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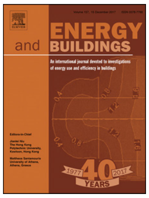

Investigations of 6-pane glazing: Properties and possibilities

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ABSTRACT

Today there is increasing interest and demand for energy savings in the building sector. Windows still represent a weak point in the building envelope with respect to thermal performance due to thermal losses from the interior to the exterior as well as overheating of the interior due to excessive solar radiation from the exterior environment into the interior. However, windows and glazing structures enable the utilisation of daylight and heat from incident solar radiation, while at the same time providing comfort and a view to the outdoor surroundings. Multipane glazing and windows may represent a possible way to lower energy consumption related to heating and cooling. In this study, a multipane glazing structure, more specifically a 6-pane glazing, has been constructed and investigated with regard to various properties and possibilities. The general configuration of the 6-pane glazing is described. Furthermore, properties such as *U*-value, solar energy transmittance, visible transmittance, solar heat gain coefficient, glass pane temperatures, vapour permeability, economical aspects, and comfort of living, among others, are analysed. Finally, a case study is presented that demonstrates a 50% reduction in the annual energy consumption after renovation with this 6-pane glazing.

1. Introduction

Intermittence is one of the major drawbacks regarding renewable energy sources and represents a fundamental problem in reducing fossil fuel use and carbon emissions. In a recent study, Sinn [1] showed that in order to resolve the seasonal volatility issue in Germany it would be necessary to store energy from August throughout the winter months until March due to the heating demand. There are few seasonal energy storage options, and most cannot be applied on a large scale.

In heating dominated countries, with few exceptions, substantial CO_2 emissions result from a building's heating demand. These emissions may be difficult to eliminate with (non-hydropower) renewable sources that are in short supply during the winter season in densely populated countries.

Already in 1995, Feist predicted that with a glazing *U*-value of $0.3\,W/(m^2K)$ zero-heating buildings could be realized [2]. It has also recently been shown [3] that for glazed buildings with system *U*-values as low as $0.3\,W/(m^2K)$ the heating demand diminishes. The remaining cooling demand can be favourably synchronised with solar radiation, where maximum photovoltaic generation nearly coincides with the maximum power needed for cooling. In this way, the building would not need a winter power reserve and it obviously would not need any seasonal energy storage.

Unfortunately, with the existing triple and quadruple glazing window systems a *U*-value of $0.3\,W/(m^2K)$ is inaccessible [4]. Therefore, some main technologies in advanced glazing [5] have emerged in recent years, i.e. vacuum glazing [6], aerogel glazing [7,8], and multipane glazing [9]; the latter includes multilayer all-glass products and multilayer glass/polymer combination products. Separately, a 'water flow glazing' technology demonstrator [10] was presented, where water flows within the inner of a two-chamber unit. There, water-induced corrosion of the float glass will have to be addressed.

Vacuum glazing offers good centre of glass performance; however, total window performance is poor due to substantial heat loss through the edges. Aerogel windows have the lowest potential *U*-values, but they have poor visual control and should be protected from moisture [11]. The use of intermediate polymer

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films in multipane glazing, where coated polymer films create a multi-chamber glazing unit, solves the weight issue. The main disadvantage of using polymer films is related to low emissivity (low-e) coatings on the polymer substrate that have worse performance than their glass counterparts [12]. Additionally, the price of coated polymer films is several times higher than that of thin low-e coated glass panes.

Recently, multipane glazing, such as quadruple glazing, has become recognised in European countries. In addition to the increased weight issue, the main concerns for multipane glazing are related to the thermal stresses due to high chamber temperatures, which can pose a problem as regards the robustness and lifetime of such units [9]. Failure of an insulating glass (IG) unit commonly results in water vapour condensation between the glass panes, due to the natural phenomenon of water vapour migration through the edge seal system. When the desiccant is saturated, or the seal – consisting of the primary and secondary seal – is broken, condensation occurs [13] and consequently corrosion of silver low-e coatings occurs.

Low-e coatings effectively reduce the thermal transmittance of a window by restraining the radiative heat transfer [14,15]. Low-e coatings are composed of several layers of metals, usually silver, and ceramics. Silver is sputtered over a prepared substrate, i.e. the glass surface, and adheres by physical forces alone. If the silver is exposed to the atmosphere under room conditions, several monolayers of water vapour will be adsorbed on the surface [16] and slowly disintegrate the adhesion of the silver through diffusion to the substrate. The appearance of low-e corrosion determines the primary lifespan of the glazing unit [17]. Therefore, for an IG unit with an edge sealing system to have a long service life the primary sealant must maintain its low gas and vapour permeabilities, and the secondary sealant must maintain good mechanical integrity when exposed to a variety of environmental factors. Studies have shown that the simultaneous action of water, elevated temperatures, and solar radiation constitute the greatest stress on the edge seal system of an IG unit [18,19]. Accelerated ageing and the durability of double-glazed sealed insulating window panes and their impact on the heating demand of buildings have been investigated by Asphaug et al. [20].

A new 6-pane glazing, with an exceptionally low system thermal transmittance of 0.3 W/(m^2K), has been developed. The 6-pane insulating glass unit is composed of six individual glass panes. The selected external solar control pane keeps the temperature of the intermediate glass panes and the sealant system safely below 80 °C, and the temperature differences on the individual intermediate glass panes are kept below 40 °C. Moreover, a special inventive approach was used to mitigate the pressure variations of the sealed unit [21].

6-pane glazing promises many attractive features such as exceptional energy performance and greatly improved thermal comfort. Most intriguingly, for a glazing with such a low U-value, there is no need for modulated external shading, which could obstruct occupants' view [3]. And last, the 6-pane glazing provides excellent sound insulation due to the thickness of the IG unit.

