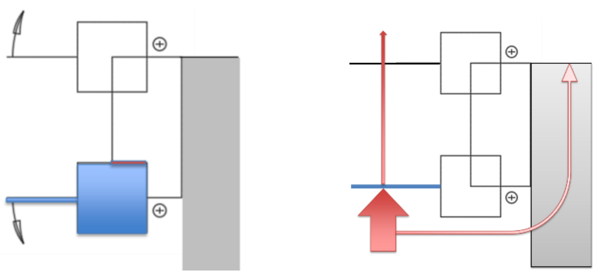
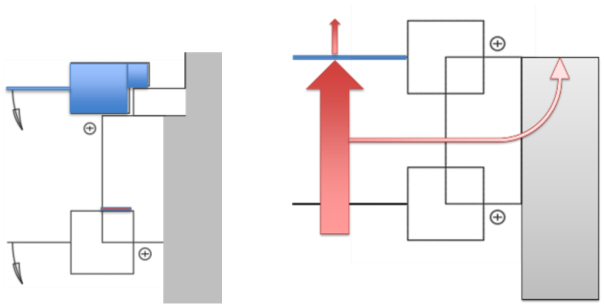
Table 4. Description of the Case study objects.

Object & Location	Castle in Welt	Villa in Vienna	University in Vienna	Monastery in Wilhering	Architectural office in Salzburg	Governing office in Innsbruck
Illustration						
Type of Window	Rahmenstock	Pfostenstock	Pfostenstock	Doppelrahmen	Pfostenstock	Rahmenstock
Positioning of window in the wall niche	In the niche	In planar position of outer perimeter	In planar position of outer perimeter	In planar position of outer perimeter	In planar position of outer perimeter	In the niche
Turning direction	To the inside	To the outside	To the outside	To the inside	To the outside	To the inside
Splitting	Dipterous + dipterous transom window	Dipterous + transom window	dipterous	dipterous	dipterous	dipterous
Usage of rooms	Residential	Residential / empty (retrofit ongoing)	Office	empty	Office	Office
Specific comment	Change of glass.	Outer part of window newly constructed	New window sashes	New window, stone panel casement	New construction of whole casement window	New construction of whole casement window

Results & Discussion of monitoring results and thermal performance.

In five of six demonstration sites the vacuum glass equipped windows showed not only a significant improvement of the window U-values (the measured U_W-value dropped from values between 2.0 and 2.5 $W.m^{-2}.K^{-1}$ to values around 1 $W.m^{-2}.K^{-1}$), but did not show any traces of condensation (on the sash with the vacuum glazing implemented; Note that for vacuum glazing on the inner sash the outer float glass sash did show traces of condensation). The control windows (original state) showed significantly higher U_W-values, and – at some occasions – also showed traces of condensation. The one demonstration site that showed condensation of the vacuum-glazing equipped windows turned out to have flaws connected to the window seals and thus tightness issues. It is believed that the correction of this will stop any condensation to happen. The question, if the implementation of vacuum glass can be recommended for the inner or the outer layer of the window cannot be answered in general, as this – following the case study sites – is highly dependent from the type of casement window and the position of the glass layers in relation to the wall opening. Moreover, the perimeter material around the window niche influences the suitable position (in case of highly conductive wall materials the application of the vacuum glass on the inside is favourable). Table 5 provides an analytical model regarding the heat flow reduction of windows featuring vacuum glazing on the inside and on the outside including the flank heat transfer as illustration. Furthermore, the implementation potential of window seals and/or the air tightness of the overall construction is of high importance as is the heat distribution system (radiators bring more heat convection close to the window surfaces and help avoiding condensate in contrast to low-temperature underfloor radiative heating systems). Needless to say, specific detailed planning is required for any retrofit planning encompassing vacuum glass windows. However, it could be proven both in virtual (Simulation) and real experiments (lab and on-site tests and monitoring) that vacuum glass could offer a feasible way to improve casement windows' energy performance without severe change of the windows and thus the façade's appearance. As such, it seems that this improvement could be a feasible contribution to both the protection of built cultural heritage and reduction of building related energy consumption.

Table 5. Analytical model of the impact of application of vacuum glazing on the inner sash and on the outer sash (including the energy transfer via flanking material); (Illustrations © Authors)

Application on the inner window sash	Application on the outer window sash.
	
Possible / recommendable for all casement windows, under consideration of heat distribution devices, general shape of the window, tight seals within the inner sash, humidity levels in the room, orientation of the window, and prevailing microclimatic conditions.	**Possible / recommendable for all casement windows except Pfostenstockfenster and windows with highly-conductive panelling/wall materials**, under consideration of heat distribution devices, general shape of the window, tight seals within the inner sash, humidity levels in the room, orientation of the window, and prevailing microclimatic conditions.

Discussion in view of heritage protection & Conclusion

As discussed in the introduction, the replacement of casement windows with modern-day single layer multi-pane windows in historic facades is often a fundamental distortion in the corresponding façade appearance and thus a threat to the built cultural heritage of cities. The Austrian monuments office thus states in their guideline onto energy performance of building stock that a replacement of exiting historic window constructions is regularly a no-go in building conservation (BDA 2011, BDA2021). However, the necessity to severely reduce building-related energy consumption requires also technologies for improvement of existing buildings. Windows are considered one of the building construction elements that are “weak spots” in the envelope, and thus is their improvement considered a leverage improvement (as illustrated in this contribution, with a reduction of the heat loss through the casement windows by over 50%). As such, new approaches are required that encompass both the improvement of the thermal performance of the windows and ensure the upkeep of the appearance of buildings and preservation of the historic casement windows. While the integration of multi-pane insulation glass is considered as overcritical due to their thickness, strong effect and distortion both window appearance and geometry, the vacuum glass panes do neither bring these negative effects, nor are yet mentioned in the pertinent guidelines as possible solution. Given their slim thickness as well as the proven energy saving potential, future guidelines should consider these glasses possible at least in non-super-sensitive contexts (e.g. in areas of not-so-strict heritage protection, such as “ensemble protection”).

Funding

The R&D projects mentioned in this contribution were generously funded by the Austrian Research Promotion Agency FFG. Table 6 shows the grant numbers, project duration, project websites published by the funding agencies’ promotion partner and the calls the projects were funded in.

Table 6. Information about Funding of the mentioned projects.

Project	Focus	Type	Duration	FFG Proj. Number	Call
VIG-SYS-RENO	Existing Windows	Exploratory R&D Project	2014–2015	845225	City of Tomorrow (CoT), 1st Call
MOTIVE	New Windows	Exploratory R&D Project	2016–2017	854690	CoT, 3rd Call
FIVA	New Windows	Collaborative R&D Project	2018–2020	867352	CoT, 5th Call
VAMOS	Existing Windows	Collaborative R&D Project	2019–2021	878272	CoT, 6th Call

The authors acknowledge the contribution by the companies involved in the projects (see Figure 2).

Conflict of Interests Disclosure

The authors declare no conflict of interest.

Author Contributions

Conceptualization: Pont, Schober
Data curation: Schuss, Wölzl, Pont, Schober
Formal Analysis: Pont, Schober, Schuss, Wölzl, Hauer

Funding acquisition: Pont, Schober, Wölzl
Investigation: Pont, Schober, Wölzl
Methodology: Schober, Pont, Wölzl, Schuss, Haberl, Hauer
Project Administration: Pont, Wölzl, Schober
Software: Pont, Wölzl, Schuss
Validation: All authors
Visualization: Schober, Wölzl, Pont
Writing – original draft: Pont
Writing – review & editing: Pont

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