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10 Years of Research toward Vacuum Glass Integration into new and existing window constructions: A Review

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Abstract (English)

While windows are still considered as weak spot in contemporary new and existing building envelopes, exciting new technologies are on the edge to emerge into the market. Amongst these technologies, vacuum glass products are considered to have a major impact on the improvement of the thermal performance of windows. The authors conducted 5 in-depth research projects in the past 10 years that focussed on the integration of vacuum glass products into new and existing window constructions. Thereby, a wide range of different additional aspects and interests had to be covered, e.g. heritage protection aspects for historically relevant windows or motorization of windows toward integration into building automation systems. The contribution on the one hand intends to emphasize the importance of the discipline building physics for these R&D efforts, and on the other hand to showcase the reached results of the projects. These results encompass high-performance windows with very low U-values and minimized effects of frame/glazing thermal bridges at glass thicknesses below one cm, as well as traditional casement windows which can be kept as part of the envelope (desireful from environmental footprint/circular economy point of view) but at the same time deliver a highly improved thermal performance.

Kurzfassung (german)

Fenster werden noch immer als (thermischer) „Schwachpunkt in den Gebäudehüllen bestehender und neuer Gebäude betrachtet, jedoch gibt es aktuell spannende neue technologische Entwicklungen, die die (thermische) Performance von Fenstern stark verändern/verbessern können. Die Autoren dieses Beitrags haben in den vergangenen zehn Jahren fünf Forschungsprojekte zur Integration von Vakuumglasprodukten in neuen und bestehenden Fensterkonstruktionen durchgeführt. Dabei wurden verschiedenste, wesentliche Aspekte untersucht, die von Gebäudeautomation/Motorisierung von Fenstern bis zum Denkmalschutz verschiedenste Disziplinen berührten. Dieser Beitrag soll auf der einen Seite die Bauphysik als ganz wesentliche Triebfeder der Entwicklungen unterstreichen, auf der anderen Seite die Ergebnisse dieser Forschungsbemühungen zusammenfassend darstellen. Die Ergebnisse bestätigen, dass Vakuumgläser im Stande sind, sehr effiziente und zarte Hochleistungskonstruktionen bester thermischer Performance zu ermöglichen, sowie einen wesentlichen Beitrag zum Erhalt historischer Fensterkonstruktionen unter starker thermisch/energetischer Gebäudeverbesserung lediglich durch minimalinvasivem Tausch von Floatgläsern zu Vakuumgläsern zu leisten.

Introduction

Whereas the cultural history of windows is a rich and interesting one, windows always have been considered as a weak spot in building envelopes in view of structural design and protective functionalities of the hull. These functionalities pertain to thermal and acoustical insulation, water- and wind/air-tightness, as well as protection against blending and overheating in the hot season. In central Europe the technological advances of window technologies of the past 250 years generated maybe the technically most advanced windows world-wide, however the history of advancements is a quite linear one: The improvement history includes adding additional window sashes (casement windows), introduction of window seals, multplying the glass panes per window (double glazing, triple glazing), introduction of foils attached to window panes that influence the radiative heat transfer characteristics through the glasses, employing different gases as fill gases for interstitial spaces, development of tight edge seals, and the standard-application of turn-and-tilt fittings. It can be assumed that these linear improvements have reached their maximum efficiency, but – to deploy their best performance – such windows regularly are heavy, triple-glazing constructions with rather prominent frame constructions.

