Dow Performance Silicones

Sustainability Driven Trends and Innovation in Glass and Glazing

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Abstract

Increased global urbanization has caused tall buildings to become an inevitable building form making the façade and especially the glazing areas of paramount importance for the overall heat loss and heat gain of the building. The substantial technological advances in insulating glass and glazing systems made during the past 25 years have improved the possibility for designing well-functioning buildings with glass as the major material for the building envelope. More recently, sustainable design principles have begun to drive certain macro-trends in construction that are also starting to affect façade design, requiring reduced energy consumption, cradle-to-grave material and component assessment, and measures to improve the well-being and safety of building occupants. Emerging new glass and glazing technologies are driven by sustainable design. The paper discusses in detail technologies for improved thermal insulation glazing (novel low E coatings, gas-filling, warm-edge spacers, aerogel filled glazing, vacuum glazing). The contributions of silicone materials to energy savings and sustainability of glazing systems are highlighted in a few examples.

1. Introduction

Building designers and owners have always been fascinated with the extensive use of glass in building envelopes. However, in tall buildings, having a high ratio of façade-to-roof surface areas, the façade and especially the glazing areas are of paramount importance for the overall heat loss and heat gain of the building, and, therefore, require special attention. The substantial technological advances in insulating glass and glazing systems made during the past 25 years have improved the possibility for designing well-functioning buildings with glass as the major material for the building envelope. The research efforts documented, for example, by the Lawrence Berkeley National Laboratory since the 1980s are reflecting this tremendous progress[1]. More recently, sustainable design principles have begun to drive certain macro-trends in construction that are also starting to affect façade design:

- Reduced energy consumption (zero-energy buildings)
- Cradle-to-grave material and component assessment
    - Optimal use of embodied energy in building materials
    - Reduction of toxic emissions associated with production processes
    - Minimization of the use of scarce, non-renewable natural resources
    - Ability to recycle and reuse materials or components at the end of their useful life
- Well-being and safety of building occupants
    - Improved thermal comfort
    - Increased natural day-lighting in buildings (while minimizing glare)
    - Enhanced interior air quality (ventilation, low toxic emissions, low volatile organic content)
    - UV protection, explosion blast protection, etc.

New glass and glazing technologies are emerging to address some of the macro-trends driven by sustainable design. The following is a list of some of the major advances, just to name a few:

- Improved thermal insulation glazing (novel low E coatings, gas-filling, warm-edge, aerogel filled glazing, vacuum glazing)
- Adaptable (chromogenic, switchable) glazing
- Light diffusion glazing
- Prismatic glazing for angular selective solar control
- Double-layer façades
- Integration of photo-voltaic
- Innovative structural use of glass

Many of the benefits resulting from the technologies are only achievable by an integrated approach to façade design. Consequently, the manner in which glazing is incorporated into a complete fenestration system and then the building façade, and in fact the manner in which the building façade is integrated into the entire building, will be increasingly important in future. Furthermore, in its role as a transparent façade system, glazing systems must perform an increasingly wider range of 'functions', which in turn challenges a wide range of performance criteria.

In future, the combination of advances made in glass and glazing technology over the past 25 years with new, emerging technologies will allow the design and construction of dynamic and responsive façades that provide the following functionality[2]:

- Enhanced sun protection and cooling load control while improving thermal comfort and providing most of the light needed with day-lighting;
- Enhanced air quality and reduced cooling loads using natural ventilation schemes employing the façade as an active air control element;
- Reduced operating costs by minimizing lighting, cooling and heating energy use by optimizing the daylighting-thermal tradeoffs;
- Improved indoor environments leading to enhanced occupant health, comfort and performance.

2. Energy Efficiency of Glass and Glazing with Consideration of Sustainability

Worldwide, windows are responsible for a disproportionate amount of unwanted heat gain and heat loss between buildings and the environment[3]. In the USA, over 3% of total energy consumption is lost through windows, in Sweden this figure is 7%[4] and in Britain 6% for residential buildings alone[5].

The most important energy-related performance challenges for glazing are to (1) control heat loss, (2) admit daylight with minimal solar heat gain, (3) dynamically control solar heat gain and glare, and (4) redirect incident daylight for more effective use in buildings. In cold climates, the most important parameter to consider is heat loss from the building to the environment and, thus, the thermal transmittance ('U-value') of the insulating glass unit becomes the overriding concern. In hot climates, heat gain via glazed areas is the most important aspect to consider. This paper is primarily focused on measures suitable for reducing heat loss and heat gain, since these are the primary factors in the climate-driven operational energy consumption of a building.

2.1. Improved Thermal Insulation (Reduced Heat Loss) – Current Solutions for Cold Climates.

The single most important innovation in glazing technology over the last 25 years has been the development and widespread use of large area, low cost, multi-layer thin film coatings. This type of spectrally selective glazing, which is used to minimize heat loss, reflects low-wave infrared (IR) radiation emitted by the interior of the building, while permitting most visible light from the exterior to enter. Spectral selectivity is achieved by a microscopically thin, low-emissivity (low-E) coating on the glass or on a film applied to the glass or suspended within the insulating glass unit. Since the coating is intended to reflect IR radiation back into the room, it is generally located on glass surface #3 (for double-glazing systems).

After their introduction in the early 1980s, low-E coatings have rapidly gained share in the insulating glass (IG) market. A strong driving force for the quick introduction of these coatings had been the fact that glass surfaces with low thermal emittance can virtually eliminate the thermal infrared radiation loss through the glazing and thus drastically improve the thermal insulation properties of a window, resulting in lower heating energy cost and higher thermal comfort[6]. The reduced thermal loss is reflected in the lower center-pane U-value of about 1.6 (W/m^{2}K) for standard low-E IG units, or even lower, for the most advanced low-E stack and gas filling combinations. For comparison, a double glazed uncoated IG unit has a center-pane U-value around 3.0 and a single pane around 6.0 (W/m^{2}K). The center-pane U-value of an IG unit depends strongly on the emittance of the second or third glass surface (counted from the exterior) as shown in Figure 1.

