Numerical Simulation of Thermal Performance of Window Retrofit Options for Historic Buildings

C. Misiopecki [1], A. Gustavsen [2],

ABSTRACT

Today saving energy and reducing carbon emissions is one of the top priorities for countries and communities. Windows are inseparable components of the building envelope with a significant impact on the indoor environment given they provide daylight, fresh air and views to the outside. The thermal transmittance of fenestration components is almost always lower than for walls, thus fenestration contributes substantially to the heat losses through the building envelope. Improved fenestration products have a huge potential to provide energy savings. Windows in historic buildings have a significant role in defining the style and character of individual buildings, thus historic fenestration should be respected as an integral part of the architectural heritage of the building. Currently, replacements of the traditional windows are performed more often than window retrofits due to the bad shape of window, cost or lack of knowledge of improving window efficiency. Regardless of the chosen solution the energy retrofit / upgrade of existing windows or window replacement (with unit of appearance and construction matching original window) usually leads to two-glass layer construction with an air gap in between. This study investigates different options for enhancing the performance of this kind of construction. Different glazing configurations also including shading devices have been investigated numerically in this study. Each configuration has been evaluated in terms of thermal, solar and visual properties. In addition, shading devices potential of improving window thermal performance is evaluated. Some general comments regarding application challenges and cost of each technology / solution are made.

Keywords

Windows, retrofits, upgrading, U-value, SHGC, visual transmittance, historical buildings

1. Introduction

Today saving energy and reducing carbon emissions is one of the top priorities for countries and communities. Energy use in buildings worldwide accounts for over 40% of the primary energy use and for around 24% of greenhouse gas emissions. This energy use and these emissions include the direct usage of fossil fuels (on-site), and the indirect use of energy in the form of electricity, heating, cooling and the embodied energy of the construction process and materials [1].

A study carried out by the International Energy Agency (IEA) shows that existing buildings will use most of the energy consumed by all buildings in the future. Predictions show that new buildings will only contribute 10-20% of the total energy consumed by buildings by 2050 in most industrialized countries. This indicates that more than 80% of the energy used in structures will be consumed by buildings that already exist [2].

Existing buildings may still be functional, occupied and be located in a prime location. Many of them have historical value and should be preserved. This motivates further research in retrofitting strategies, focusing on energy saving while preserving historical values.

Windows are inseparable components of the building envelope and façade design. On the one hand, windows contribute to a better standard of living by providing daylight and useful heat gains. On the other hand, windows may cause higher heat losses and undesirable heat gains. The thermal transmittance of fenestration components was in the past and remains till today lower than for walls. Even in new buildings a large share of the heat losses through the building envelope can be due to windows [3]. Therefore, improved fenestration products have a huge potential to provide energy savings.

Moreover, windows have a significant role in defining the style and character of individual buildings. Their design, materials used and technical solutions represent the historical style of the building. Fenestration products used in a building can be so special that based on their size, articulation, subdivision and formal variations, the age of the building can be determined with an accuracy of 10-20 years. Thus, historical windows should be respected as an integral part of the architectural heritage of a building [4] [5].

Recently, the replacement of traditional windows is performed mostly due to building efficiency legislation [6]. Inappropriate replacement windows or upgrades can ruin the historical value of the building dramatically and, in addition, cause problems of building physics nature, like condensation, and increased thermal bridging. In order to determine if window upgrading in historical buildings is possible, detailed studies should be conducted. The appearance of the window must be considered at the same level as thermal window performance. Regardless of

1 Ph.D. Candidate, Norwegian University of Science and Technology, Trondheim, Norway, cezarymisiopecki@gmail.com

2 Professor, Norwegian University of Science and Technology, Trondheim, Norway Arild.Gustavsen@ntnu.no

the chosen solution: energy retrofit / upgrade of existing windows or window replacement (with unit of appearance and construction matching original window) usually leads to two-glass layered constructions with a wide air gap in between. Examples of such a construction can be seen for cases of wooden and metal windows with secondary storm window / glazing installed from the inside. Installation of storm windows is a very popular and widely used upgrading option. Moreover, this glazing construction is also present in double-windows (so called box-windows), which were used in many European countries from 1855 to 1970 [4]. Improving efficiency of such construction is usually performed by application of glazing with better insulating properties. Technically, each layer (outside or inside glazing) might be modified / upgraded. Usually because of appearance and technical issues – the inner glass layer is modified.

This motivated us to investigate different options of enhancing performance of a double glass layer construction with air in between. Different glazing configurations also including shading devices have been investigated numerically. Each configuration has been evaluated in terms of thermal, solar and visual properties. In addition, the shading devices potential of improving the window's thermal performance is evaluated. Moreover, some general comments regarding application challenges and the cost of each technology / solution are made.