Vacuum glazing products emerged in the past 20 years in the glass product market, as the century long challenge of a durable vacuum within the glass has been argued to be solved. By a vacuum glazing product, regularly two parallel glass panes are understood that have a small, evacuated interstitial space of often less than a millimetre. For the upkeep of form and vacuum, a grid of tiny distance pillars is integrated, as well as a tight edge seal around the panes perimeter. Moreover, most vacuum glazing products encompass a getter surface that shall filter remaining particles from the evacuated space, as well as an evacuation opening. Given that the heat transfer processes conduction and convection require a medium, which is not there in the evacuated gap, such glass products regularly feature very good thermal insulation performances. However, the edge seal, which is in most cases made of glass or metal, and the distance pillars, pose linear and point thermal bridges and need to be addressed in window design and construction efforts. Recent developments – however – seem to advance over the issues of cold edge seals by technological progress and goal-oriented engineering and name it "new generation vacuum glass", in contrast to the older "1st generation vacuum glass" (VGLASS, 2024). Figure 1 illustrates the major terminology and constituents of typical (1st generation) vacuum glazing products and their implementation in frame constructions. Given the thermal characteristics of vacuum glass products – high thermal insulation capabilities as a rather slim system thickness - an application both in new window constructions and as an option for energy-efficiency-increasing retrofit of historically meaningful building stock seemed and seems viable: Back in 2014 (when the authors started their R&D efforts), this potential had not been exploited given the few publications that focussed on the integration of vacuum glass products in new/contemporary and historic windows. In clear words: While R&D focused a lot on the technology of vacuum glass products, application research into the (European) window technology sector had not been deployed in a satisfactory way.

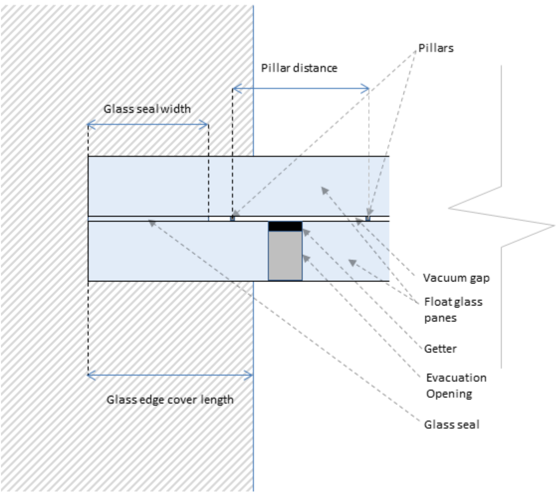


Figure 1: Key terminology of (1st generation) vacuum glass products plus their integration in framing materials (source: the authors)

The objective of this contribution is to review the deployed methods and derived results of 10 years of research on windows with implement vacuum glass products. Thereby, connected challenges and prerequisites that made these efforts possible are described from an ex-post perspective. Moreover, most recent R&D efforts are delivered as an outlook.

Use cases, prerequisites & observations

As indicated, vacuum glass products offer R&D opportunities both for new window constructions as well as for the retrofit of existing, historically meaningful windows, such as Viennese Gründerzeit casement windows. Thereby, the objective for these two use cases has common aspects but also differences: New windows can be optimized toward an optimal thermal performance and should be designed to meet today's aesthetic taste. The integration of other contemporary technologies, such as building automation integration and motorization for high-standard and autonomous hygienics ventilation seems a logical choice. Moreover, non-off-the-shelf operation/opening schemes and patterns can be considered for such windows that e.g. help to save space in interior spaces by opening to the outside. In contrast, historically meaningful windows shall be thermally improved and aesthetically preserved at the same time. As such any intervention needs to be compatible with the slim wooden elements of existing constructions and at the same time requires a careful consideration of the linear thermal bridge along the vacuum glass' edge seal. Figure 2 illustratively subsums the different research directions necessary.

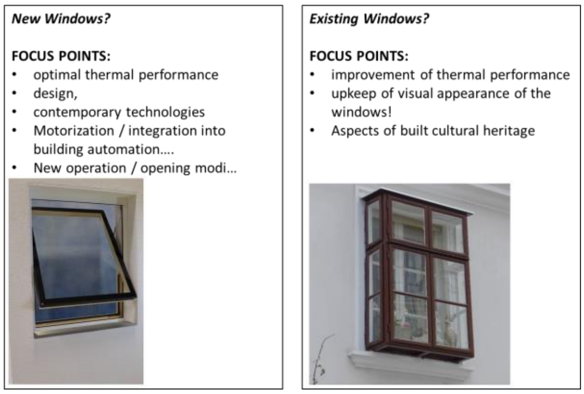


Figure 2: Research direction differences regarding vacuum glass integration into "old" and "new" windows (source: the authors).