The thermal emittance of uncoated glass is about 0.84, which was reduced to about 0.10-0.20 by the first available coatings. Thus, a radical improvement in energy performance was achieved. With the introduction of sputtered (soft) dielectric-metal-dielectric low-E coatings it was possible to reduce the emittance further to below 0.10 and with today's state of the art technology it is possible to achieve a thermal emittance even below 0.05.

Heat losses through an insulating glass unit can be further reduced by optimizing the spacing (glazing gap) between the two glass panes. Therefore, a spacer width of 16 mm, rather than 12 mm as used in the past, is becoming increasingly the norm. Spacers wider than 18 mm are seldom used, because convective conductance increases substantially for wider glazing gaps[7]. The convection of gas between the panes can be reduced by selection of fill gases with a higher density than air (1.29 kg/m^3 at 0°C), such as argon (1.78 kg/m^3), krypton (3.71 kg/m^3) or xenon (5.86 kg/m^3)[8]. All noble gases are colorless, odorless and non-toxic, UV-stable and have no impact on light transmission; but argon is most widely used, since it is also the cheapest gas on the market. Using argon or krypton instead of air in low-E IG units allows an improvement of the center-pane value of ca. 0.3 W/m^{2}K for glazing gaps wider than 9 mm.

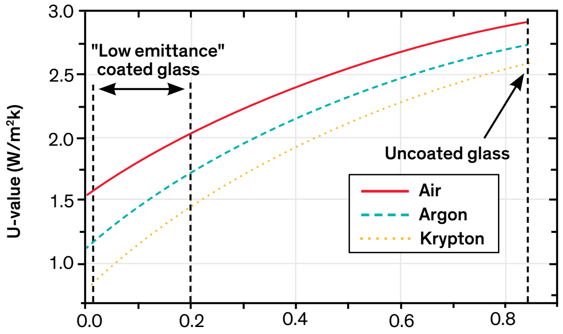


Figure 1 – U-value calculated according to EN 673[9] versus emittance for the third surface (counted from the outside) and for different gas fill (12 mm spacer width). Low emittance glazings have emittance values below 20% (0.2) and uncoated glass has about 84% (0.84)[10]

Measuring the thermal conductivity (U-value) of an IG unit at the center of glass pane ignores the influence of the edge seal region on the overall thermal performance of the unit. In conventional IG edge-seal systems, spacers made of thermally high-conductive materials, such as aluminum or steel, create an extended linear thermal bridge. New spacer systems reduce the heat loss via these thermal 'short-circuits'; the inside glass edge of an IGU in a heated building during winter remains considerably warmer, i.e. it has a 'warm edge'. The term 'warm edge' is therefore used to describe the function of an IG edge-seal with improved thermal properties (reduced thermal transmittance) that prevents heat from escaping from the building. Warm edge spacers are becoming increasingly popular in North America and in Europe, since they also reduce the risk of mold formation on the interior sash surfaces. Figure 2 shows, as an example, the degree of condensation or frost occurring on the interior surface of an IG unit for a regular metal spacer, a warm-edge spacer with lower metal content, and a silicone rubber foam spacer that is completely free of metal components.

The insulation value of an IG unit can be further improved by increasing the number of glazing gaps, i.e. the number of air- or gas-filled spaces between the panes. For instance, a doubling of the gas layers from double- to triple-glazing for argon- or krypton-filled, low-E coated IG units roughly cuts the U-value into half. Therefore, triple-glazed, krypton-filled, low-E coated IG units achieve a center-pane U-value below 0.6 (W/m^{2}K). At this level, the window will outperform an insulated wall in winter, even when oriented to the north in a cold U.S. climate[26].

While IG units with a targeted center-pane U-value of 0.5 (W/m^{2}K) have become the 'holy grail' of research, not every option that is technically achievable automatically implies a financially or environmentally sound decision. Table 1 shows various glazing options and their additional embodied energy versus a standard specification, which in this study was defined as air-filled double-glazing without low-E coating, 4 mm thick glass panes, and a 20 mm wide aluminum spacer[11]. Xenon-filled IG units were not considered in this analysis due to the prohibitively high embodied energy of collecting xenon gas[12,13]. For standard-sized IG units (1.2 m x 1.2 m, 16 mm glazing gap), the contribution of the different fill gases to the total embodied energy may be substantial, representing 11.85 KJ, 508.2 MJ and 4.50 GJ for argon, krypton and xenon, respectively[14,15], while the contribution of a low-E coating (8.42 MJ[35]) is relatively low when compared to the contributions made by krypton or xenon gas fillings.

Embodied energy is the energy consumed by all of the processes associated with the production of a product or a complete building, from the acquisition of natural resources to product delivery. The embodied energy of a product is one of the most common measures of its associated environmental burdens. The energy requirement does not in itself measure environmental impact; it is however useful as a proxy for the level of stress that energy use during production and delivery may cause in the environment. Whereas the energy used in operating a building can be readily measured, the embodied energy contained in the structure is difficult to assess. This energy use is often hidden and can only be fully quantified through a complete LCA. In the above study[35] by Menzies, embodied energy levels for all types of glazing units were calculated using data from Weir[36]. Embodied energy calculations included the energy required to obtain raw materials, energy used in manufacturing and packaging processes, and transportation energy consumption incurred to get the IG units to site.