2. Scope, assumptions, limitations.

2.1 Scope

The scope of the paper is to:

- Investigate different window improvement options for double glass layered constructions with air in-between the panes, in terms of:
  - Thermal insulating properties (U-value),
  - Solar properties / performance (Solar Heat Gain Coefficient - SHGC). Please note that this study aims to show the maximum SHGC which can be achieved for each configuration. Number of glass layers and low-e coatings limits SHGC value to a certain level. Usually lowering the value of SHGC can be done by applying additional / other coatings with different spectrally selective properties,
  - Visual performance (specifically Visual Transmittance - VT) – similar as for SHGC, possibly high values which can be achieved for each configurations are reported,
  - Condensation resistance – this study does not aim to perform full condensation assessment of each configuration. Only the temperature of the center of the innermost pane is reported (the surface facing the indoor environment).
  - Application challenges and cost – general comments regarding application of each technology are made.
- Assess different shading devices influence on thermal performance and condensation. Shading devices are used in two locations – in between glass layers and on the inner side of the room.

2.2 Assumptions

The following assumptions were made:

- It was assumed for modeling purpose that shading devices placed between glass panes or on the inside of the inner pane, creates airtight cavity/cavities between glazing and shading device. In some market available solutions there might be some air exchange occurring, between environment and air gap, or between air gaps in the case where shade is located between the glass layers. However, from a technical point of view, it is possible to make those spaces relatively airtight (experiments will be performed in later studies to investigate this issue).

2.3 Limitations

- Frame and glazing edge effects are not considered in the study - only center-of-glazing properties are reported. Reported values standing alone cannot be directly used for determining the U-value of entire fenestration product (especially for windows including many relatively small glass panes), but still show the difference between the glazing part of the various solutions.
- Temperature of center-of-glass surface facing indoor environment is not the lowest temperature which may occur for a complete window. Thus this temperature cannot be used for condensation risk assessment. In this study this temperature is presented for initial comparison of different glazing systems. Complete windows will be studied in later research.
- This study shows possible high values of SHGC and VT for each configuration. SHGC and VT values can be lowered by application of different coatings, like low-e and coating with different spectral selective properties – which might influence color / transparency of glazing. Those properties should be determined for the needs of each climate and case separately.

3. Method

3.1 Definitions of window properties

The following properties of different glazing configurations are investigated numerically in the presented study:

- **U-value** [W/m^2K]– describes thermal insulating properties of fenestration product. The lower the U-value, the better the window's ability to resist heat losses. U-value is usually expressed in unit – [W/m^2K]. In this study the U-values for center-of-glazing are calculated using software WINDOW 7.0 [7].
- **SHGC** – (stands for Solar Heat Gain Coefficient) – determining solar heat gain through a fenestration product relative to the incident solar radiation. SHGC values are in the range of 0 to 1, where 1 indicates maximum heat gain – equal to the heat gain which would occur through the same area, without fenestration or any obstacle. In this study SHGC value is determined for incidence angle equal to 0° using WINDOW 7.0 software and database.
- **VT** – (stands for Visible Transmittance of light in the visible spectrum). This value tells how much light (in the visible portion of the light spectrum) passes through the glazing material. VT is important for assessing: daylight comfort, privacy and glare control. For clear glass

visible transmittance is at the level of 90% while for glazing with several layers and reflective coatings may be lower than 10%. VT value is estimated for each configuration using software WINDOWS 7.0.

- **Condensation Resistance** – defines how well a fenestration product resists condensation of water vapor (present in air) on a window surface. This ability is expressed as a number in range of 1 to 100. The higher the number the better, and the better the window is at resisting condensation. However, in this study products are only compared using lowest temperatures, which will occur on the center-of-glazing of the surface facing indoor environment. Those temperatures are calculated using software WINDOW 7.0.