From an ex-post perspective, important observations (O) and prerequisites (P) can be named that were of immanent importance in the past 10 years of research (compare Pont et al. 2023a) :

O1: While vacuum glass R&D work dates back to Zoller's work in 1913, little R&D efforts on to VG integration in windows have been conducted prior to out efforts.

O2: The Central European window industry acknowledged the potential of VG, but was kind of reluctant in doing pioneering work as single companies due to certain preconceptions (regarding glass availability and durability).

O3: For the glass producing industries, VG would mean the loss of one glass pane in comparison to triple glazing (at least in a VG basis configuration of two glass panes). Moreover, due to patents, VG glass production might be connected with technological investments and licences fees.

O4: In general, windows are still considered the weak(est) spots of the building envelope in cold and moderate climates.

P1: Given the scepticism toward glass durability, extensive testing of the characteristics of VG was required.

P2: Clear and well-defined development objectives (as well as non-goals) for new and existing windows had to be stated for successful integration.

P3: To steer toward success, a strong consortium and peer group of different stakeholders from academia and industry is pivotal, as well as a self-critical and multiperspectival assessment of all development steps. Thereby, we managed to ensure a trustful and open communication atmosphere, so that cross-competitor collaboration worked out fine during the projects.

Outline of the different R&D projects

We started back in 2014 with the exploratory project VIG-SYS-RENO (2014-2015), in which the principle characteristics of vacuum glazing products as retrofit alternative for casement windows were explored. Thereby, principle characteristics of different vacuum glass products were lab-measured, and simulation- and lab-based retrofit possibilities for casement windows employing vacuum glass were verified. Subsequently, another exploratory project named MOTIVE (2016-2017) was conducted. In this project, disruptive new approaches for new windows with vacuum glass products were envisioned in a high number and subjected to principle simulation and small-scale mock-up testing. As the Austrian window producing industry as well as the fitting and window seal industries pointed out their interest in that direction, we started a collaborative project named FIVA (2018 – 2020) to furtherly develop new windows with vacuum glass. As a result, we obtained four functional prototypes of non-off-the-shelf highly-insulating windows with vacuum glass. To follow up the retrofit track started in the beginning, the project VAMOS (2019-2021) was conducted. Here, six real building test sites were selected and casement windows were updated with vacuum glass products. In this project different small scall Austrian carpentry enterprises were our partners. One of the window prototypes of the FIVA project (an offset-and-sliding window) was chosen for a contract research together with a large scale fitting producing company, resulting in fruitful collaborations in the SLIDE and MOVISTA projects (2021 – ongoing).

Methodology

The multiperspectival and iterative work routines required to develop and test vacuum-glass equipped windows requires different approaches, methodologies and background knowledge of various domains, including carpentry, industrial engineering, building physics, normative testing, monitoring and diagnostics, and – in the very end – marketing/communication skills. Figure 3 illustrates the workflow / workpackage distribution of the project FIVA, which was focussing on the development of new windows with vacuum glass together with major players of the Austrian window building industry. Thereby, the iterative approach in improving the construction, the thermal as well as the acoustical performance of the window prototypes formed a key element in the development of four window prototypes. In later stages of the project, the rather final functional prototypes were subjected to typical test routines such as air-tightness, tightness against wind-driven rain, etc.. Moreover, (end-)user related aspects were worked upon, as new window typologies require a certain acceptance by consumers, otherwise they will not end up as a successful building component in view of industrial planning and economics.