Metal spacer

Reduced metal
component spacer

No metal foam spacer

Figure 2 – Condensation and frost forming on interior pane for different spacer systems (Courtesy of Edgetech I.G. Inc., Cambridge, Ohio, U.S.A., www.edgetechig.com/)

IG Type (glazing, infill gas, coating)	Specification[a]	IG Unit Center-Pane[b] U-Value (W/m^{2}K)	Additional Embodied Energy Per IG Unit (MJ)
Double, air, no coating	4 – 20Air – 4	2.76	Standard specification
Double, air, low-E	4e – 20Air – 4	1.58	8.42
Double, argon, low-E	4e – 16Ar – 4	1.31	8.43
Double, krypton, low-E	4e – 12Kr – e4	0.94	525.04
Triple, argon, low-E	4e – 16Ar – 4 – 16Ar – e4	0.65	161.56
Triple, krypton, low-E	4e – 12Kr – 4 – 12Kr – e4	0.52	1167.14

(a) Glass specification details the width of glass panes (in mm), width of glazing gap (mm) and type of infill gas. 4e represents a 4 mm glass pane with one low-emissivity coating. Position of low-E coating is indicated. Example: 4e – 12Kr – e4 represents a double-glazed IG unit, krypton filled, with low-E coatings on surfaces (2) and (3) – counting the number of glass surfaces from the exterior to the interior.

(b) Center-pane U-value is for the complete IG unit, including glass panes, inert gas, and low-E coating.

Table 1 – U-Value and Embodied Energy of Alternative IG Unit Specifications (as studied by Menzies35)

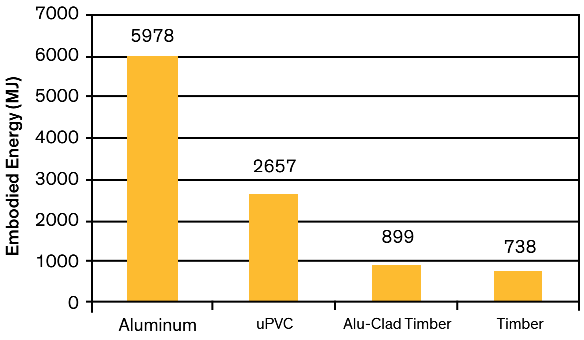
Menzies studied the energy and CO_2 emission savings resulting from the replacement of existing IG units with the alternative IG units listed in Table 1 in existing window frames for four buildings in Scotland. Higher specification glazing could have saved between 1.7% and 20.3% of the energy used to heat the buildings. Balancing the potential energy saved through improved glazing in the buildings, against the additional embodied energy required to manufacture and supply the units, allowed for an energy payback period to be evaluated. Krypton filled windows all had a considerably longer payback period than air or argon-filled windows, with payback periods of up to nine years. Payback periods for argon-filled windows ranged from 15 days (doubleglazed) to 1.5 years (triple-glazed). Low-emissivity coatings would have repaid themselves in embodied energy terms in around 20 days. The use of low-E coatings (versus uncoated IG) would have reduced CO_2 emissions from electricity production by around 10%; the financial cost of the low-E coating would have been paid back in under five years, and in terms of energy, in only one month.

The study further showed that the financial cost of improved IG unit specification at the initial build stage is substantial (based on selling prices in the United Kingdom). However, the financial payback periods (adjusted for interest) for low-emissivity coating and argon gas in either double- or triple glazing were acceptable (6-16 years) compared to the lifespan of the IG unit. The cost of double- or triple-glazed krypton filled IG units clearly could not be recovered within 100 years.

For conventionally framed windows, the material used to manufacture the frame not only governs the physical characteristics of the window, such as frame thickness, weight, and durability, but it also has a major impact on the thermal performance and the embodied energy of the window. The embodied energy of different frame types varies considerably (Figure 3), with timber corresponding to the lowest embodied energy, followed by aluminum-clad timber, uPVC, steel and aluminum[16 17].

While aluminum has a high embodied energy, it should be remembered that unlike uPVC it is easily recyclable and up to 93-95% of the embodied energy can be recouped (the production process of secondary or recycled aluminum is fairly simple and requires only 5-7% of the energy needed for primary aluminum). In its first incarnation, aluminum is a comparatively expensive material, partly because of the large amounts of energy consumed in smelting the alumina into aluminum. However, aluminum can be recycled repeatedly without any deterioration in quality. The more often the metal is recycled, the more competitive its lifetime cost becomes.

Thermally-broken aluminum can be an environmentally sustainable choice as a window frame or façade material in commercial buildings, provide excellent durability and achieve reasonable thermal performance, especially in combination with warm-edge IG units. For residential glazing applications, timber or aluminumclad timber frames provide high sustainability and good thermal performance. Aluminum-clad timber windows also excel in durability and low maintenance (Asif[37 40]). Double- or triple-glazed, low-E coated, argon-filled insulating glass provides the best overall sustainability and energy saving. The thermal performance of IG units can be further improved by using warm-edge spacers.



Note: Embodied energy figures are for standard size window (1.2 m x 1.2 m) with double-glazed insulating glass unit with low-E coat and argon gas fill (16 mm spacer width)

Figure 3 – Embodied Energy for Standard Sized Window Based on Different Frame Materials

Low-E coatings may also be applied to plastic films that are suspended between two glass panes forming in effect a triple-glazing system with two cavities (see Figure 4). This technology offers a number of benefits:

- Easier recyclability of the float glass
- Low E coating may be applied on both sides of the film (improved thermal performance and material efficiency)
- Effective blocking of ultraviolet radiation (reduced color fading of interior materials).

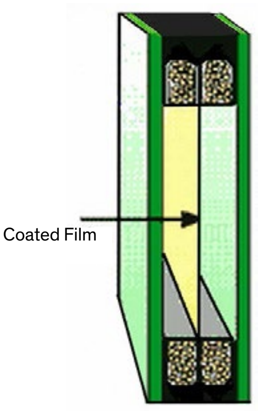


Figure 4 – Low E coated film suspended between two glass panes

2.2. Reduced Solar Heat Gain – Current Solutions for Warm, Sunny Climates

Spectrally selective glasses are also used to minimize solar gain during summer. These glazings absorb or reflect heat-generating radiation arriving at a building's exterior surface while permitting most visible light to enter. Tinted glasses, which absorb certain radiation wavelengths, have long been in use. In the past, these glasses were dark colored – typically brown or gray – in order to be effective. Today's high-performance tinted glass, which has a light blue or light green tint, offers both higher visible transmittance and a lower solar heat gain coefficient. However, absorption of radiation remains less efficient than reflection, because some of the heat absorbed by tinted glass continues to be transferred to the building's interior. Highly reflective glass has been and is still used to minimize heat gain, however, this glass generally has low visible transmission. Therefore, low emissivity coatings are increasingly used in controlling solar gain since they offer virtually clear appearance, admit more daylight and permit much brighter, more open views to the outside while still providing much of the solar control of the dark or highly reflective energy-efficient glass of the past.