3.2 Considered glazing options

This study considers different glazing products and different configurations in order to determine the best thermal, solar and visual performance. The following glazing solutions / technologies are considered:

- 2P – double-pane IGU (Insulating Glazing Unit) is a type of so-called insulating glazing which consists of glass panes, connected and sealed by spacer and sealant. This connection creates a sealed gap, which can be filled with different gases, typically argon, krypton, xenon or gas mixtures. That type of glazing was introduced in the 80s and is still widely used today. In the study, 2P glazing was modeled as a unit which consists of two 3 mm thick glass panes and 12 mm wide spacer. The unit employs different low-e coatings on different surfaces. Gas mixture: 95% of argon and 5% of air is used as a gas fill. Such a configuration is relatively cheap. The U-value of the 2P glazing unit used is calculated to be 1.22 W/m^{2}K – for a unit with employs one low-e (emissivity of 0.037) coating placed on surface number 3 (counted from the outside).
- 2P slim profile – is a type of double-pane glazing, incorporating slimmer spacer than a standard 2P unit in order to reduce the entire unit thickness. Those units are usually used for retrofitting purpose. Different types of this kind of glazing have been investigated by other authors [8]. Typically, slim profile double glazing units have overall unit thickness of 8.2 to 16 mm. Those units consist of two glass panes (3 mm thick) and spacer between – of thickness in the range from 3 to 8 mm. In order to achieve insulating properties below 2 W/m^{2}K krypton or a mixture of krypton and xenon is used as fill gas [9]. For the calculations in this study the following design of the 2P slim profile unit is used. A unit consists of two 3 mm thick glass-panes and 4 mm thick spacer. The gap is filled with a mixture of 95% of krypton and 5% of air. Calculated U-value for this unit (including one low-e coating on surface 3) is 1.79 W/m^{2}K.
- Vacuum glazing is a type of glazing which consists of two glass panes with a vacuum between them. Because of pressure gradient, vacuum glazing employs metal pillars between glass panes which are necessary in order to prevent glass breakage / deflection. Using pillars causes negative issues. Firstly, those that are visible from a certain distance, secondly causing thermal bridging, thus contributing to additional heat loss. Experimental testing of this kind of glazing has shown a U-value equal to 1.0 W/m^{2}K [9], while the manufacturer reports performance of the center of glass of around 1.4 W/m^{2}K [10]. In the study of Baker [9] it is not clear whether measurement accounted for effects caused by steel pillars. The maximum size of a unit which can be manufactured are 2400 mm x 1350 mm. Vacuum glazing has soldered edges in order to maintain vacuum. This can cause increased edge heat losses. The unit which parameters used in this study is based on, is a product manufactured by Pilkington. The former product name was enrgiKare, now it is Spacia™ and it is the same unit as tested by Baker [9]. The unit consists of 4 mm thick glass panes, a vacuum gap (thinner than 1 mm), and a 3 mm thick glass pane is used for further assessment. The following properties of vacuum are used:
  - Pressure – 0.0133 Pa / 0.00010 Torr,
  - Vacuum thickness – 0.4 mm,
  - Pillars (circular shape – diameter 0.5 mm, spacing 20mm) [10].

  Calculated U-value of such a unit employing one low-e coating is equal to: 1.36 W/m^{2}K.
- 3P – three pane IGU - incorporates 3 glass panes and two spacers. The typical configuration of 3P glazing is three 3 mm thick glass panes and two gaps filled with argon (12 mm thick) or filled with krypton (6 mm thick). For retrofitting purposes where thickness of unit plays an important role - thinner units are preferable. In our study the configuration of a 3P glazing unit with 9 mm thick gaps, filled with 95% krypton and 5% air was chosen. Triple pane units are usually relatively heavy and require stronger frames for their support. In order to address that issue, a suspended plastic film may replace the intermediate glass pane. 3P units with suspended films can be used with a variety of filling gases and can achieve the same properties as regular 3P units [11], while reducing weight and unit thickness (around 3mm). However, in this study the case with suspended film was not modeled. It can be assumed that units employing suspended film glazing can achieve similar performance to conventional 3P glazing, while keeping thickness of unit comparable to standard 2P units [11]. In this study, the 3P unit is modeled as a construction consisting of three 3 mm thick glass panes and two 9 mm thick gaps. A gas mixture containing 95% of krypton and 5% of air was used as filling gas. Calculated U-value of the unit with low-e coating applied to surface no. 3 and 5 equals 0.57 W/m^{2}K.
- Adhesive thin plastic films have already been used for many years in window technology mostly in order to improve glazing solar performance (lowering SHGC). Manufactures have over the years proven its durability and performance. For residential use, those films are often covered by lifetime warranty. Most of those films are made of thin polyester film (around 0.025 mm of thickness), which incorporates micro-thin transparent metal coatings – those define the solar spectral properties. Recently, new types of adhesive films were introduced, which along with solar spectral properties also

provide low emissivity. Such a film is able to improve thermal insulating properties of the window by reducing radiation losses. These kinds of films are offered e.g. by the company Vista (products EnerLogic™: VEP35 SR CDF and VEP70 SR CDF) [12] [13]. The films maybe incorporated in historical window upgrades – since they can be easily applied on the existing glass. This study considers configurations which use adhesive coatings. The market available product VEP70 SR CDF was chosen over VEP35 because of its higher Visible Light Transmittance and higher SHGC value [9]. For modeling purposes the following parameters of film VEP70 SR CDF [13] were used (in the case of enchasing single glass performance):

- Emissivity – 0.09
- VT – 70%
- SHGC – 0.51*

* This value is reported by the manufacturer and is calculated according to ISO 15099 [14] using NFRC boundary conditions [15].