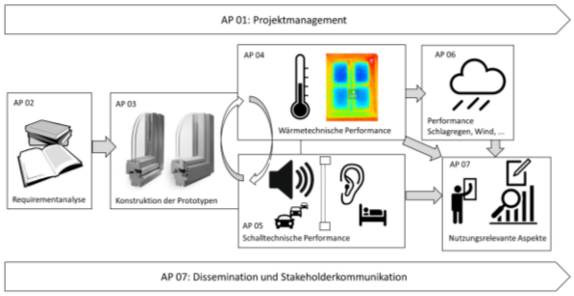


Figure 3: Work package distribution of the project FIVA (source: the authors)

Typically, we deployed in our research and development work the following methods:

(i) Paper/Sketch-based design as a basis for iterative construction improvement: Based on technical drawings of vacuum glass products and (existing) window technologies, both in 2D sectional drafts, and 3D sketches, the integration of the vacuum glass products in existing (casement) window frames was elaborated on, as was compatibility checking with existing frames of contemporary window products. While for the former the change of the frame geometry was no option, for the latter we soon ended up understanding that existing window frame constructions were far from easy to be adopted for vacuum glazing products due to a lack of edge seal cover and thus causing issues with perimetral thermal bridge effects (condensation). As such, - even before having a proof via simulation – it was decided to tackle new windows with vacuum glass rather with disruptive new approaches then to continue the linear development efforts of past decades.

(ii) Simulation (and calculation): Simulation has been an important instrument within the past ten years, given its possibilities to offer quick and easy insights into the performance of a certain design. From perspective of building physics, we deployed numeric thermal bridge simulation for obtaining key performance indicators of the window construction details (both in 2D and 3D simulations). These indicators encompassed the f_{Rsi}-value, the minimum surface temperatures as well as temperatures within the construction at certain critical points (e.g. condensation risk behind rubber seals). Beside thermal simulations, in recent years numeric methods for mechanical behaviour of fixed and moving parts of frame developments has been deployed. Needless to say, at certain points during the development process both the assumed input data in the modelling (e.g. "replacement conductivity of the vacuum gap") as well as the "relative" result information coming from simulations (e.g. comparison of surface temperature of different construction variants) had to be critically assessed and validated/verified.

(iii) Lab testing and monitoring: A major effort during the early years of the described efforts was the testing of vacuum glass products in view of thermal, acoustical, mechanical, and durability characteristics. While ten years ago no industrial vacuum glass production was running in Europe, the purchasement of vacuum glass panes meant comparably long delivery times as the panes were coming from the United States, or Far East Asia to our test facilities. Of course, the durability of the glass products became an even more important topic given this situation regarding delivery times: A typically asked question by carpenters was "What shall I do, if one of the panes breaks? How long will it take to get a replacement?" This issue on the one hand was worsened by global events such as COVID-19 or the container ship traffic jam in Suez Canal, but also lost relevance due to the fact that in 2020 a European production line started. In later stages, monitoring efforts have been conducted especially for the casement windows with vacuum glazing improvement. Here we were able to proof that our simulations that assumed extreme boundary conditions could act as a solid basis for a performance prediction of the vacuum glass equipped windows. However, in reality, the importance of careful craftmanship during installation and setting up windows with vacuum glass turned out as crucial, as e.g. gaps in rubber seal could negatively influence the window performance and outnumber the thermal improvement by the vacuum glass pane.

(iv) Aspects of craftsmanship and industrial engineering: During the collaborative R&D projects focusing on new windows and retrofitted casement windows, aspects of effective assembling, structural performance of components, prefabrication in factories, transport, mounting, connection with the surrounding wall systems, finetuning of moving parts, and maintenance became an important and to-be-considered perspective majorly brought in by the industry partners. This happened in iterative development steps in a ping-pong exchange with simulation efforts. The industrial partners also manufactured functional prototypes and mock-ups for lab- and real-life testing. A very important aspect in this methodological approach also was to reduce the complexity of designs in view of the "KISS"-principle (keep it super simple), as we often identified possible but hard to realize solutions which we omitted from further development steps as their chance to become built reality was sparse.

(v) Peer assessment: As already mentioned, an open and constructive atmosphere in the multi-head involving R&D projects was a critical necessity that allowed quick progress. The work progress was in that sense subjected to a permanent internal peer review. In later stages, external peer review was also obtained in the different projects: Four prototypes of disruptive new windows employing vacuum glazing technologies have been exhibited in the annual symposium of Austrian wndow- and door-manufacturing institutions. There, peers were asked to critically assess these prototypes by filling a structured assessment form. Regarding the casement window realizations that were subjected to an extensive monitoring of key performance indicators, people working or living close to these demonstration windows were asked to provide additional, subjective feedback.