The objective of this work is to present miscellaneous aspects of this new and promising 6-pane glazing system. First, the general technical and physical characteristics of the 6-pane glazing, including the measured seasonal dependence of the solar energy transmittance for the 6-pane glazing, will be presented.

Second, the longevity issues of the 6-pane glazing unit will be addressed. The effects of the elevated temperatures caused by the solar radiation absorption of the intermediate panes, which constitute the greatest stress in the glass unit, will be analysed.

Third, the economical aspects of the 6-pane glazing will be presented. The material and manufacturing costs of the 6-pane glazing versus its benefits will be discussed.

Finally, a short case study of an office building renovation in Oslo at Wergelandsveien 7 in 2015 will be presented.

2. General properties of 6-pane glazing

2.1. 6-pane glazing unit configuration

The 6-pane glazing unit consists of an outer solar control pane, intermediate low-e coated panes, a heat-treated expansion pane [21], and an inner pane (Fig. 1). The first four chambers from the outside are a hermetically sealed group filled with an insulating gas, typically consisting of 90% argon. The outer spectrally selective solar control pane and the choice of intermediate panes with low visible light absorptance (i.e. high visible light transmittance, LT) limit the temperature of the intermediate panes and edge seal system to below 80 °C. The secondary sealant provides the structural strength to hold the panes apart at a fixed distance and prevents excessive movement of the primary seal under different environmental stresses. Between the perforated, desiccant filled spacers and glass panes, there is a thin layer of a flexible primary seal that is highly impermeable to water vapour. The primary function of the seal is to reduce water vapour and gas permeation through the edge-of-glass area. As the mechanical strength of viscous PIB is negligible, a secondary sealant is applied around the perimeter of the glass as required for the mechanical integrity of the whole IG unit.

When the insulating gas within the group of sealed chambers expands due to solar-radiation-related heating this causes the expansion pane to bulge out towards the inner pane, thereby decreasing the volume of the open chamber and reducing the pressure of the insulating gas within the group of sealed chambers by giving way to their expansion. Since the open chamber allows for air exchange with the surrounding atmosphere, the pressure within the open chamber will not increase, and correspondingly, the inner pane will not bulge.

The total thickness of the 6-pane glazing unit varies with changes in the outer and inner panes due to the safety and security glass options. The total thickness of the standard 6-pane unit shown in Fig. 1 is 117 mm.

2.2. 6-pane glazing U-value

The thermal transmittance of the transparent part of the window (U_g-value) is dependent on the number of glass panes, the quality, the positions of the low-e coatings, and the gas fill used. The thermal transmittance of glass for the 6-pane unit with an open chamber without low-e coatings (Fig. 1), which was calculated according to EN 673:2011 with LBNL (Lawrence Berkeley National Laboratory) WINDOW 7.4 software for a unit size of 1250 mm × 2500 mm, is U_g-value = 0.26 W/(m^2K). The internal and external heat transfer coefficients used were $h_i = 7.7$ W/(m^2K) and $h_e = 25$ W/(m^2K), respectively. The 6-pane glazing unit had a vertical orientation, the external temperature was set to 0 °C, and the internal space temperature was set to 20 °C.

2.3. Seasonally dependent solar energy transmittance

The total solar energy transmittance factor (g-value), analogous to solar heat gain coefficient (SHGC), is calculated as the sum of the direct solar energy transmittance (T_{sol}) and the secondary heat transfer factor of the glazing towards the inside, with the latter resulting in heat transfer by convection, conduction, and long-wave IR-radiation of that part of the energy gained from incident solar radiation absorbed by the glazing [22,23]. The g-value and corresponding visible light transmittance (LT) for the presented 6-pane glazing is dependent on the outer pane's solar control coating.

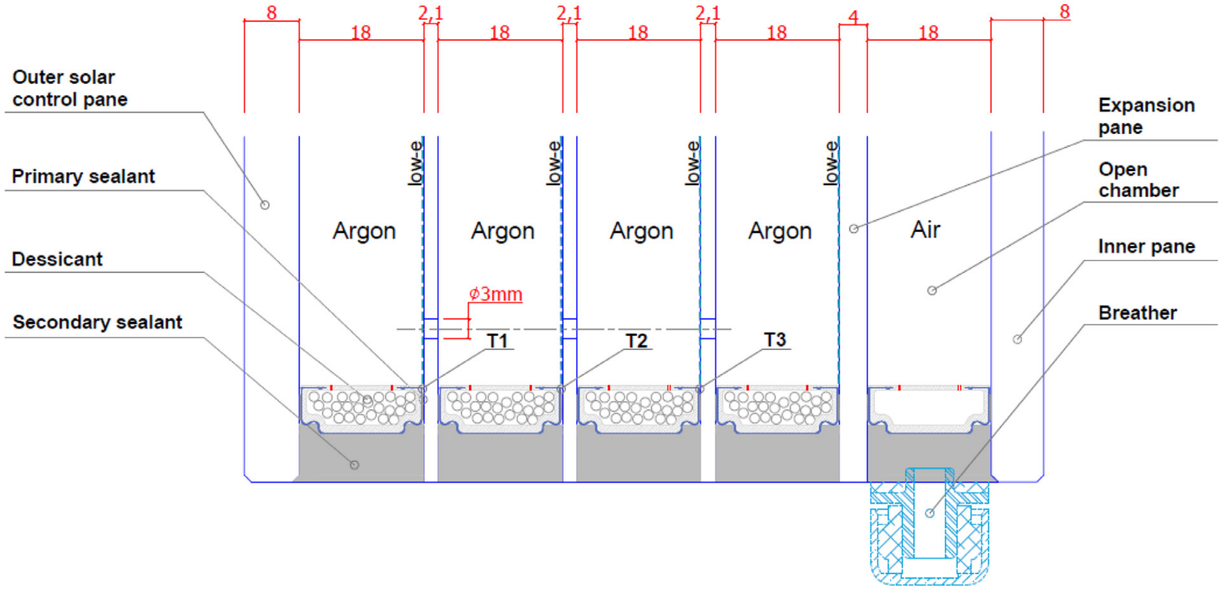
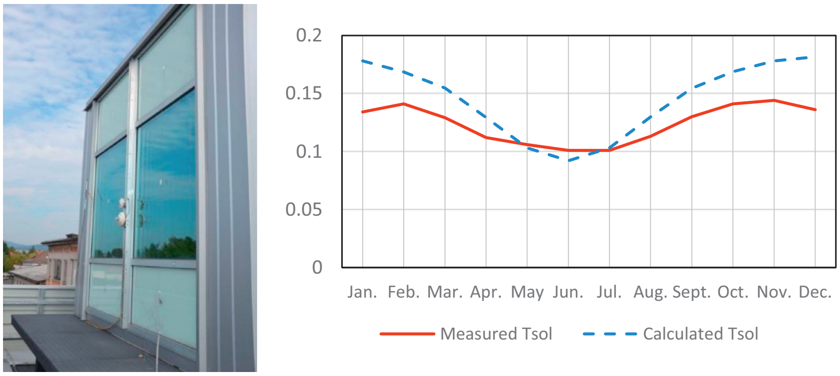