• Shading devices – not only contribute to better occupant comfort (solar gain and glare control) but also contribute to improving window insulation properties. Wood et al. [16] experimentally investigated different strategies of improving the thermal insulating properties of historical, relatively low performing windows. Window shutters, curtains and different types of blinds were investigated. A double-hung window was restored and tested in the climatic chamber. Additional insulation was added on the interior side, tested and compared with the reference window. It was found that heavy curtains give 39% reduction in heat loss through the glazing, well fitted EPS shutters 64%, reflective roller blinds 66% and honey comb blinds a reduction around 60%. This motivated us to investigate the use different shading options in this study in order to enhance glazing thermal performance. Both options of installing shading devices in the wide air cavity and on the window's interior side were considered. The following types of shading were considered.

• Honeycomb-type blind. WINDOW 7.0 has the ability of calculating glazing thermal improvements using different shading options including honeycomb blinds (one-row construction). The methodology has been described by Curcija [17]. In that study, the size of single cell was set at 11 mm, for best thermal performance, based on findings [17]. In order to improve the thermal properties of honeycomb blinds – two-row systems have been used. For configurations including shading devices SHGC and VT were not reported, since blinds may be manufactured using different materials (having different spectral / visible properties) and those should be determined for individual cases - taking into account building location/ climate/purpose etc. The aim of using shades was to assess its insulating potential while shades remain closed –during the night or during the day in situations when the room is not occupied and heat gains are not desirable. The methodology described in papers [17] and [18] is used in order to assess thermal resistance of two - row honey comb shading units – with cell size of 11 mm. The geometry used for calculating the thermal performance is presented in Figure 1. Thermal resistance of the shade was calculated to be 0.20 m2K/W. The average blind thicknesses was assumed to be 16 mm, thus the conductivity was calculated to be 0.115 W/mK and this value is used further for calculations in WINDOW 7.0. Example picture of considered honey comb blind is presented in Error! Reference source not found..

• Additionally "plain-type" roller blinds are modeled in the study, which consist of plain material. These make a negligible contribution in conductive heat exchange – because of the very low material thickness. However, they can improve thermal performance by splitting the air cavity – which results in two separated convection loops and additional thermal resistance. As with honeycomb shades, the values of solar / visual performance are not reported.

• Pyrolytic low-e coatings (so-called hard coatings – are used in this study for surfaces which are facing a wide air gap). Using hard coatings was necessary, since those surfaces are exposed for cleaning / maintenance. The emissivity on those surfaces was set to 0.16 [19].

Figure 1 – Left: Sketch of double row honeycomb shades used for thermal calculation in THERM 7.1. Right: Temperature distribution of double row honeycomb shade determined by THERM 7.1.

Figure 2 – Example of double-row honeycomb shade. [20]

3.3 Numerical simulations

Numerous heat flow calculations have been performed to evaluate the glazing configuration properties. Calculations are carried out using the computer program WINDOW 7.0, developed by Lawrence Berkeley National Laboratory (LBNL), California, USA. WINDOW 7.0 evaluates glazing properties according to ISO EN 673 [21] while using ISO boundary conditions [14]. This method of calculation has been validated by other authors with good agreement between experimental and modeling results has been achieved [22].

4. Results

All together 37 different glazing configurations are proposed and considered. Simulation results are presented in Table 1, in which the first column indicates the technologies which are used for each set of configurations. The column labeled "Temp" – shows the lowest temperature on the most internal surface of the unit, facing the indoor environment. Cases 1 and 2 are presented for reference purposes; respectively they represent one glass pane construction (e.g. original 1P window before adding secondary glazing or storm window) and a typical construction of box-type windows with two clear glass layers. Cases from 3 to 9 use thin adhesive films manufactured by company EnerLogic with two different shading strategies. Cases from 10 to 13 and 17 to 20 represent respectively 2P and 2P slim profile configurations along with different shading strategies. Cases from 14 to 16 and 21 to 23 uses, in addition to 2P, EnerLogic films applied to the outside of the glass pane (this represents a construction in which the external glass pane remains original). Cases from 24 to 27 and 28 to 30 represent respectively options incorporating 3P glazing unit with different shading strategies and 3P glazing units with adhesive films applied to the outside glass. Similarly, cases from 31 to 34 and 35 to 37 represent vacuum glazing with different shading devices.