Results

Where did we arrive with our research and development efforts conducted in the previously mentioned projects? The following subsections provide insight into the obtained results, however, can only act as an appetizer for the full-scale reports about the research project published by the Austrian Research Promotion Agency (via www.nachhaltigwirtschaften.at; Pont et al. 2018a, Pont et al. 2018b, Pont et al. 2020, Pont et al. 2023b)

Existing, historically relevant casement windows

Within the VIG-SYS-RENO project the connection joint between vacuum glass and wooden frames of casement windows was identified as the critical performance point (given that end users might not accept condensation or icing on recently retrofitted windows. However, simulation suggested that without a fundamental change of the geometry and/or material of the wooden window profiles, an immanent condensation risk would persist. Additionally, the impact of application of vacuum glass in the external or internal sash turned out to be of interest. The old rules of thumb that highly insulating layers should be positioned as far as possible on the external perimeter of constructions, while layers of high diffusion resistance should be positioned as far as possible on the inner side of constructions are difficult to apply, given that vacuum glazing products regularly possess both a high diffusion and conduction resistance. Figure 4 illustrates some simulation results of the temperature contours along the inner perimeters of both the inner and outer sashes of a casement window for different cases (float/float, vacuum/float, float/vacuum). It can be clearly seen that the application of vacuum glass on the inside does lead to a colder interstitial space and lower surface temperature on the outer sash, while an application on the outside does not severely affect the temperatures of the other sash. As these results come from a thermal bridge simulation tool, certain convective effects might not be seen in the figure. Figure 5 shows a schematic about the heat flow characteristics of inner versus outer sash application of vacuum glass in casement windows. Given these (and other) results of the VIG-SYS-RENO project, it became evident that realization and real-life monitoring are required to be able to assess the performance of vacuum-glass equipped windows. As such, in the VAMOS project six real demonstration sites were chosen, and at each site three casement windows of widely identical configuration regarding orientation, adjacent room usages and shading were improved by small scale carpenters. Thereby, one casement window was kept in original state (regularly float/float configuration with one exception of insulation glass/float), while the other two were equipped with vacuum glass on the inner respectively outer sash. All of the windows were subjected to rigorous long-term monitoring (see Figure 6). Table 1 provides an overview about the demonstration sites and the different characteristics of the corresponding windows. We were able to proof that the U-values of the windows experienced a significant improvement, and that – in case of proper accompanying measures (such as radiators in the rooms, implementation of seals, etc.) – no condensation risk at normal (not extreme) Winter conditions would occur.

Table 1: Demonstration site characteristics

IMAGE	DESCRIPTION
	Schloss in Wels | Type: Rahmenstock in der Leibung | innen öffnend | 2fgl. + Oberlicht | Wohnraum | Glastausch
	Villa in Wien | Type: Pfostenstock außenbündig | außenöffnend | 2flg. + Oberlicht | Wohnung | Außenfenster neu
	TU Wien | Type: Pfostenstock außenbündig | außen öffnend | 2flg. | Büroraum | Flügel neu.
	Stift Wilhering | Type: Doppelrahmen außenbündig | innen öffnend | 2-flg. | leer | Neufenster im Steingewände
	Arch. Office/ Salzburg | Type: Pfostenstock außenbündig | außen öffnend | 2 flg. | Büroraum | Neufenster
	Office / Innsbruck | Type: Rahmenstock in der Leibung | innen öffnend | 2.flg. | Büroraum | Neufenster