Because of its solar heat transmission properties, spectrally selective glazing benefits both buildings in warm climates, where solar heat gain can be a problem, and buildings in colder climates, where solar heat gains in summer and interior heat loss in winter are both of concern. In other words, different variants on these glazings are appropriate for buildings throughout a wide range of climates. In order to obtain high solar control efficiency, these low-E coatings generally are based on two reflective (silver) layers in the coating stack and therefore are often referred to as low-E^2 ('low-E-square') coatings. This spectrally selective glazing causes little change in daylight transmittance, but reduces solar heat gain by 50-70%, compared to conventional low-E coatings and by an even greater factor compared to conventional tinted glasses with equivalent light transmittance. Whereas the ratio of visible transmittance to solar heat gain ranges from .6 to 1.0 for most conventional glazings, spectrally selective glazings have a ratio of 1.1 to 1.8 or up to three times the 'efficacy' of more conventional glazings[26]

2.3. Improved Thermal Insulation (Reduced Heat Loss) – Future Solutions for Cold Climates.

There are several useful techniques to produce glazing systems with center-pane thermal conductances (U_g) in the range of 0.6 (W/m^2K). These include: (1) three-layer windows with two low-E coatings, argon or krypton gas fills, and low-conductance warm-edge spacers; (2) vacuum windows with two glass layers, a narrow spacing, and a low-E coating; (3) aerogel windows filled with highly insulating silica aerogel (a micro-porous material with excellent insulating properties); and (4) various transparent insulating materials, e.g., transparent honeycombs, inserted between glass panes

Multilayer windows and glazings are commercially available today using well-proven technology. Since the sash and frame represent from 10 to 30% of the total area of the window unit, the frame properties have a significant impact on the overall thermal performance of the window[18]. Therefore, at least in Europe's cold climates, the main focus of research and development today is on reducing the thermal conductivity of the frame materials. The current state-of-the-art allows the achievement of an overall thermal transmittance of a window (U_w) below 0.8 (W/m^2K), for instance, by combining an argon-filled triple-glazed IG unit with a polyurethane-foam insulated aluminum-clad timber window frame.

Silica aerogel or xerogel insulation made from silanes using well-established silicone sol/gel chemistry is recognized as the lightest, most effective insulation material in the world (see Figure 5). This advanced technology is being used already today in translucent, light diffusing skylight and window units. These units provide high thermal insulation value without the need for expensive, heavy and thick triple or quadruple glazing, do not require special gas fills – which means that there is no risk of gas leakage – and improve the sound insulation performance of the window. The translucent daylighting units are produced by inserting either aerogel/xerogel powder or an aerogel treated plastic batting between the glass sheets. Translucent aerogel or xerogel filled units are increasingly chosen for light-diffusing daylighting in both commercial and residential buildings as they offer the advantages of soft, natural light, privacy, and insulating values that are unmatched by standard vision windows (see Figure 6).

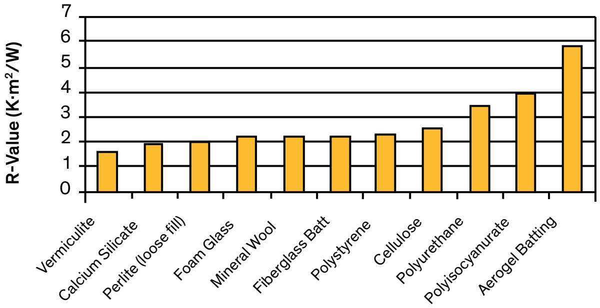


Figure 5 – Thermal resistance (R-value in K·m²/W) for different insulation materials

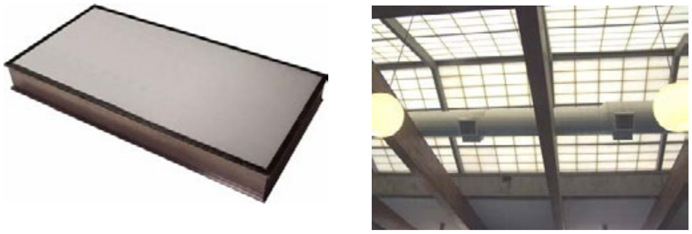


Figure 6 – Translucent daylighting panel and installed skylight system (Courtesy of Aspen Aerogels, Inc., Northborough, MA, U.S.A., www.aerogel.com/)

Translucent aerogel window units provide the following benefits:

- Reduced solar heat gain
- Reduced down drafts from overhead skylights
- Improved resistance to condensation (on interior glass surface)
- Higher energy efficiency (energy and cost savings)

Current research on aerogel filled IG units is primarily focused on producing highly transparent aerogels (see Figure 7) that can be used either in transparent glazing products or integrated into translucent daylighting systems, offering the ability to 'tune' the performance of the fenestration solution.

Figure 7 – Highly transparent aerogel interlayer system (Courtesy of Aspen Aerogels)

Multiglazed IG units, especially triple and quadruple-glazed units, are wide, heavy and difficult to install, particularly for retrofitting to existing buildings. Therefore, during the past 15-20 years substantial research has focused on highly efficient vacuum glazing systems, which are only 8-12 mm wide. Evacuated glazing consists of two sheets of glass, hermetically sealed, with an evacuated gap between the glass sheets. An array of support pillars or ribbons is used to keep the glass sheets separated after evacuation. Low-E coatings may be used on the inner glass surfaces to reduce radiative heat transfer. The edge seal may be fused with solder glass or metal. Recent research at the University of Ulster, Ireland, has identified an indium alloy as a low-temperature solder for vacuum IG units. The low melting temperature of the alloy of 160°C allows the use of soft low-E coatings and tempered glass in vacuum IG units. In Japan, a vacuum glazing with an U-value of 0.45 W/(m²K) and a thickness of only 6 mm has been recently developed[19].