The lowest U-value is reported for configuration including 3P glazing, EnerLogic adhesive films and honeycomb type shading. U-value for that configuration equals 0.33 W/m^{2}K (closed shade) and 0.44 W/m^{2}K (open shade). As well for that configuration the lowest values of SHGC and visual transmittance are reported - equal 0.33 and 0.49 respectively.

As expected, results shows that honeycomb type shading provides better thermal improvement than plain shades.

Temperatures for center-of-glazing, except for the reference cases, of the surface facing indoor environment are higher than 16°C, which should not cause condensation problems in typical situations. However, please note that these are not the lowest temperatures that may occur in the glazing surface facing the indoor environment. (see above).

5. Discussion

Figure 3 presents and compares the solar, visible and thermal performance of simulated configurations, without shading devices. The red-dotted line indicates a U-value equal to 0.8 W/m^{2}K. This is the limit suggested by International Passive House Association.

Each configuration has been characterized in "cost" and "installation challenge" groups. Four cost classes are introduced. Class marked with single $ sign – represents the cheapest solution / configuration. In this class, the method of upgrading the glazing with adhesive films is placed. This method does not require replacing window frames or glazing. Film installation takes place on the building site and it is relatively fast and cheap. The second cost class ($$) includes 2P and 2P slim profiles, since these technologies are well developed and have been on the market for many years. The third cost class ($$$) includes more expensive 3P glazing and 3P with suspended films - since the manufacturing process of those units requires more materials and labor. It was concluded that the most expensive technology is the vacuum glazing, despite the fact that in most cases this kind of glazing can be used directly in existing frames, because of its low thickness. These units require advance production techniques; moreover as they are not in mass production, they are relatively expensive.

The next classification addresses installation challenges. In the "fairly easy to accommodate" group, technologies were included which do not require changing or manufacturing a new frame / sash. Adhesive films, vacuum glazing and 2P slim profile were classified as fairly easy to accommodate, thanks to their relatively low thickness and can be fitted to existing frames.

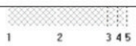
In this group two solutions are selected as the most suitable. Adhesive films (e.g. case no 3) – are able to provide thermal improvement by 38% in comparison to case no 2, while keeping VT and SHGC values at a relatively high level. This option is the least time and labor consuming of all the options. However, the achieved performance of 1.75 W/m^{2}K is relatively low. The second preferable solution is 2P slim profiles. Example case no 17, which incorporates this glazing provides very good thermal performance (1.06 W/m^{2}K, reduction of 80% in comparison to case no 2), while keeping VT and SHGC at a high level. It appears that vacuum glazing units have no advantages over 2P slim profile, except slimmer unit around 3 mm and slightly better thermal performance.

The next group which includes technologies classified as "required new construction" – are configurations which can be used both for upgrades of existing windows and in new constructions (e.g. unit reconstruction or adding storm windows). However, applying these solutions for upgrading will typically require manufacturing a new, secondary sash in the case box windows or new frames for secondary glazing/ storm windows. This is necessary in order to provide enough space and support for those glazing units. If the window is manufactured from scratch, it is relatively easy to design frames which will support these glazing units.

As was expected in this group, 3P units show better performance over 2P units. However, 2P units achieve relatively low U-values (close to U-values suggested for passive houses for the entire window product). 2P has advantages of thinner and lighter units – but this can be overcome by 3P units which incorporate suspended films.

Figure 4 shows and compares different units (with shading devices) in a similar way to Figure 3. Thermal performance of each configuration is assessed for 24 hours a day, with the assumption that shades remain closed during the night for 9 hours each day (example from 10 PM to 7 AM) and for the rest of the day – remain opened – 15 hours. This kind of regular controlling strategy can be achieved by an automatic control system. VT and SHGC values are reported for day operation (shading devices are open). Additional costs for installing shades are not included since shade installation might be required for the occupant's visual comfort. Installing honey-comb shades enhances thermal insulation the most for not highly performing configurations, like case 3 and 4. Application in these cases of honeycomb shades lowers