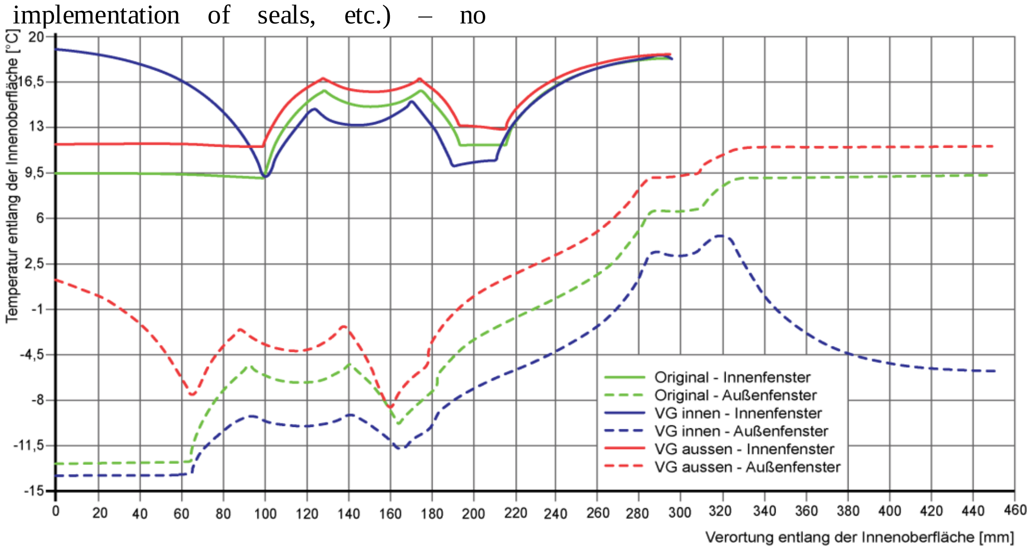


Figure 4: Simulation results of Inner surface temperatures of inner and outer sashes of different configurations (float/float, float/vacuum, vacuum/gloat; illustration by the authors)

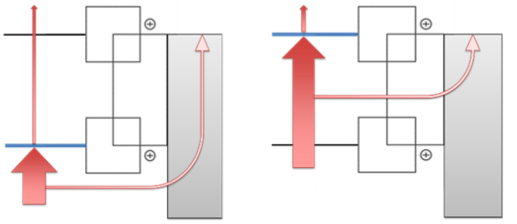


Figure 6: conceptual schematics about vacuum glass application onto the inner sash (left) and outer sash (right): While the application on the inner sash helps against increased thermal bridge effects at the window/wall joint, the outer sash application ensures increased interstitial space temperatures (illustration by the authors).

Figure 6: top: one of the examined case-study buildings; bottom: Monitoring equipment in a vacuum-glass equipped casement window (source: the authors)

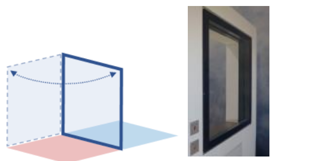
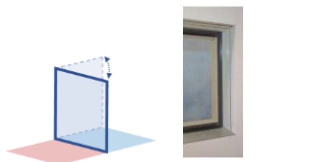
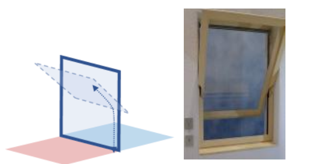
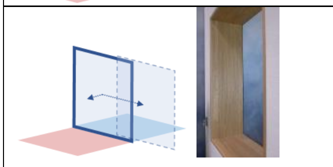
Both from measurements and from calculations/simulations it was found that the casement windows can be significantly improved (drop from 2.5–3.5 W.m^{-2}.K^{-1} to 0.5–1.5 W.m^{-2}.K^{-1}). For a typical Viennese *Gründerzeit* building the improvement of float/float casement windows would result in about 10% decrease of Winter season heating demand, dependent on the Window to Wall Ratio of the corresponding building.

Functional prototypes of new windows

In the MOTIVE project and later in the FIVA project, we were able to generate different non-off-the-shelf vacuum glass windows, in part utilizing rather exotic operation/opening schemes. During the FIVA project, four different functional prototypes could be developed, tested, and realized as mock-ups.