Fig. 1. Technical drawing of the 6-pane glazing unit. It consists of an outer, spectrally selective, solar-control pane, an inner pane, and intermediate low-e panes (T1, T2, T3). Four chambers, from the left outer side, with insulating gas are connected through small 3 mm holes to equalise the gas pressure. Between the fourth pane and the inner pane there is an expansion pane that forms an open chamber, which allows for pressure equalisation with the surrounding atmosphere through a special hydrophobic breather. The 6-pane glazing unit's edge seal consists of a polyisobutylene (PIB) primary seal, a secondary seal, and a spacer bar with desiccant.



a)

b)

Fig. 2. (a) The test stand for measuring solar energy transmittance for a 6-pane sample, with nominal values T_{sol} = 0.17, g = 0.24, and LT = 0.38 (EN 410), from the case study building referred to in Chapter 5 of this report, measured in Ljubljana [25]; (b) Seasonally dependent T_{sol}, measured and calculated monthly values. The monthly irradiance-weighted clear sky T_{sol} was calculated for the 21st day of the month, for Ljubljana's latitude and the solar irradiation data from the work by Masters [26].

By choosing appropriate outer solar-control-coated glass pane, the nominal *g*-value can be engineered to the range from 0.11 to 0.30, where the corresponding visible light transmittance ranges from 0.17 to 0.48. The *g*-values and LT values were calculated with the LBNL WINDOW 7.4 software for a range of pane selections that comply with the 80 °C temperature limit of the intermediate panes.

However, due to incidence-angle-dependent Fresnel reflections [24], the optical characteristics also vary seasonally as the sun's average elevation and light diffusivity vary throughout the year. Year-long measurements of the real-world solar energy transmittance of a 6-pane glazing unit in Ljubljana, Slovenia are presented below.

Two spare 6-pane glazing units, with dimensions of 1035 mm × 1405 mm, from the case study building referred to in Chapter 5 were used for test stand measurements (see Fig. 2a). The indoor temperature of the climate chamber from behind the test stand in winter and summer was set to 22 °C and 25 °C, respectively. The climate chamber with the 6-pane IG unit test stand was situated in Ljubljana and was oriented to the south. The measured T_{sol} on the 6-pane glazing test stand was determined as a quotient of the measured monthly solar irradiation transmitted to the inner side and the measured monthly irradiation on the external side of the test stand IG unit [25].

Fig. 2b shows the resulting measured monthly values of T_{sol}. For comparison, the LBNL WINDOW 7.4 software calculated a clear sky T_{sol} for an identical glass composition, which is also shown in Fig. 2b.

The calculated T_{sol} for a clear sky in winter months approaches a nominal (EN 410) T_{sol} value of 0.17. The sun is low in the winter and the average sun incidence angle is nearly normal. In the summer the average sun incidence angle increases the Fresnel reflections of the multiple glass panes and the calculated T_{sol} decreases accordingly. The measured T_{sol} additionally depends on diffuse light conditions, which also increase the average incidence angle of the light hitting the glass unit. At the measured points, days with diffuse light decrease the T_{sol} in winter. The measured points in summer show T_{sol} values consistent with ground-reflected light incident normally on the glass unit showing slightly higher T_{sol} than calculated for clear sky conditions. The measured T_{sol} is 30%

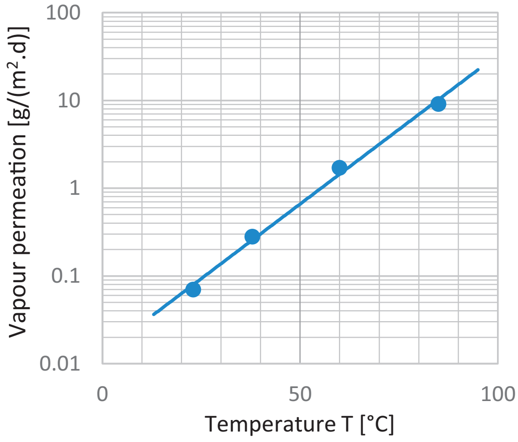


Fig. 3. The least squares exponential curve used to fit the experimental vapour permeation data. The PIB primary sealant increases the vapour permeability with increased temperature. Measured points per ASTM F 1249, 1 mm film, 100% relative humidity.

less than nominal value in summer (valid for Ljubljana's climate and latitude), which is beneficial for decreasing cooling demand.

3. 6-pane glazing intermediate glass temperatures and multipane unit longevity

By increasing the number of intermediate panes, and hence the number of chambers formed, the desired thermal transmittance could in principle be decreased. However, even the clearest coated glass or polymer film panes absorb some of the solar radiation passing through. This causes heating of the individual panes of the glass units, particularly the first or second intermediate panes adjacent to the exterior pane. Hence, excessive temperatures, as well as increased pressure, may lead to the premature failure of both primary and secondary sealing materials or even to thermal stress induced cracking of the intermediate panes.