Table 1 Modeling results

	No	Screen (outside environment on the left)	Configuration*	Low-e*	U-value [W/m²K]	SHGC	VT	Temp [°C]
ref	1	Single glass pane	3-	-	5.83	0.90	0.90	5
	2		3-120(A)-3	-	2.80	0.74	0.81	13
EnerLogic (EL) films	3		3-120(A)-3	3(0.09)	1.75	0.58	0.63	16
	4		3-120(A)-3	2(0.09)and3(0.09)	1.65	0.39	0.49	16
	5		3-50(A)-16(S)-50(A)-3	2(0.09)and5(0.09)	0.70	x	x	18
	6		3-50(A)-16(S)-50(A)-3	5(0.09)	0.92	x	x	17
	7		3-60(A)-1(S)-60(A)-3	2(0.09)and5(0.09)	0.86	x	x	18
	8		3-60(A)-1(S)-60(A)-3	5(0.09)	1.20	x	x	17
	9		3-120(A)-3-10(A)-1(S)	3(0.09)	1.34			17
2P	10		3-120(A)-3-12(Ar95%)-3	3(0.16)and5(0.037)	0.84	0.56	0.70	18
	11		3-50(A)-16(S)-50(A)-3-12(Ar95%)-3	5(0.16)and7(0.037)	0.59	x	x	19
	12		3-60(A)-1(S)-60(A)-3-12(Ar95%)-3	5(0.16)and7(0.037)	0.70	x	x	18
	13		3-120(A)-3-12(Ar95%)-3-10(A)-1(S)	3(0.16)and5(0.037)	0.74	x	x	18
2P + EL	14	See case 10	3-120(A)-3-12(Ar95%)-3	2(0.09)and3(0.16)and5(0.037)	0.78	0.36	0.54	18
	15	See case 11	3-50(A)-16(S)-50(A)-3-12(Ar95%)-3	2(0.09)and5(0.16)and7(0.037)	0.48	x	x	19
	16	See case 12	3-60(A)-1(S)-60(A)-3-12(Ar95%)-3	2(0.09)and5(0.16)and7(0.037)	0.55	x	x	19
2P slim	17	See case 10	3-120(A)-3-4(K95%)-3	3(0.16)and5(0.037)	1.06	0.57	0.70	
	18	See case 11	3-50(A)-16(S)-50(A)-3-4(K95%)-3	5(0.16)and7(0.037)	0.70	x	x	18
	19	See case 12	3-60(A)-1(S)-60(A)-3-4(K95%)-3	5(0.16)and7(0.037)	0.85	x	x	18
	20	See case 13	3-120(A)-3-4(K95%)-3-10(A)-1(S)	3(0.16)and5(0.037)	0.90	x	x	18
2P slim + EL	21	See case 14	3-120(A)-3-12(K95%)-3	2(0.09)and3(0.16)and5(0.037)	0.98	0.36	0.54	18
	22	See case 15	3-50(A)-16(S)-50(A)-3-4(K95%)-3	2(0.09)and5(0.16)and7(0.037)	0.56	x	x	19
	23	See case 16	3-60(A)-1(S)-60(A)-3-4(K95%)-3	2(0.09)and5(0.16)and7(0.037)	0.66	x	x	18
3P	24		3-120(A)-3-9(K95%)-3-9(K95%)-3	3(0.16)and5(0.037)	0.46	0.48	0.63	19
	25		3-50(A)-16(S)-50(A)-3-9(K95%)-3-9(K95%)-3	5(0.16)and7(0.037)	0.38	x	x	19
	26		3-60(A)-1(S)-60(A)--3-9(K95%)-3-9(K95%)-3	5(0.16)and7(0.037)	0.41	x	x	19
	27		3-120(A)--3-9(K95%)-3-9(K95%)-3-10(A)-1(S)	3(0.16)and5(0.037)	0.43	x	x	19
3P + EL	28	See case 24	3-120(A)-3-9(K95%)-3-9(K95%)-3	2(0.09)and3(0.16)and5(0.037)	0.44	0.33	0.49	19
	29	See case 25	3-50(A)-16(S)-50(A)-3-9(K95%)-3-9(K95%)-3	2(0.09)and5(0.16)and7(0.037)	0.33	x	x	19
	30	See case 26	3-60(A)-1(S)-60(A)-3-9(K95%)-3-9(K95%)-3	2(0.09)and5(0.16)and7(0.037)	0.36	x	x	19
Vacuum	31	See case 10	3-120(A)-4-1(V)-3	3(0.16)and5(0.037)	0.88	0.57	0.70	18
	32	See case 11	3-50(A)-16(S)-50(A)-4-1(V)-3	5(0.16)and7(0.037)	0.62	x	x	18
	33	See case 12	3-60(A)-1(S)-60(A)-4-1(V)-3	5(0.16)and7(0.037)	0.73	x	x	18
	34	See case 13	3-120(A)-4-1(V)-3-10(A)-1(S)	3(0.16)and5(0.037)	0.77	x	x	18
Vacuum+ EL	35	See case 14	3-120(A)-4-1(V)-3	2(0.09)and3(0.16)and5(0.037)	0.82	0.37	0.54	18
	36	See case 15	3-50(A)-16(S)-50(A)-4-1(V)-3	2(0.09)and5(0.16)and7(0.037)	0.51	x	x	19
	37	See case 16	3-60(A)-1(S)-60(A)-4-1(V)-3	2(0.09)and5(0.16)and7(0.037)	0.58	x	x	19