Continued improvements in both vacuum and transparent aerogel window technology could make them a strong competitor to gas-filled multiglazed IG units in the next 10+ years. Simulations of annual energy requirements show that the best performance in a cold climate is obtained when the highest possible solar heat gain factor is maintained while the conductance (Ug) is reduced. Even the solar energy available on the north façade is more than sufficient to counter small daytime losses and turn the window into a net energy provider. A viable vacuum window or aerogel window could provide equivalent thermal conductance values to triple-glazed, gas-filled IG units with somewhat higher solar gain values, thus providing an even greater energy saving benefit. Such windows will also provide warm interior surfaces and thus excellent thermal comfort, with minimal risk of condensation[26].

2.4. Smart Glazing – Future Solutions to Minimize Solar Gain and Optimize Comfort of Occupants.

Although current state-of-the-art spectrally selective coatings are highly optimized to maximize the daylight/cooling load ratio, they cannot respond to changing exterior illumination (sun, clouds) conditions. The next big advances in coated glazings will be 'smart glazings' that respond dynamically to changing occupant and building needs. After 15 years of laboratory development these coatings are now beginning to be scaled up in prototype form for use in buildings. These smart glazings can be divided into two major categories, (1)

Figure 8 – TPS sealed PV IG façade unit (left: schematics, middle: connector penetration, right: actual stepped PV IG unit) (Courtesy of Bystronic Glass, Lenhardt Maschinenbau, Neuhausen-Hamberg, Germany, www.bystronic-glass.com/)

'passively activated', such as thermochromic (heat sensitive) or photochromic (light sensitive), and (2) 'actively controlled', such as electrochromic or gasochromic, which can be switched on and off as needed with a small applied voltage or small amount of hydrogen, respectively. Each of these should ultimately find a market niche but the actively controllable options are likely to be the preferred choice, assuming the remaining durability and cost issues can be favorably resolved[26]. Switchable glazings can be either integrated into traditional multi-glazed IG units or combined with future, improved technologies for minimizing heat loss, such as vacuum- or aerogel glazings.

2.5. Façades as Energy Suppliers – Example: PV Integration.

The traditional role of the glazing has been as a 'climate moderator', mediating between the changing outdoor conditions and the relatively constant desired indoor conditions by filtering and modifying energy flows. Using the novel technologies described above, the next few years should see continued advances in efforts to use the façade to directly become an energy and service provider to the building, a source of heat, light, and 'onsite electric power'. A quick analysis of the magnitudes of energy flows at a façade suggests that there is more than adequate energy available at a building site to power most buildings. For example, the luminous flux contained in a square meter cross-section of sunlight in summer at moderate latitudes is enough to adequately light about 200 m^2 of interior building space. The fundamental challenge is distributing and controlling those flows that are not readily stored, such as daylight, and storing and managing the release of heat and power[26].

Photovoltaic (PV) modules provide one option for capturing the solar energy flow hitting the surface of a building. Solar PV solutions are not only an environmentally friendly option, but also a cost effective one. The cost of producing one Watt of solar power decreases 20 percent every time the PV industry's capacity doubles, which, at current growth rates, is every few years. Already today, various technical options exist that allow the integration of semi-transparent PV modules for daylighting control into façades. These semi-transparent modules are based on thin-film PV technology where the sensitive parts of the module are protected from moisture by encapsulation or lamination with an organic polymer, such as EVA or PVB. A critical issue in the long-term performance and reliability of PV modules [1], especially polycrystalline thin-film modules without frames and edge seals, is their resistance to moisture ingress.

For many module types, exposure to water or moisture is an important lifetime-limiting factor[20 21 22]. During service exposure, adhesive bonds between encapsulant and substrate materials of PV modules can weaken, leading to moisture ingress and/or delamination failure. The high propensity of EVA and PVB for water absorption implies higher failure rates in high humidity climates than in arid geographical areas. Adhesion of EVA and PVB can be improved by use of suitable silane adhesion promoters or primers[23]. Very recently, an alternative method of integrating thin-film modules into an IG unit was developed[24]. In this method, the thinfilm PV glass element is incorporated into an IG unit sealed with a multi-layer thermoplastic spacer (TPS), and, subsequently, with a secondary sealant. This approach eliminates the lamination or encapsulation process. The uninterrupted application of two TPS material layers provides an excellent vapor barrier at the perimeter of the IG unit despite the cable penetrations and ensures the PV module is completely protected against moisture ingress. Figure 8 shows a schematic drawing of a PV IG façade unit and an actual stepped PV IG unit.

3. Contribution of Silicone Technology to Energy Saving and Sustainability of Glazing Systems.

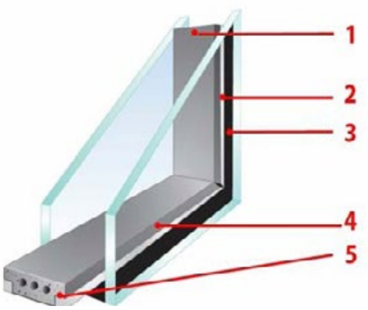
Silicone materials make both direct and indirect contributions to energy savings and sustainability of glazing systems. The direct contributions result from their use as sealing and insulation materials; while the indirect contributions are a consequence of their longevity or the longevity they provide to the glazing components. The following discussion covers only some of the key benefits that silicone materials provide in insulating glass and glazing.