Table 2 illustrates these functional prototypes A- D and some key characteristics, as derived from simulations. By using a high-end vacuum glass with an U_g-value of 0.4 W.m^{-2}.K^{-1} (system thickness less than 1 cm), we were able to achieve very good U_{Win}-values (all below 0.8 W.m^{-2}.K^{-1}). Note that the minimum temperature indicated in the table is based on a steady-state indoor-outdoor temperature difference of 30 Kelvin (20 °C indoor temperature, -10 °C outdoor temperature). Moreover, the U-values of these functional prototypes were used by utilizing the corresponding procedures of EN ISO 10077 (2018, 2020), which – at the time of conducting this research – did not consider the existence of vacuum glazing products and their specifications.

Table 2: Functional prototypes as key results of the FIVA project (authors)

SCHEME / ILLUSTRATION	DESCRIPTION
	Type A- Turn window to inside: f_{Rsi}: 0.74 | $\theta_{si,min}$: 12,23 °C | U_{Win}:0.78 W.m^{-2}.K^{-1}
	Type B- Turn window to outside f_{Rsi}: 0.77 | $\theta_{si,min}$: 13,05 °C | U_{Win}:0.72 W.m^{-2}.K^{-1}
	Type C- Swing window f_{Rsi}: 0.75 | $\theta_{si,min}$: 12,55 °C | U_{Win}:0.68 W.m^{-2}.K^{-1}
	Type D- Sliding Window f_{Rsi}: 0.74 | $\theta_{si,min}$: 12,07 °C | U_{Win}:0.64 W.m^{-2}.K^{-1}

These functional prototypes were subjected to a peer review in the framework of the Fenster-Türen-Treff 2020 in Salzburg. Figure 6 illustrates the exhibition with the mock-ups, and table 7 illustrates the evaluation of different characteristics of the functional prototype in the Austrian school grade system (1… excellent, 5 non satisfactory).

Figure 7: Exhibition of functional vacuum glass window prototypes at the Fenster-Türen-Treff 2020 in Salzburg (source: the authors)

Table 3: Peer Evaluation results of the four functional prototypses (source: the authors)

CRITERIUM	A	B	C	D
Aesthetics	1.7	2	2.4	1.2
Contemporaneity	1.8	2.4	2.6	1.6
Degree of innovation	2.1	2	2.2	1.2
Feasibility of construction	1.8	2.4	2.6	2.1
Aspects of mounting	1.8	2.4	2.2	2.4
Aspects of operation	1.7	2.4	2.5	1.7
Acceptance amongst customers	1.9	2.4	3	1.8
Average	**1.8**	**2.3**	**2.5**	**1.7**

While all of the prototypes were evaluated benevolently by the peers, prototypes A and D were favoured due to innovation (D) and aspects of customer acceptance, mounting and operation (A). These prototypes and the exhibition formed the results of the project FIVA and illustrated the potential of new, innovative windows with vacuum glazing, motorization/automation, and integration of innovative technologies. Thereby, a key message of the project outcome was (and still is) that some disruptive innovations should be integrated in any upcoming development step of new window technologies.

In-detail development of the offset-sliding window

Prototype D of the FIVA project not only encompassed a high degree of innovation and a new operation/movement pattern for a window, but also showed that there is a need for specific development of corresponding components pertaining to seals, frame technologies, and – above all – fitting technologies. The original prototype D utilized telescope rails as used for automotive systems (e.g. trucks of the firefighters), and those rails never were intended to act as window fittings. Their structural properties, their dimensioning and resistance against external meteorological conditions, as well as their thermal conductivity never were designed to act in a transparent building component of a building envelope. As such, the project SLIDE/MOVISTA (KDM-INNO, 2024) was formed, together with a major player of the fitting industry to in-depth develop fitting technologies for this type of window, back in 2021. After two years of intensive development work, the MOVISTA window was exhibited at the largest world fair of building components, the Bau 2023 in Munich, Germany. It was well perceived by peers and end-customers, and despite the fact that the prototype shown was not yet available on the market, several visitors suggested that they instantly would purchase a large amount of these window due to its possibilities of integration into building automation, its aesthetics, the space-saving operation scheme and the robustness of the integrated technologies. Figure 8 illustrates the operation/opening scheme of the window prototype schematically, while Figure 9 shows the exhibited window prototype.