* The following abbreviations were assigned in order to present each configuration: A-air, Ar-argon, K-krypton, S- shading device, V-vacuum. Example of decoding, case no 11: construction: 3 mm glass – 50 mm air gap – 16 mm shading device – 50 mm air gap – 3 mm glass – 12 mm gap filled with argon (95%) and air (5%) – 3 mm glass, low-e coatings: surface no 2 (counting from left side) low-e (emissivity equals to 0.09), surface 5 (emissivity 0.16), surface 7 (emissivity 0.037).

Note: shading devices of thickness of 16 mm symbolize honey comb shading, 1 mm shading device symbolize plain shade. Low-e which emissivity values are: 0.16 are hard coating, 0.09 EnerLogic thin films, 0.037 soft coatings.

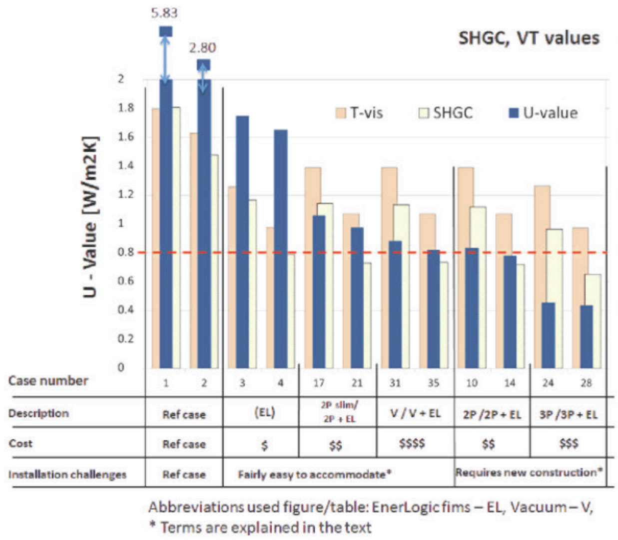


Figure 3 Comparison of different configuration performance (excluding shading devices).

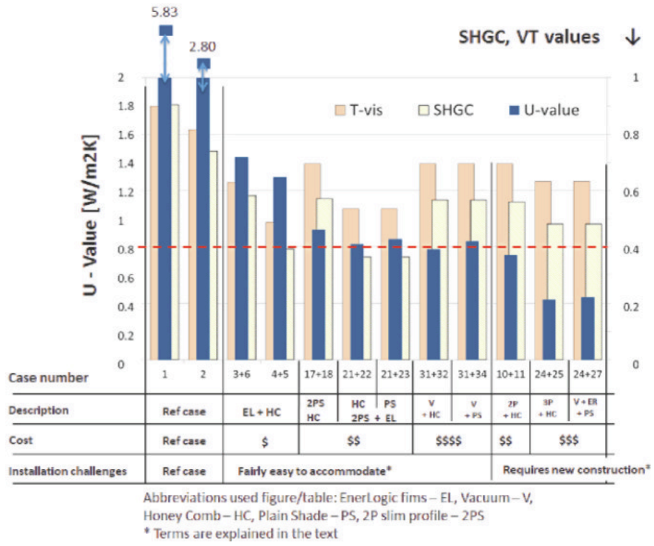


Figure 4 Comparison of different configuration daily performance (assumption was made that shading devices remained closed 9h per day (24h)).

U-value respectively to the value of 1.5 and 1.3 W/m^{2}K (see Figure 4, cases: 3+6 and 4+5). Using honeycomb shade with 2P slim profiles and 2P can lower U-value to values suggested by the International Passive House Association (in the case where two EnerLogic films were added on the original glazing). Using shades with highly performing units – like 3P -does not actually result in large U-value improvement.