The lifespan of the IG unit depends primarily on the sealing system performance. The most important aspect is the water impermeability of the IG sealing system combined with a desiccant that protects the low-e coatings from water-based corrosion. In all materials, the level of water permeability exhibits strong temperature dependency due to changed molecular dynamics. When the material heats up, the molecules vibrate more, expand in volume, thus water vapour permeation is increased through the increased molecular mobility caused by the increased intermolecular volume.

Insulating glass units exhibit elevated insulating gas pressure when irradiated by the sun. Increased insulating gas pressure stretches the primary PIB seal and thus reduces its effectiveness as a water vapour barrier. The highest pressure coincides with the highest vapour permeation; thus, the viscoelastic mechanical properties of the secondary seal play an essential role in ensuring the long-lasting effect of low-e coatings.

In the 6-pane glazing, we quantify water vapour permeation through the PIB sealant barrier, which influences the lifespan of the sealed glass unit. In our calculations, the least-squares exponential curve fitting method was used to fit the experimental vapour permeation data (Fig. 3). As can be noticed, the PIB sealant significantly increases the vapour permeability with increased temperature. The water vapour permeation at room temperature is approximately 0.1 g/(m^2d) and increases to nearly 10 g/(m^2d) at 80 °C (Fig. 3).

Lawrence Berkeley National Laboratory software Window 7.4 was used to determine the individual pane temperatures and the

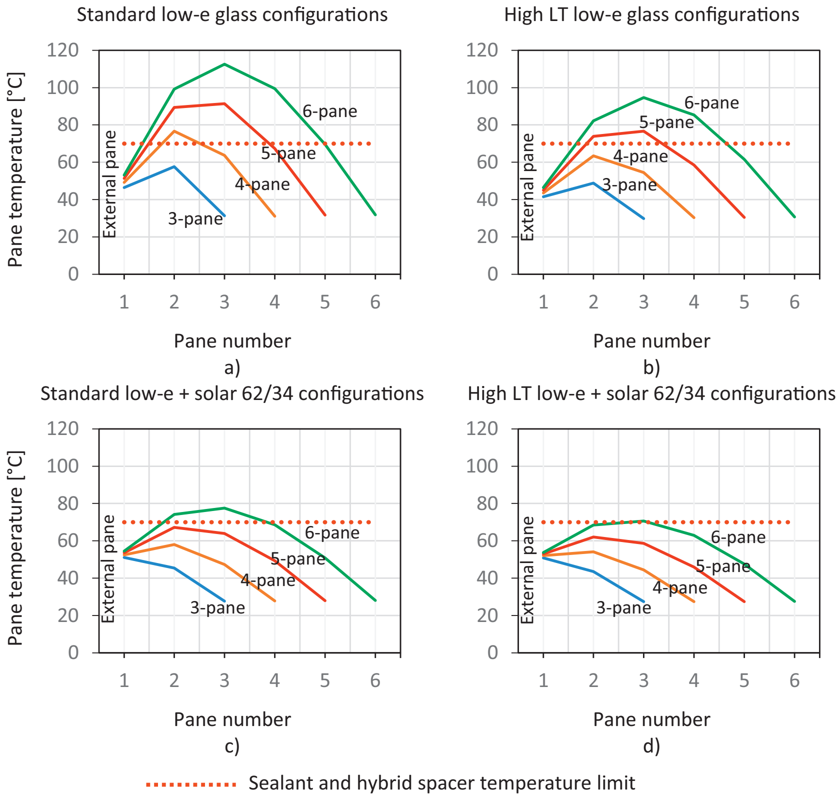


Fig. 4. Individual glass pane temperatures with sealant and hybrid spacer temperature limit [27] marked as a dotted horizontal line for the following multipane configurations (with 3, 4, 5 or 6 panes) having (a) standard low-e glass; (b) high LT low-e glass; (c) standard low-e + solar control 62/34 exterior glass; and (d) high LT low-e + solar control 62/34 exterior glass.

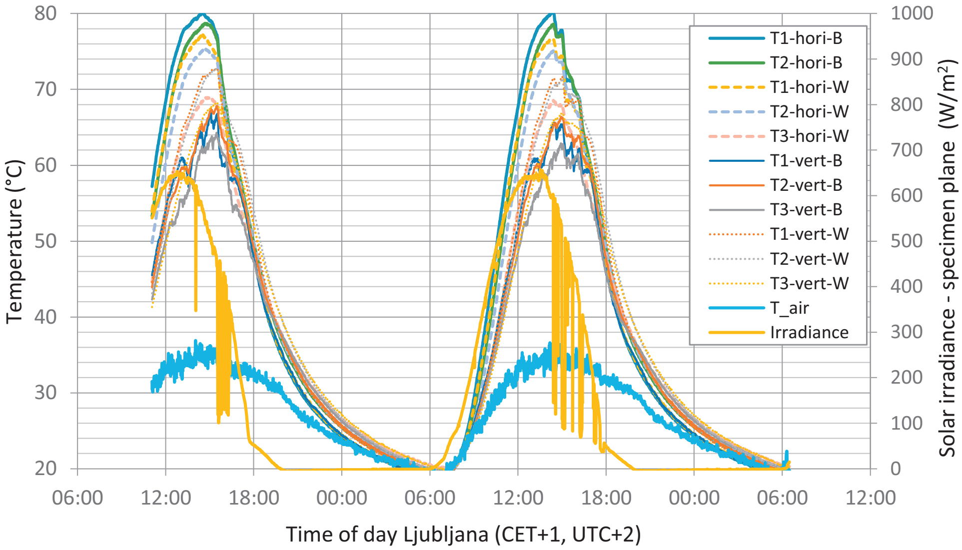


Fig. 5. Measured temperatures of the primary sealant for two 6-pane glazing units with *g*-value = 0.28 and LT = 0.46, oriented to the south, measured in Ljubljana, August 2018. Thermocouples were positioned within the PIB primary seal in front of the second, third, and fourth glass panes (counted from the outside) at the centre of the right vertical and bottom horizontal spacers. The graphs are marked as Tx – y – B/W, where Tx denotes the position depending on the intermediate glass pane number (see Fig. 1), y denotes the vertical or horizontal position, and B/W denotes a black or white spacer-equipped glass unit. The black spacer unit sensor T3 suffered an outage, hence its data is not shown [27]. Measurements were conducted as part of TIGR4smart program.