3.1. Improved Heat Insulation and Improved Longevity of IG Unit (Silicone Warm-Edge Spacer)

Silicone sealants have a low coefficient of thermal conductivity (λ), typically around 0.25 (W/(m·K)). This low conductivity can be further lowered by foaming the cured product. The type of medium density silicone foam used in the manufacture of metal-free warm-edge spacers is quoted by prEN ISO 10077-2 (2000)[25] as having a thermal conductivity of 0.17 (W/(m·K)), i.e. silicone foam warm-edge spacers are about 950 times less conductive than aluminum spacers. In actual windows, this translates to less than half the linear thermal transmittance (Ψ) of aluminum spacers[26]. Silicone foam warm-edge spacers are not degraded by sunlight, remain flexible over an extremely wide range of service-temperatures, and provide the following benefits:

- Reduced edge-seal stress (resulting in longer service-life of the IG unit)
- Higher thermal insulation and comfort (center-pane U_g value improves by ca. 0.1-0.15 W/(m^2K))
- Less condensation on interior glass pane
- Improved sound insulation

Silicone foam spacers are capable of accommodating the edge-seal movements induced by external loads, such as differential heating, wind loads or changes in barometric pressure. Edge-seals containing rigid spacers cannot absorb movements as well as the flexible foam spacers, leading to stress cracks in the primary seal and ultimately to IG unit failure. In the USA, the flexible spacer edge-seal design is reported to have a failure rate of less than 0.01% after 5 years installation, compared with 0.1% for the lowest failure rate with the conventional spacer design, and with 4% average failure rates of IG units, also based on conventional spacer design[27.]



1 – Flexible silicone foam
2 – PIB primary seal
3 – Silicone, Polyurethane, Polysulfide, or other secondary seal (for structural glazing, silicone is required)
4 – Pressure-sensitive acrylic adhesive
5 – Pre-applied advanced multi-layer vapor barrier

Figure 9 – Novel silicone foam warm-edge spacer design with integrated polyisobutylene primary seal (Courtesy of Edgetech I.G. Inc., Cambridge, Ohio, U.S.A., www.edgetechig.com/)

A novel silicone foam spacer design, combined with a silicone secondary sealant, has recently passed the stringent requirements of EN 1279, Part 2 (moisture penetration) and Part 3 (gas loss). Combining these two materials allows silicone-sealed, gas-filled IG units to be specified in Europe for structural glazing and other highly demanding glazing applications.

3.2. Improved Heat Insulation and Improved Longevity of IG Unit (Silicone Sealed IG Units)

Silicone sealed IG units are known to excel in their durability against the exterior climate, especially in their resistance to sunlight and its ultraviolet component. Therefore, specially formulated silicone sealants are the only secondary sealants that have been approved by building code authorities for use in structural glazing systems. For example, within Europe, ETAG 002 'Structural Glazing Systems' sets strict requirements on the durability of structural glazing sealants and IG sealants used in structural glazing systems[28].

However, silicone sealants also can provide enhanced longevity and lower field failure rates to residential IG units. Recently, a US manufacturer published data on historic field failure rates for different IG unit edge seal designs and compared these to data provided in a study conducted by the American Insulating Glass Manufacturers Association (IGMA)[29]. IG units produced by this manufacturer in 1976 using aluminum spacer and a polyisobutylene (PIB)/polysulfide dual-seal system showed a cumulative failure rate of 8.5% after 20 years. This failure rate was comparable to the industry's performance. The IGMA study reported a cumulative failure rate for standard IG units of more than 9% after just 15 years field service. In 1978, the same IG manufacturer switched to a silicone secondary sealant, and units produced in 1978 with aluminum spacer and a PIB/silicone dual-seal system had a cumulative failure rate of just over one percent after 20 years. In 1993, the IG manufacturer introduced a revolutionary new edge-seal design based on a patented stainless steel spacer and a PIB/silicone dual-seal system (see Figure 10). After ten years, IG units with this edge-seal system have shown a cumulative field failure rate of less then 0.1% and the manufacturer projects a cumulative failure rate of well below 0.5% after 20 years in the field (see Figure 11).

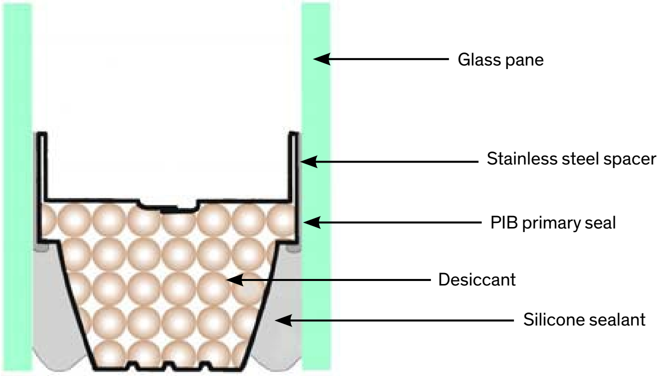


Figure 10 – Proprietary PIB/silicone dual-seal design based on patented stainless steel spacer (adapted from[30])

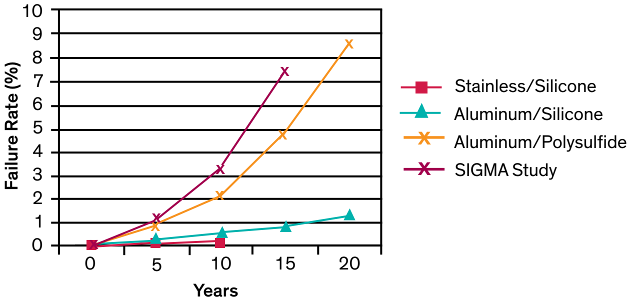


Figure 11 - Cumulative field failure rates after up to 20 years of field service (adapted from[54])

The IG manufacturer's statistics show that silicone IG sealants in conjunction with good manufacturing practices and proper edge-seal design can outperform IG units made with organic sealants. So, why do siliconesealed IG units perform that well? It is for the following reasons[31]:

- Silicone dual-seal IGU have a lower moisture penetration rate under actual service conditions, because
  - in dual-seal IGUs, the permeability of the edge-seal is almost exclusively determined by the permeability of the primary (PIB) seal, and
  - silicone secondary sealants do a better job in maintaining a low effective cross-section for diffusion through the primary seal (this is a result of their higher Young's modulus and higher elastic recovery at elevated temperatures as well as their tendency to swell very little under the influence of high moisture or water)
- Silicone dual-seal IGU achieve a higher life expectancy under actual service conditions, because
  - physical properties and adhesion of silicone secondary sealants are very little affected by the key environmental ageing factor, i.e. ultraviolet light, heat and moisture

Increased service-life and lower field failure rates translate into more efficient use of resources and embodied energy as well as lower cost to building owners.