6. Conclusion

This study shows that using vacuum glazing for upgrading two glass layer constructions with an air gap in between has no advantages over 2P slim profile units, except for the lower unit thickness (around 3 – 4 mm). 2P slim profiles seem to be the most suitable option for upgrading such a configuration. These glazing units can provide relatively good thermal performance, with moderate investment. Regarding upgrade solutions, adhesive films (e.g. EnerLogic VEP35) seem to be the most economic and relatively easy to apply option. This solution can be applied in the case of box windows which are in good condition and does not require frame or glazing fixing or replacing. Additionally, this upgrading scenario can be enhanced by using shading devices. Application of honeycomb shades gives additional thermal improvement. The U-value, calculated with the assumption that shades remain closed for 9h per day, is equal to 1.43 W/m^{2}K. However, this solution results in the lowest temperature on the surface facing the indoor environment – further investigation should be performed in order to assess condensation risk. Moreover, these findings could motivate the development of honeycomb shading with better insulating properties for this kind of upgrade strategy.

For cases requiring new construction (new secondary glazing, secondary frame or a new window unit) 2P and 3P glazing can be used. Both technologies achieve (very) low U-values. Using 2P units U-values can go to as low as 0.84 W/m^{2}K, while for 3P units this value can be lower by 50%. What window solution to use, should however be decided in each case, depending on the configuration of the building. It should also be remembered that 3P units have lower SHGC and VT values than typical 2P units. It was found that shading devices do not give high thermal improvements for these technologies.

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8. Further work

The work presented in this paper is a good starting point for further investigation of upgrading strategies for historical windows. Further work may focus on:

- assessment of condensation risk for different technologies by taking into consideration the convection loop which occurs in a relatively wide air gap,
- evaluating different technologies, taking into account edge of glass glazing performance – for different window sizes and types,
- developing shading devices with better insulating properties which are suitable for upgrading strategies,
- assessing how each technology influences airflow occurring in so-called supply / ventilation windows.

10. References

[1] K. Voss and E. Musall, "IEA-SHC Task 40 / ECBCS Annex 52 || Zero Energy Building | Zero Emission Building | Net Zero Energy Solar Buildings," 2010. [Online]. Available: http://members.iea-shc.org/task40/. [Accessed: 10-Apr-2013].

[2] International Energy Agency, Retrofit Strategies Design Guide Advanced Retrofit Strategies & 10 Steps to a Prefab Module, no. March. 2011.

[3] A. Gustavsen, D. Arasteh, B. P. Jelle, C. Curcija, and C. Kohler, “Developing Low-Conductance Window Frames: Capabilities and Limitations of Current Window Heat Transfer Design Tools,” vol. 16, no. 1, p. 2, Jan. 2008.

[4] Z. Lorinczi, “For the protection of out wooden windows - A practical guide.” 2008.

[5] W. Sedovic and J. H. Gotthelf, “What Replacement Windows Can’t Replace : The Real Cost of Removing Historic Windows,” 2003.

[6] English Heritage, “Building Regulations and Historic Buildings,” 2002.

[7] Lawrence Berkeley National Laboratory, “NFRC Simulation Manual,” no. December, 2011.

[8] N. Healh, P. Baker, and G. Menzies, “Technical Paper 9: Slim-profile double glazing. Thermal Perforamance and embodied energy,” 2010.

[9] P. Baker, “Technical Paper 1: Thermal Performance of Traditional Windows,” 2008.

[10] Pilkington, “SpaciaTM Brochoure - Frequently Asked Questions,” 2012.

[11] Alpen, “Advantages of Insulated Glass with Suspended Film,” 2012.

[12] S. DeBusk, “A Review and Examination of EnerLogic Window Film Performance Claims,” 2012.

[13] Solutia Inc., “Enener Logic Vep 70 SR CDF Series Brochure,” 2011.

[14] International Organization for Standardization, “ISO 15099 - Thermal performance of windows, doors and shading devices — Detailed calculations,” 2003.

[15] North America Fenerstration Council, “NFRC - 100 - 2010 - Procedure for Determining Fenestration Product U-factors,” 2010.

[16] C. Wood, B. Bordass, and P. Baker, “RESEARCH INTO THE THERMAL PERFORMANCE OF TRADITIONAL WINDOWS : TIMBER SASH WINDOWS - Executive summary,” 2009.

[17] R. Hart, “Use of Frame Cavity Models in THERM To Model Cell in Honeycomb Shades,” 2012.

[18] C. Curcija, “Thermal Modeling of Cellular Shades – Part 2 : Between Glazing Mounting,” 2012.

[19] Arkema, “Hard coat Low-E technology – now and in the future .,” 2004.

[20] Verticals ETC, “Webpage pictures,” 2013. [Online]. Available: http://www.blindsnh.com/honeycomb-shades.htm.

[21] International Organization for Standardization, “EN 673 - Glass in building - Determination of thermal transmittance (U-value) - Calculation method,” 1997.

[22] A. Homb and S. Uslokk, “Energy efficient windows with cultural value,” 2012.