peak pane temperature, T_p, under the following conditions: 40 °C exterior temperature, calm air, 24 °C interior temperature, and 783 W/m^2 solar radiation. Glass pane temperature calculations for 90% argon-filled sealed glass blocks with 18 mm spacers for 3, 4, 5 or 6 individual glass panes are presented below.

The measured temperatures of the primary sealant for the 6-pane glazing unit oriented to the south, measured in August 2018 in Ljubljana, are shown in Fig. 5. The tested glass units offer the highest intermediate pane temperatures from the standard permitted range. Light grey and black spacers were used in the respective units, which were identical in all other regards. Black spacers are not used with commercial 6-pane glazing units; however, the results are shown for comparison.

Depending on the temperature, water vapour permeates through the PIB seal throughout the year and slowly saturates the desiccant residing in the spacers. The PIB primary seal temperature and the corresponding water vapour permeation were simulated with consideration of the PIB sealant geometry and the permitted desiccant water content change, for different climatic areas, i.e. Munich, Venice, Madrid, and Rome. The hourly climatic data for air humidity and temperature/solar radiation used to estimate the peak hourly PIB temperature in the IG unit were taken from the Climate Design Data 2009 ASHRAE Handbook. The local climate and time of year influences on the monthly water vapour penetration rates for the 6-pane glazing configuration are shown in Fig. 6.

The observed calculations of water vapour penetration into the spacer desiccant confirm enhanced water vapour penetration in summer time and in warmer climates. A comprehensive evaluation of the lifespan of the multipane glazing is given in the study by Kralj et al. [27].

4. 6-pane glazing economics

4.1. Costs

The improved comfort of living, reduced maintenance efforts, living space gain, elimination of the need for exterior dynamic shading, and above all elimination of the need for seasonal energy storage are some of the considerable benefits of 6-pane glazing.

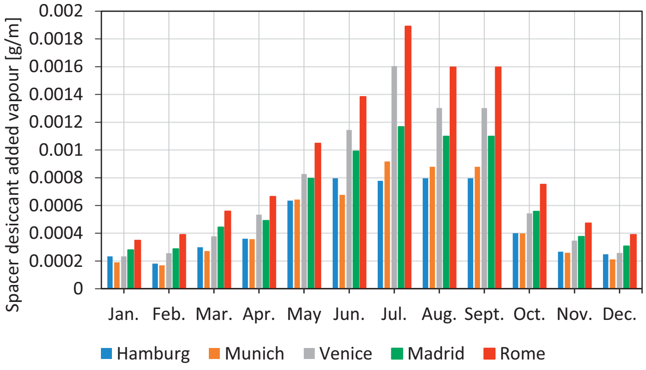


Fig. 6. Cumulative monthly water mass added to the spacer per 1 m spacer effective length modelled for a 6-pane glazing configuration with a peak pane temperature of T_p = 60 °C. The chart shows local climate and time of year influences on water penetration rates [27]. Permitted spacer added water mass is less than 1 g/m (only a small fraction of the desiccant saturation capacity can be used).

The disadvantages of 6-pane glazing are the higher glass cost and more demanding assembly process, which will at the beginning increase the up-front payment required.

Table 1 shows the typical cost-price contributors of an installed 6-pane glass façade. The given price ranges are for rectangular panels produced in high quantities (100+) with a high raw-glass utilisation fraction. Requirements as regards iron-free glass, safety interior glass, security glass outside, and exterior glass for a high wind load in skyscraper applications all influence the cost within the indicated range in Table 1.

Currently, typically sophisticated 6-pane glazing façade (installed) is priced below than systems such as closed cavity façades or double skin glass façades.

The installation cost varies from the simplest stick system installation in the Southern and Central European region to complex structural glazing installations in Sweden and Norway, where the cost might reach 200 €/m^2. With economies of scale (including automated assembly), a price comparable to triple-pane glazing systems, equipped with automated exterior shading, could be achieved.

Table 1
Typical cost-price contributors of an installed 6-pane glass façade for rectangular panels produced in high quantities with high raw-glass utilisation.

Part	Description of minimum requirements	Price range
Exterior pane	Solar control glass, 8 mm, annealed	30–120 €/m^2
Intermediate panes	2–4 mm low-e, high light transmitting, annealed	8–10 €/m^2 (3x)
Expansion pane	4–6 mm low-e toughened/semi-toughened, heat soak tested	20–30 €/m^2
Interior pane	From a 6 mm annealed pane at the low-end, to fire-rated glass at the high-end	10–400 €/m^2
Spacers, sealants, desiccant	hybrid spacers, high modulus silicone secondary seal, PIB primary seal, 3A zeolite desiccant	20 €/m^2
Expansion chamber breather	Hydrophobic vent + open-cell foam lifetime filter	10 € per unit
Assembly	Manual assembly – fully automatic	130–30 €/m^2
Support/framing	Frameless window wooden-support installations, to high-end structural glass aluminium framing with 60 mm thermal breaks	80–200 €/m^2
Transportation (1000 km)	Standard truck, 20 m	10–20 €/m^2
Installation	Central to Northern Europe	80–200 €/m^2