3.3. Reduced Embodied Energy of Window System (Silicone Bonding)

There is a wide range of existing and emerging glazing and fenestration technologies, which break new ground with respect to innovative structural use of glass. Experience gained with silicones in structural glazing and protective glazing systems and with polyurethanes in automotive direct glazing led to the development of structurally bonded window systems. In these systems, as with structural glazing, silicone sealants are used whenever the sealant is exposed (through glass) to sunlight, while polyurethane sealants may be used, as with automotive direct glazing, when the bonded section is not directly or indirectly exposed to sunlight. A key learning, direct transferable from the automotive glazing system, is that the glass panes, when bonded to the frame, act as structural (load bearing) elements in a window system. Obviously, the strength of the window then depends on the structural strength of the glass unit. However, glass has a good load bearing capability (stiffness) and can considerably contribute to the overall strength of the system. Therefore, structural bonding of the glass pane(s) to the frame and the resulting load transfer from frame to glass result in a number of benefits of bonded windows:

- Increased structural strength of window frame (load transfer from frame to glass);
- Leaner and more slender frame designs (larger vision area – increased light transmission via window opening);n
- Increased window sizes with current, standard frame cross-sections;
- Elimination of setting blocks;
- Improved thermal, sound and seismic performance of window (U-value);
- Improved protective glazing properties (resistance to burglars, bomb blasts, hurricanes, earthquakes, avalanches, etc.);
- Potential automation of glazing and bonding process.

Figure 12 - Structurally bonded uPVC window system (Courtesy of Profine International, Profine GmbH International Profile Group, Troisdorf, Germany, website: http://www.profine-group.de/)

In Europe, bonded windows have created quite some excitement within the windows industry over the past two years. Initially, this concept was primarily practiced with uPVC windows, since these currently represent the largest share of the European windows market (see Figure 12 as an example). A quick calculation shows that use of this bonding technology allows a reduction in the embodied energy of an uPVC window by up to 15%. However, very recently, this bonding technique is also being applied to the design of timber or aluminum clad timber windows, which have been discussed earlier in this paper as highly sustainable window types.

4. Outlook

The following macro-trends in façade and window construction can be identified that will determine technological developments over the next 10+ years:

- Technology improvements will continue to enhance glazing energy-efficiency and performance;
- Glazings will become 'energy suppliers' as well as 'energy managers'
- Facades will be optimized for daylighting and natural ventilation, which emerge as central design themes for the next generation of buildings.
- New structural concepts will continue to enhance curtain-wall and window manufacture

Silicone chemistry and silicone products can contribute to these developments by improving the energy efficiency and environmental sustainability of façades and windows. The direct contributions result from their use as sealing and insulation materials; while the indirect contributions are a consequence of their longevity or the longevity they provide to the glazing components.

5. References

(1) See publications posted to LBNL website: http://corbu.lbl.gov/, for instance, regarding heat gain and daylighting: http://corbu.lbl.gov/pubs/pubs.php?code=Windows%20and%20Daylighting.

(2) Selkowitz, S.E., 'High Performance Glazing Systems: Architectural Opportunities for the 21st Century', Glass Processing Days, Tampere, Finland, 13-16 June 1999, Ed J. Vitkala, Tamglass Ltd. Oy, Tampere, Finland (1999), available at website: www.glassfiles.com.

(3) Ballinger, J.A. and Lyons, P.R., 'Advanced glazing technology for Australia – research and application', *Renewable Energy* **8** (1996) 61-65.

(4) Collins, R.E., Turner, G.M., Fischer-Cripps, A.C., Tang, J.-Z., Simko, T.M., Dey, C.J., Clugston, D.A., Zhang, Q.-C., and Garrison, J.D., 'Vacuum glazing – a new component for insulating windows', *Building and Environment* **30** (1995) 459-492.

(5) Anonymous, 'DTI – Energy consumption in the United Kingdom', Department of Trade and Industry Energy (DTI) Publications, London (2002).

(6) Weir, G. and Muneer, T., 'Low-emissivity coatings in high-performance double-glazed windows, energy, monetary and environmental costs', *Building Services Engineering Research and Technology* **18** (1997) 125-127.

(7) Aydin, O., 'Determination of optimum air-layer thickness in double-pane windows', *Energy and Buildings* **32** (2000) 303-308.

(8) Hammond, G.P., 'Thermal performance of advanced glazing systems', *Journal of the Institute of Energy* **74** (498) (2001) 2-10.

(9) Anonymous, 'EN 673 – Glass in building – Determination of thermal transmittance (U-value) – Calculation method', , CEN European Committee for Standardization, Rue de Stassart, 36, 1050 Brussels, Belgium.

(10) Roos, A. and Karlsson, J., 'Performance Criteria for Coated Glazings in Windows', Glass Processing Days, Tampere, Finland, 18–21 June 2001, Ed J. Vitkala, Tamglass Ltd. Oy, Tampere, Finland (2001), pp. 653-656, available at website: www.glassfiles.com.

(11) Menzies, G.F. and Wherrett, J.R., 'Multiglazed windows: potential for savings in energy, emissions and cost', *Building Services Engineering Research and Technology* **26** (3) (2005) 249-258.

(12) Weir, G. and Muneer, T., 'Low-emissivity coatings in high-performance double-glazed windows, energy, monetary and environmental costs', Building Services Engineering Research and Technology **18** (1997) 125- 127.