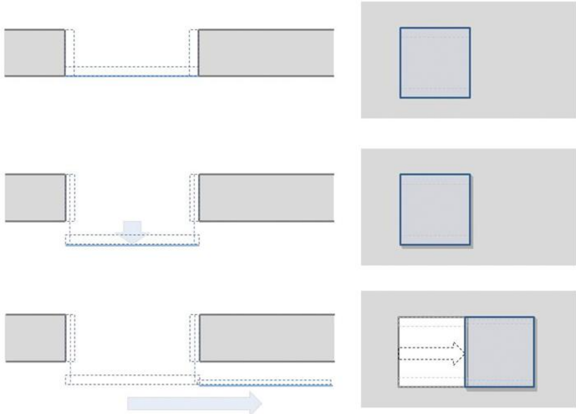


Figure 8: Principle movement pattern of prototype D/ the MOVISTA/SLIDE window (source: the authors)

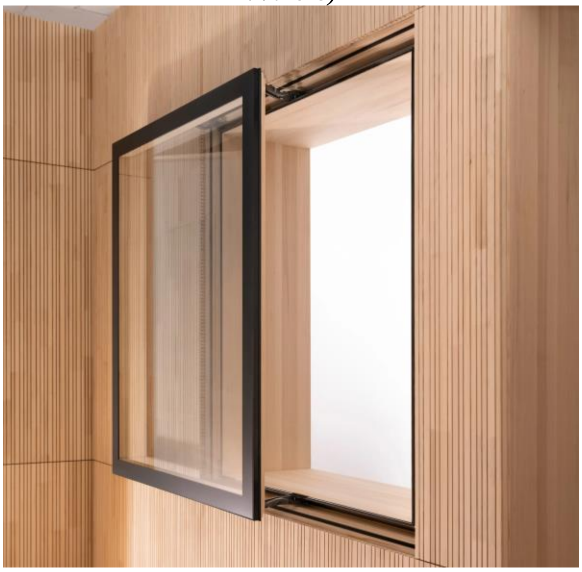


Figure 9: MOVISTA window as mockup as presented at the Bau2023 fair (Image source: KDM-inno.com)

Conclusion & Outlook

The present contribution showcased the approaches, applied methods and results of the research and development efforts onto the integration of vacuum glazing products in contemporary and historic window constructions. While the integration of vacuum glass into existing window constructions of historic meaningfulness could provide valuable energy and emission saving possibilities paired with upkeep of the appearance of these windows, the research and development stream towards contemporary/new windows employing vacuum glass showed the high potential for slim, aesthetically appealing and energy saving windows, especially if developed from scratch with certain functionalities in mind (such as integration into building automation). However, these development efforts are not yet finished. Beside further improvement of technical aspects of the shown windows, specific aspects such as sun shading into such windows are still aspects to be worked upon. Moreover, the third-party communication about the new technologies and their potential and performance aspects has to be transported to peers, the industry, the governmental bodies (e.g. for adapting retrofit subsidies into window "update" than "window replacement"), and communicated amongst end costumers, architects and clients. Aspects of circular economy, easy mounting, prefabrication, etc. also still are open topics to work-upon, which the authors and their partners are looking forward to start.

Disclaimer

As this is a review paper of ten years of research & development, please note that parts of the presented information have been previously published by the authors in different contributions. Pont et al. 2023c offers a very detailed overview of all the efforts.

Acknowledgement

The described R&D efforts would not have been possible without the generour funding of the Austrian Research Promotion Agency FFG (Projects VIG-SYS-RENO No: 845225, Motive No: 854690, FIVA No: 867352, VAMOS No: 878272). Moreover, the research and development efforts within the project SLIDE/MOVISTA have been generously supported by the company KDM/Blum. The described R&D efforts furthermore benefitted from contributions by the following peole, companies, and institutions: Fa. AGC Interpane, Fa Blum, Fa. Gaulhofer, Fa. IEB Eisele, Fa. Katzbeck, Fa. MaCo, Fa. Prohaska, Fa. Schaden, Fa. Svoboda, Fa. Wick-Norm, Fa. Winkler, and Fa. Zoller-Prantl.

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