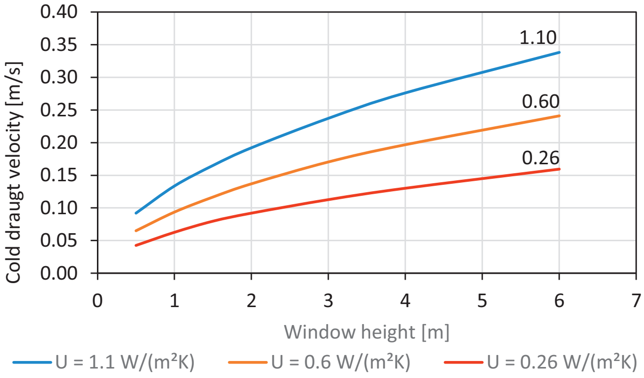


Fig. 7. Cold draught analysis for different *U*-values dependent on window height, where the outside temperature was −10 °C and the indoor temperature was 20 °C. Cold air velocities exceeding 0.15 m/s are perceived as discomforting [29]. A *U*-value of 1.1 W/(m^{2}K) corresponds to double glazing, a *U*-value of 0.6 W/(m^{2}K) corresponds to triple-pane glazing, and *U*-value of 0.26 W/(m^{2}K) corresponds to a 6-pane glazing unit.

4.2. Comfort of living

The well-being of the occupants of a building is an important parameter determined by the environmental quality of the interior. Limited or no contact with the environment and living and working with minimal daylight are often a consequence of dynamic sun shading. On the contrary, a 6-pane glazing offers uninterrupted contact with the environment. Low, seasonally selective solar gain offers summer comfort, while a system *U*-value of approximately 0.3 W/(m^{2}K) offers nearly zero heating demand in winter even in northern countries. A low system *U*-value maintains inside glass temperatures at an equable level throughout the year. Furthermore, an unprecedented draught-free zone is created around the panoramic glazing. Fig. 7 shows a cold draught at the panoramic glazing for double-pane glazed, triple-pane glazed, and 6-pane glazed units. The interior glass temperature was calculated using ASHRAE/NFRC interior conditions in Window 7.4 software. Using the glass height and interior glass pane to room air temperature difference, the natural convection velocity at a distance of 0.4 m from the vertical glass plate was calculated according to Jurelionis and Isevičius [28]. The 6-pane glazing offers cold-draught-free designs for up to 4 m high panoramic glazing.

4.3. Maintenance and space gain

Regular system maintenance and proper handling are critical for ensuring that operable and automated systems meet energy and occupant comfort requirements. The maintenance costs of an automated shading system can be substantial. For instance, the cost of maintaining the California Academy of Sciences building automated shades adds up to $30,000 annually [30].

On the contrary, the 6-pane glazing unit with a solar control coating may offer living comfort and does not require special maintenance.

The 6-pane glazing also allows for space savings. Especially in Scandinavia, there are regulations requiring builders to combine triple-pane glazing with up to 0.5 m thick insulated parapets to meet energy performance requirements [31]. A 6-pane glazing unit can outperform such a configuration energy-wise and offer up to 0.4 m space savings for the building circumference. Given the location's real estate pricing particularities, this space savings might well be enough to make up for the extra up-front investment for the transition to fully glazed 6-pane façades.

4.4. Dispensing with seasonal energy storage

The exceptional problem of the unfeasibility of seasonal energy storage required to offset winter grid power demand for all tentative-renewable energy supplies was exposed in a study by Sinn [1]. To compensate for the seasonal volatility an energy buffer of staggering proportions would be required. For Germany alone, this buffer would need to hold 42.93 TWh [1]. This is 17-times more than the whole EU geo-potential for hydro-pumping energy storage, which would be impossible to build anyway as many national parks would need to be flooded. No economical technologies exist now, nor will in the foreseeable future, that could facilitate seasonal energy storage on the massive scale needed.

With 6-pane glazing, buildings with a heating demand of less than 1 kWh/(m^{2}a) could be built. In our opinion, such zero-heating buildings [2] or nearly-independent near zero-energy buildings [32] would utilise grid PV power or on-site PV power mainly for cooling and regular daily use of appliances. In winter, the heating requirement, depending on the climate region, may be attenuated to the level of close to or essentially zero and thus render the related seasonal energy storage requirement obsolete.

5. Case study: renovation of Wergelandsveien 7, Oslo, Norway

Before the renovation, the Wergelandsveien 7 building (Fig. 8) in Oslo was equipped with triple-pane glazing with wooden framing without low-e coating, having been built in the 1960s. The estimated U_g-value before the renovation was 2.2 W/(m^{2}K). Below the windows there were parapets with a *U*-value of 0.59 W/(m^{2}K) [33]. The renovation consisted of 'hot-swap' facade modernisation and modernisation of the HVAC system. It is not specified how much each component contributed to the energy end-savings reported below.

Two glazing systems were used in the renovation, as shown in Fig. 9. The ground floor featured large panoramic 6-pane glazing

Table 2
Annual energy consumption per m^2 and total energy consumption for the situation before the renovation and the expected vs. measured consumption after renovation [35].

	Specific energy consumption (kWh/(m^{2}a))	Total energy consumption for 10,000 m^2 (GWh/a)
Before renovation	220	2.2
After renovation: expected	100	1.0
After renovation: reported	110	1.1

Fig. 8. The Wergelandsveien 7 building before (left) and after renovation (right).