(13) Asif, M., Davidson, A., and Muneer, T., 'Embodied energy analysis of aluminium-clad windows', *Building Services Engineering Research and Technology* **22** (3) (2001) 195–199.

(14) Wei, G. and Muneer, T., 'Energy and environmental impact analysis of double-glazed windows', *Energy Conversion Management* **39** (1998) 243–256.

(15) Fernie, D. and Muneer, T., 'Monetary, energy and environmental implications for infill gases used in highperformance windows', *Building Services Research* **17** (1996) 43–45.

(16) Asif, M., 'Life cycle assessment of aluminium-clad timber windows', PhD Thesis, Napier University, Edinburgh, Scotland, United Kingdom (2002).

(17) Venkatarama-Reddy, B.V. and Jagadish, K.S., 'Embodied energy of common and alternative materials and technologies', *Energy and Buildings* **25** (2003) 129-137.

(18) According to EN ISO 10077-1 and -2, the thermal transmittance of a window is now calculated by a uniform method on a European level according to $U^w = (A_g \cdot U_g + A_f \cdot U_f + l_{fg} \cdot \Psi_{fg}) / (Ag + Af)$, wherein the equation parameters are defined as follows:

U_w	thermal transmittance of window (W/(m²K))
A_g	area of the glass (IGU) (m²)
U_g	thermal transmittance of glass (IGU) (W/(m²K))
A_f	area of frame (m²)
U_f	thermal transmittance of frame (W/(m²K))
l_{fg}	length of contact frame/glass (m)
Ψ_{fg}	linear thermal transmittance of frame to glass transition zone (W/(mK))

See: Anonymous, 'ISO 10077-1:2000 "Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 1: Simplified method', ISO International Standardization Organization, Geneva, 2000 and 'EN ISO 10077-1 – Thermal Performance of Windows, Doors, and Shutters – Calculation of Thermal Transmittance, Part 1: Simplified Method (ISO 10077-1:2000)', CEN European Committee for Standardization, July 2000.

(19) Asano, O., Futagami, T., Takamoto, T.,and Minaai, T., 'Vacuum Glazing for Transparent Thermal Insulating Material', Glass Processing Days 2003, Ed J. Vitkala, Tamglass Ltd. Oy, Tampere, Finland (2003), pp. 623-625.

(20) Anonymous, 'Absorption and desorption of water in glass/ethylene-vinyl-acetate/glass laminates', Polymer Testing, in print (manuscript accepted for publication on 2006-04-20 by Elsevier).

(21) Realini, A., 'MTBF – PVm – Mean Time Before Failure of Photovoltaic modules', Final report BBW 99.0579, Federal Office for Education and Science (BBW) Bern, Switzerland (June 2003).

(22) Jorgensen, G., Terwilliger, K., Glick, S., Pern, J., and McMahon, T., 'Materials testing for PV module encapsulation', presented at the National Center for Photovoltaics and Solar Program Review Meeting Denver, Colorado March 24-26, 2003, published (NREL/CP-520-33578) by NREL – National Renewable Energy Laboratory, Golden, Colorado, U.S.A (May 2003).

(23) Pern, F.J. and Jorgensen, G.J., 'Enhanced adhesion of EVA laminates to primed glass substrates subjected to damp heat exposure', presented at the 31st IEEE Photovoltaics Specialists Conference and Exhibition, Lake Buena Vista, Florida, January 3–7, 2005, published (NREL/CP-520-37391) by NREL – National Renewable Energy Laboratory, Golden, Colorado, U.S.A (February 2005).

(24) Anonymous, 'System solution for the manufacturing of photovoltaic-TPS® insulating glass units', Bystronic Glass, Lenhardt Maschinenbau GmbH, Neuhausen-Hamberg, Germany, website: www.bystronic-glass.com/.

(25) Anonymous, 'prEN 10077-2 – Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 2: Numerical method for frames', CEN European Committee for Standardization, August 2000.

(26) Calculations of linear thermal transmittance of edge-region Ψ (W/m K) for different spacers and two insulating glass units, from (Frank, 1994), calculations performed with a wood frame with U_f = 1.6 W/m²K and IG units with U_g = 2.7 W/m²K and U_g = 1.2 W/m²K yields Ψ (W/m K) as 0.046 and 0.057 for aluminum and 0.020 and 0.023 for silicone foam, respectively – Frank, T., 'Thermal improvements of IG edge seals', Seminar 'Energy Research in High-Rise Construction', 15/16 September 1994 (in German).

(27) Czanderna, A.W., 'Seal durability in insulating glass units: Summary of technical issues and recommendations to the Department of Energy', R. Anderson and J. R. Pitts, Editors, National Renewable Energy Laboratory (NREL), Golden, Colorado, U.S.A. (December 2000).

(28) Anonymous, 'ETAG 002 - Structural Sealant Glazing Systems, Part 1 (24 September 1998), Part 2 - Coated Aluminium Systems (16 January 2002), Part 3 - Systems incorporating profiles with thermal barrier (25 May 2002)', EOTA - European Organisation for Technical Approvals, Avenue des Arts 40, 1040 Brussels, Belgium.

(29) Anonymous, 'SG2000-00, SIGMA 20-Year Correlation Study', Insulating Glass Manufacturers Alliance(IGMA), Ottawa, Ontario, Canada (2000), website: http://www.igmaonline.org/).

(30) Anonymous, 'Cardinal® IG with XLEDGE™ - A New Direction With Reduced Risk', Cardinal Glass Industries Inc., Eden Prarier, Minnesota, U.S.A., website: www.cardinalcorp.com/.

(31) Wolf, A.T., 'Design and material selection factors that influence the service-life and utility value of dualsealed insulating glass units', 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia, 17–21 March 2002, CSIRO Publishing Service (2002) and Hautekeer, J.-P., Wolf, A.T., and Zhou, W., 'Key factors governing technologies used on the growing China insulating glass market', Glass Processing Days China 2006, Ed J. Vitkala, Tamglass Ltd. Oy, Tampere, Finland (2006), available at website: www.glassfiles.com.