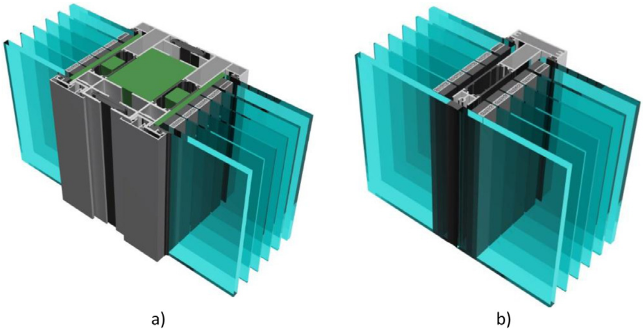


Fig. 9. Framing configuration: (a) upper floors glass element size: 1166 mm × 1436 mm; calculated glazing system U-value = 0.36 W/(m^{2}K) according to EN ISO 12631:2012; input parameters: U_g-value = 0.24 W/(m^{2}K); thermal transmittance of frame U_f = 0.80 W/(m^{2}K); linear thermal transmittance Ψ = 0.016 W/(mK); (b) ground floor glazing system properties: glazing system calculated U-value = 0.32 W/(m^{2}K) according to EN ISO 12631:2012; input parameters: U_g-value = 0.26 W/(m^{2}K); thermal transmittance of frame U_f = 0.80 W/(m^{2}K); linear thermal transmittance Ψ = 0.016 W/(mK).

units with a U_g-value of 0.26 W/(m^{2}K), while the upper floors had customised 6-pane glazing units with 20 mm spacers and a U_g-value of 0.24 W/(m^{2}K) calculated according to EN 673. Both glass types had a nominal EN 410-calculated g-value of 0.24, visible light transmittance LT=0.38, and direct solar energy transmittance, T_{sol} = 0.17. Detailed data sources are given in the study by Leskovšek [34].

The building has performed flawlessly and to the client's satisfaction for the last three years. The application of the 6-pane glazing without modulated external solar shading has demonstrated that such a system's performance is also predictable. If the reported values are accurate, then the 10% discrepancy between the achieved and the calculated energy performance is an excellent achievement (Table 2).

6. Conclusions

A 6-pane insulating glass (IG) unit was engineered and analysed. A general description of the composition of the 6-pane glazing unit has been provided. Important characteristics such as U-value, variable solar energy transmittance, visible transmittance, solar heat gain coefficient, glass pane temperatures, seal water vapour permeability, economical aspects including comfort of living, among others, were investigated. Moreover, the examined case study shows that the annual energy consumption was reduced by approximately a factor of two after renovation with the 6-pane glazing.

Through connecting low U_g-value with moderate g-value solar-control glass the following feats were achieved:

(a) IG unit internal temperatures were reduced to achieve reasonable lifespan which until now was deemed unattainable for windows panes incorporating more panes than the 4-pane glazing configurations;
(b) cost savings were achieved by omitting commonly assumed heat-treated intermediate glass panes and by omitting modulated exterior sun-shading;
(c) the glazing system heat transmittance could be decreased to as low as 0.3 W/(m^{2}K). Therefore, during the winter season the heating requirement may be reduced to a very low level and thus render the need for seasonal energy storage much less essential. The need for seasonal energy storage represents for the time being an insurmountable obstacle to expanding renewable energy in heating dominated areas.

Nevertheless, the complex engineering of the IG unit, requiring the handling of internal temperatures, pressure, and seal stress/deformations, is still the main downside, leading to a lack of confidence in the longevity the IG unit due to the general lack of experience with this type of IG unit design.

Future work needs to focus on moving towards automatic IG unit assembly, which will result in lower product costs. Moreover, costs could also be decreased by providing a wider range of structural support options, which are few for the time being. The most important step is to present the market with the option of moving to 6 panes, which represents an entirely new paradigm shift in designing cost-efficient nearly zero-heating buildings.

Conflict of interest statement

Authors Aleš Kralj, Marija Drev and Matjaž Žnidaršič are employees of the Reflex company which is manufacturer and R&D partner of the subject-matter 6-pane glazing. Aleš Kralj and Matjaž Žnidaršič have contributed to the industrial IP which was assigned to the employer according to the internal rules.

No interest is declared for authors Boštjan Černe, Jože Hafner and Bjørn Petter Jelle.

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References

[1] H.W. Sinn, Buffering volatility: a study on the limits of Germany's energy revolution, Eur. Econ. Rev. 99 (2017) 130–150, doi:10.1016/j.euroecorev.2017.05.007.

[2] W. Feist, Erfahrungen mit Häusern ohne aktives Heizsystem, in: IBK, Jubil. 200, “Stahlbeton” Ohne Stahl? Wärmedämmung “Statt” Heizung? Darmstadt (1995).

[3] L. Vanhoutteghem, G.C.J. Skarning, C.A. Hviid, S. Svendsen, Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses, Energy Build. 102 (2015) 149–156, doi:10.1016/j.enbuild.2015.05.018.

[4] I. Chmurny, Triple or quadruple glazing? Appl. Mech. Mater 820 (2016) 242–247, doi:10.4028/www.scientific.net/AMM.820.242.

[5] M. Casini, M. Casini, Advanced insulation glazing, in: Smart Build., 2016, pp. 249–277, doi:10.1016/B978-0-08-100635-1.00007-1.

[6] Y. Fang, T.J. Hyde, F. Arya, N. Hewitt, R. Wang, Y. Dai, Enhancing the thermal performance of triple vacuum glazing with low-emittance coatings, Energy Build. 97 (2015) 186–195, doi:10.1016/j.enbuild.2015.04.006.

[7] E. Cuce, P.M. Cuce, C.J. Wood, S.B. Riffat, Toward aerogel based thermal superinsulation in buildings: a comprehensive review, Renew. Sustain. Energy Rev. 34 (2014) 273–299, doi:10.1016/j.rser.2014.03.017.

[8] B.P. Jelle, R. Baetens, A. Gustavsen, Aerogel insulation for building applications, in: Sol-Gel Handbook, 2015, pp. 1385–1412, doi:10.1002/9783527670819.ch45.

[9] S. Grynning, B.P. Jelle, A. Gustavsen, T. Gao, B. Time, Multilayer Glazing Technologies: Key Performance Parameters and Future Perspectives, Aalborg University, Department of Civil Engineering, Aalborg, Denmark, 2016.

[10] M. Nikolaeva-Dimitrova, M. Stoyanova, P. Ivanov, K. Tchonkova, R. Stoykov, Investigation of thermal behaviour of innovative water flow glazing modular unit, Bulg. Chem. Commun. 50 (2018) 21–27.

[11] B.P. Jelle, A. Hynd, A. Gustavsen, D. Arasteh, H. Goudey, R. Hart, Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities, Sol. Energy Mater. Sol. Cells 96 (2012) 1–28, doi:10.1016/j.solmat.2011.08.010.

[12] A.A. Solovyev, S.V. Rabotkin, N.F. Kovsharov, Polymer films with multilayer low-E coatings, Mater. Sci. Semicond. Process. 38 (2015) 373–380, doi:10.1016/j.mssp.2015.02.051.

[13] S.L. Garvin, J. Wilson, Environmental conditions in window frames with double-glazing units, Constr. Build. Mater. 12 (1998) 289–302, doi:10.1016/S0950-0618(98)00008-7.

[14] B.P. Jelle, S.E. Kalnæs, T. Gao, Low-emissivity materials for building applications: a state-of-the-art review and future research perspectives, Energy Build. 96 (2015) 329–356, doi:10.1016/j.enbuild.2015.03.024.

[15] B.P. Gao, Tao, Jelle, Silver nanoparticles as low-emissivity coating materials, Transl. Mater. Res. 4 (2017) 015001.

[16] T.E. Graedel, Corrosion mechanisms for silver exposed to the atmosphere, J. Electrochem. Soc. 139 (1992) 1963–1970, doi:10.1149/1.2221162.

[17] R. Meszaros, M. Wild, L. Wondraczek, Effects of substrate and long term corrosion on PVD-multilayer coatings for architectural glazing, Glas. Technol. Eur. J. Glas. Sci. Technol. Part A 54 (2013) 177–184.

[18] A.T. Wolf, L.J. Waters, Factors governing the life expectancy of dual-sealed insulating glass units, Constr. Build. Mater. 7 (1993) 101–107, doi:10.1016/0950-0618(93)90039-F.

[19] S. Van Den Bergh, R. Hart, B.P. Jelle, A. Gustavsen, Window spacers and edge seals in insulating glass units: a state-of-the-art review and future perspectives, Energy Build. 58 (2013) 263–280, doi:10.1016/j.enbuild.2012.10.006.

[20] S.K. Asphaug, B.P. Jelle, L. Gullbrekken, S. Uvsløkk, Accelerated ageing and durability of double-glazed sealed insulating window panes and impact on heating demand in buildings, Energy Build. 116 (2016) 395–402, doi:10.1016/j.enbuild.2016.01.015.

[21] A. Kralj, R. Hajdinjak, Multi Chamber Gas Filled Construction Panel, 2012 EP 2729635B1.

[22] European Standard, CEN EN 410: Glass in Building—Determination of Luminous and Solar Characteristics of Glazing, 2013.

[23] B.P. Jelle, Solar radiation glazing factors for window panes, glass structures and electrochromic windows in buildings—measurement and calculation, Sol. Energy Mater. Sol. Cells 116 (2013) 291–323, doi:10.1016/j.solmat.2013.04.032.

[24] A. Roos, P. Polato, P.A. Van Nijnatten, M.G. Hutchins, F. Olive, C. Anderson, Angular-dependent optical properties of low-e and solar control windows—simulations versus measurements, Sol. Energy 69 (2001) 15–26, doi:10.1016/S0038-092X(01)00019-6.

[25] J. Hafner, S. Jordan, Steklene fasade: toplotni odziv prozornega steklenega fasadnega elementa Q-Air v realnih vremenskih razmerah, Gradbenik (2018) 88–90.

[26] G.M. Masters, Renewable and Efficient Electric Power Systems, John Wiley & Sons, Inc., 2005, doi:10.1002/0471668826.

[27] A. Kralj, M. Drev, M. Žnidaršič, J. Hafner, B. Černe, Multipane Glazing Durability, 2018, doi:10.13140/RG.2.2.32947.48162.

[28] A. Jurelionis, E. Isevičius, CFD predictions of indoor air movement induced by cold window surfaces, J. Civ. Eng. Manag. 14 (2008) 29–38, doi:10.3846/1392-3730.2008.14.29-38.

[29] Danish Standard, DS/CEN/CR 1752. Ventilation for buildings—design criteria for the indoor environment., in: Int. Organ. Stand., 2001, p. 2920.

[30] D. Lehrer, K. Zelenay, M. Perepelitza, High-performance Facades Design Strategies and Applications in North America and Northern Europe, University of California, 2011.

[31] Byggteknisk forskrift (TEK17), (n.d.). https://dibk.no/byggereglene/byggteknisk-forskrift-tek17 (Accessed 27 March 27, 2018).

[32] M. Drev, B. Černe, M. Žnidaršič, A. Geving, A. Kralj, Nearly independent, near-zero energy building, in: R. Holopainen, V. Raasakka (Eds.), PHN17 8th Nord. Passiv. House Conf., Helsinki, Finland, 2017, pp. 255–260.

[33] K. Malovrh Rebec, M. Drev, F. Knez, A. Kralj, B. Černe, Multipane single and double skin transparent façade building performance in terms of indoor daylight, heating and cooling requirements, in: Adv. Build. Ski. 12th Conf. Adv. Build., 2017, pp. 774–784.

[34] U. Leskovšek, Calculation of U Value Project: Werelandsveien, Ljubljana, Slovenia, 2015, doi:10.13140/RG.2.2.28121.57442.

[35] S.F. Enova. Results and Aactivities 2015, N-7030 trondheim, 2015. ISBN 978-82-92502-99-0.